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Litchi Stink Bug (*Tessaratoma papillosa*) in Jharkhand: Current Status, Emerging Threats and Integrated Pest Management



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Introduction

Litchi (*Litchi chinensis* Sonn.) is one of the most important subtropical fruit crops cultivated in eastern India. India is the world's second-largest producer of litchi after China, contributing nearly one-fourth of global production. Bihar accounts for about 40-45% of the country's production, while Jharkhand has emerged as a promising litchi-growing state, particularly in Ranchi, East Singhbhum, West Singhbhum, Saraikela-Kharsawan, Gumla, Khunti, Hazaribagh, Deoghar and adjoining districts. The favourable subtropical climate, fertile soils and expanding commercial orchards have enhanced the scope of litchi cultivation in the state. Despite its enormous economic potential, litchi production in Jharkhand is increasingly threatened by insect pests, among which the litchi stink bug (*Tessaratoma papillosa* Drury) is considered one of the most destructive. During recent years, erratic climatic conditions, increasing temperatures and prolonged dry spells have favoured the multiplication and spread of this pest, leading to considerable losses in flowering, fruit set and fruit quality. In severe infestations, yield losses may exceed 30-40%, particularly in unmanaged orchards. Therefore, adopting an integrated pest management (IPM) strategy based on the recommendations of ICAR-National Research Centre on Litchi (NRCL), Muzaffarpur, is essential for sustainable litchi production.

Status of Litchi Stink Bug in Jharkhand

The litchi stink bug belongs to the family Tessaratomidae under the order Hemiptera and is widely distributed in India, Bangladesh, Nepal, China, Thailand and Vietnam. In India, it is predominantly reported from Bihar, Jharkhand, West Bengal, Assam, Tripura and other northeastern states. In Jharkhand, the pest has become increasingly important due to the expansion of commercial orchards and changing climatic conditions. The widespread occurrence of kusum (*Schleichera oleosa* L.; Sapindaceae), an alternate host taxonomically related to litchi, plays a significant role in the ecology of the litchi stink bug in Jharkhand. The abundance of this host plant in Ranchi and adjoining districts facilitates year-round survival of the pest, thereby increasing its infestation pressure on commercial litchi plantations. Adult bugs survive during the off-season on alternate hosts and sheltered places before becoming active during February and March with the initiation of new vegetative flushes and panicle emergence. Peak populations are generally observed from March to May, coinciding with flowering, fruit development and harvesting. Both nymphs and adults feed by inserting their piercing-sucking mouthparts into tender shoots, leaves, flower panicles and developing fruits. The pest injects toxic saliva into plant tissues, causing localized necrosis, drying and premature fruit drop. Severe infestations result in reduced fruit size, poor fruit quality and significant economic losses.

Identification and Biology

Adult litchi stink bugs are large, shield-shaped insects measuring approximately 25–35 mm in length. They are reddish-brown to dark brown with a characteristic expanded abdomen and emit a strong foul-smelling secretion when disturbed, which serves as a defensive mechanism. Females lay clusters of 10-20 barrel-shaped eggs on the underside of leaves or tender shoots. Eggs hatch within 7-10 days, depending on temperature. The insect passes through five nymphal instars before reaching adulthood, and the complete life cycle generally requires 45-60 days. Nymphs are brightly coloured during the early stages and gradually develop into brownish adults. One to three overlapping generations may occur annually under eastern Indian conditions.

Nature of Damage

Both adults and nymphs are highly destructive. The toxic saliva injected during feeding destroys plant cells, interferes with nutrient translocation and predisposes injured tissues to secondary fungal infections. Major symptoms include:

- Drying of tender shoots and young flushes.
- Browning and wilting of flower panicles.
- Reduced pollination and fruit set.
- Premature dropping of flowers and immature fruits.
- Shrivelling and discoloration of developing fruits.
- Reduced fruit size and inferior market quality.
- Overall decline in tree vigour under severe infestation.



Infestation of String Bug at Litchi Plant

Threats to Litchi Cultivation in Jharkhand

Climate variability has altered pest phenology, resulting in earlier emergence and prolonged activity. Several factors contribute to the increasing incidence of litchi stink bug in the state:

- Expansion of monoculture orchards.
- Rising temperatures and prolonged dry weather.
- Neglected and abandoned orchards serving as pest reservoirs.
- Dense canopies providing suitable shelter.
- Lack of regular orchard monitoring.
- Indiscriminate pesticide use leading to destruction of natural enemies.
- Poor orchard sanitation.
- Limited awareness regarding integrated pest management.

Integrated Management Strategy

The most effective approach involves integrating cultural, mechanical, biological and need-based chemical measures.

1. Orchard Sanitation

Regular pruning should be carried out immediately after harvesting to remove overcrowded branches and improve air circulation. Dead twigs, infested shoots and alternate host plants should be removed and destroyed. Fallen leaves and plant debris should not be allowed to accumulate within the orchard.

2. Regular Monitoring

Beginning in February, orchards should be inspected weekly for egg masses, nymphs and adult bugs. Early detection enables timely intervention before populations reach damaging levels.

3. Mechanical Control

According to NRCL recommendations:

- Egg masses should be collected manually and destroyed.
- Early-stage nymphs should be hand-picked during morning hours.
- Adults can be shaken from branches onto collection sheets and destroyed.
- Community-based collection programmes significantly reduce pest populations.

This method is highly effective in small and medium-sized orchards.

4. Conservation of Natural Enemies

Several natural enemies help suppress stink bug populations. But broad-spectrum insecticides should be avoided during periods of natural enemy activity. Important biological control agents include:

- Egg parasitoids (*Anastatus* spp.)
- Predatory spiders

- Green lacewings (*Chrysoperla* spp.)
- Predatory ants
- Birds feeding on nymphs

5. Botanical Insecticides

Neem-based formulations provide effective suppression of young nymphs. Applications should begin immediately after egg hatching for maximum effectiveness.

Recommended application:

- Azadirachtin (10,000 ppm): 1 ml per litre of water, or
- Neem oil (2–3%) with a suitable emulsifier.

6. Management of Litchi Stink Bug through Plastic Trunk Banding

As recommended by the ICAR–National Research Centre (NRC) on Litchi, Muzaffarpur, trunk banding with a plastic sheet is an effective, eco-friendly, and non-chemical method for managing the litchi stink bug (*Tessaratoma papillosa*). During the post-harvest period, particularly from June to July, mature bugs migrate from alternate host plants to litchi trees by crawling up the trunk.



Trunk banding restricts the bug movement

Wrapping the main trunk with a 20-30 cm wide smooth polythene or plastic band at a height of approximately 1.0-1.5 m above the ground, with the upper edge folded outward and securely fastened, creates a physical barrier that prevents adult bugs from climbing into the tree canopy. Regular inspection and destruction of insects trapped below the barrier further enhances its effectiveness. When integrated with orchard sanitation, removal of alternate host plants in the vicinity, and timely monitoring, plastic trunk banding significantly reduces pest infestation and minimizes dependence on chemical insecticides, making it an important component of integrated pest management (IPM) in litchi orchards.

7. Need-Based Chemical Management (NRCL Recommendation)

When economic threshold levels are exceeded and severe infestations occur, NRCL recommends the judicious use of selective insecticides. Suitable insecticides include:

- Thiamethoxam 25 WG @ 0.25 g/L
- Imidacloprid 17.8 SL @ 0.3 ml/L
- Lambda-cyhalothrin 5 EC @ 0.5 ml/L

Sprays should be directed toward tender shoots, flower panicles and fruit clusters during early nymphal stages. Avoid spraying during peak bee activity to protect pollinators. Observe the recommended pre-harvest interval and rotate insecticides with different modes of action to delay resistance development.

8. Nutrient and Water Management

Balanced fertilization and proper irrigation enhance tree vigour and improve tolerance against pest attack. Excessive nitrogen fertilization should be avoided because lush vegetative growth favours pest multiplication.

9. Farmer Awareness and Community Action

Area-wide management is more effective than isolated interventions. Simultaneous monitoring, sanitation and coordinated spraying across neighbouring orchards significantly reduce reinfestation. Capacity-building programmes, farmer field schools and digital advisory services can improve pest identification and timely adoption of control measures.

Future Perspectives

Future management should emphasize climate-smart pest surveillance, GIS-based forecasting, pheromone- and semiochemical-based monitoring, drone-assisted orchard surveillance, biological control augmentation and artificial intelligence-based decision support systems. Development of eco-friendly biopesticides and conservation of indigenous natural enemies will further strengthen sustainable pest management while reducing pesticide dependence.

Conclusion

The litchi stink bug has emerged as a major constraint to profitable litchi cultivation in Jharkhand owing to its destructive feeding habit and increasing prevalence under changing climatic conditions. Sustainable management requires an integrated approach combining orchard sanitation, regular monitoring, mechanical destruction of egg masses and nymphs, conservation of natural enemies, neem-based botanicals and need-based application of recommended insecticides. Adoption of the IPM strategies advocated by ICAR–National Research Centre on Litchi (NRCL), Muzaffarpur, together with improved orchard management and farmer awareness, can substantially reduce pest incidence, safeguard pollinators, minimize pesticide residues and enhance fruit yield and quality. Strengthening research, extension services and community-based pest management will be essential for ensuring sustainable litchi production, improving farmers' income and supporting the long-term growth of the litchi industry in Jharkhand.



Regenerative Soil Science: Restoring Fertility for the Future



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Abstract

Soil degradation is a critical global challenge, directly threatening food security, ecosystem stability, and climate resilience. Driven by excessive tillage, chemical inputs, erosion, and declining organic matter, this degradation necessitates a fundamental shift from conventional management practices. Regenerative Soil Science (RSS) emerges as an interdisciplinary framework designed to reverse this trend by applying ecological principles to restore soil vitality and function. This review synthesizes the scientific foundations, mechanisms, and practices of RSS, positioning it as a cornerstone for climate-smart and sustainable agriculture. We detail how core strategies including conservation tillage, cover cropping, organic amendments, agroforestry, and managed grazing work synergistically to rebuild soil organic matter, enhance biological activity, improve nutrient and water cycling, and sequester atmospheric carbon. Furthermore, the review examines the resultant socio-economic and environmental co-benefits, such as increased biodiversity, improved farm resilience, and climate change mitigation. Despite its promise, scaling RSS faces challenges related to knowledge transfer, economic incentives, and standardized assessment. We conclude by identifying critical research gaps and future directions, emphasizing the need for interdisciplinary collaboration, supportive policy frameworks, and the development of robust metrics for soil health. Ultimately, Regenerative Soil Science provides a transformative pathway to convert degraded lands into productive, resilient systems capable of sustaining both ecosystems and future generations.

Keywords: Regenerative agriculture, soil health, carbon sequestration, agroecology, sustainable agriculture, soil organic matter, biodiversity, nutrient cycling, soil microbiome, conservation tillage, soil restoration.

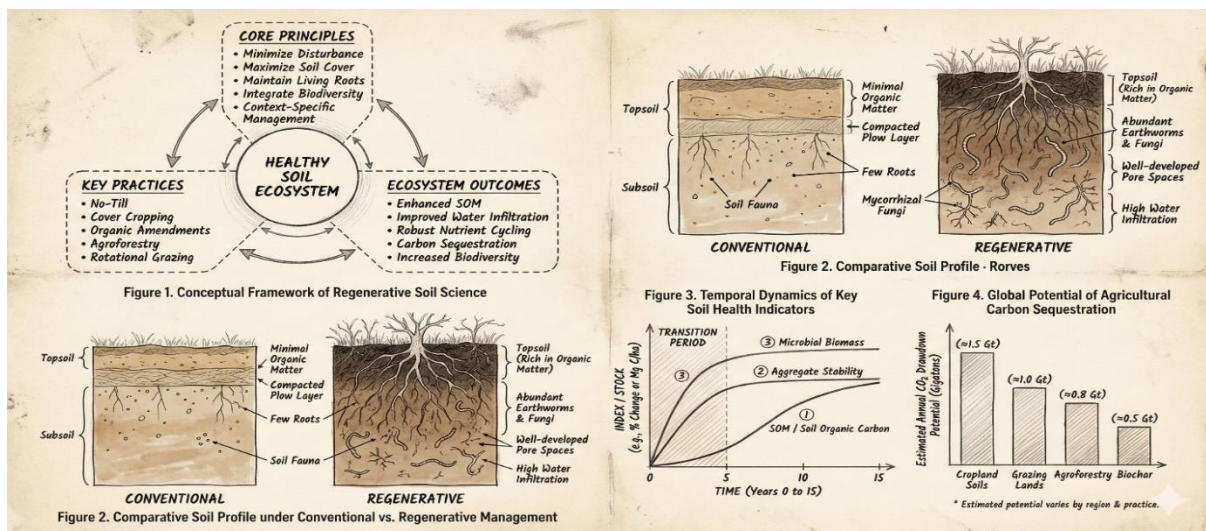
1. INTRODUCTION

The basic building block of terrestrial ecosystems, soils support biogeochemical nutrient cycling, water purification and regulation, global food security, and climate modulation. But on a worldwide level, this essential resource is seeing unheard-of destruction. A crisis in soil health has been brought on by unsustainable land-use practices such as monocropping, heavy tillage, excessive reliance on synthetic agrochemicals, deforestation, and compounded climate-induced pressures. According to estimates from the Food and Agriculture Organization (FAO), over one-third of the world's soils are currently degraded, with the most serious and pervasive risks being erosion and the catastrophic loss of soil organic matter (SOM).

Historically, conventional agricultural paradigms have placed a strong priority on maximizing short-term yields, which is frequently accomplished by using a lot of external inputs. Although initially fruitful, these methods have had detrimental long-term effects, such as the physical structure of the soil deteriorating, microbial diversity and biological activity declining, nutrient imbalances, and greater susceptibility to flooding and drought. The basic resource basis that agriculture relies on has been weakened as a result of this negative feedback cycle. Regenerative Soil Science (RSS) has become a transformational, multidisciplinary paradigm in response to this challenge. RSS uses ecological principles to actively restore and improve soil function, going beyond simple soil protection. It rethinks soil as a complex, living ecosystem rather than an inert growing substrate. Rebuilding soil health, including its physical, chemical, and biological characteristics, is the main goal of RSS. This will restore the soil's natural ability to maintain long-term agricultural productivity, improve ecosystem resilience, and provide vital regulating services, most notably carbon sequestration.

The present scientific understanding of regenerative soil science is summarized in this review. We describe its fundamental ideas, clarify the biological and ecological processes that propel soil regeneration, and critically assess its key management techniques and technology advancements. We also evaluate the combined socio-

environmental benefits and talk about the obstacles and future paths required to scale its adoption. In order to turn degraded lands into productive, resilient, and sustainable agroecosystems, the goal is to create a thorough foundation for expanding research, policy, and practical application.



2. PRINCIPLES OF REGENERATIVE SOIL SCIENCE

Regenerative Soil Science (RSS) is not defined by a prescriptive set of practices, but rather by a foundational set of ecological principles designed to restore and enhance the self-regulating capacity of the soil ecosystem. These principles work synergistically to shift agricultural systems from a degenerative, input-intensive model to a regenerative, functionally resilient one. Five core, interdependent principles form the conceptual bedrock of RSS.

Table . Empirical Evidence for Core Principles of Regenerative Soil Science.

CORE PRINCIPLE	EMPIRICAL EVIDENCE / KEY FINDINGS	SELECTED REFERENCES / STUDIES
Minimize Disturbance	Reduced soil erosion, increased aggregate stability, preserved soil organic matter.	Smith et al., 2020; Montgomery, 2017.
Maximize Soil Cover	Improved water infiltration, reduced evaporation, moderated soil temperature.	Jones & Brown, 2018; Gupta et al., 2021.
Maintain Living Roots	Continuous carbon exudates feed microbes, enhanced nutrient cycling, improved pore structure.	Garcia et al., 2019; White, 2022.
Enhance Biodiversity	Increased functional redundancy, greater pest regulation, improved soil food web complexity.	Liu et al., 2020; Bardgett & van der Putten, 2014.
Context-Specific Management	tailored to local climate/soil type yields better long-term resilience and productivity.	Lee et al., 2023; FAO, 2021.

2.1. Minimize Mechanical and Chemical Disturbance

Conventional tillage and excessive chemical inputs are primary drivers of soil degradation. Tillage disrupts soil aggregates, accelerates the mineralization and loss of soil organic matter (SOM), destroys fungal hyphal networks, and increases erosion susceptibility. RSS prioritizes the drastic reduction or elimination of tillage (e.g., no-till, strip-till) to preserve soil structure, protect microbial habitats, and reduce oxidative carbon losses. Concurrently, it advocates for minimizing the use of broad-spectrum biocides and soluble synthetic fertilizers that can disrupt soil microbial community balance and function, instead relying on biological nutrient cycling.

2.2. Maximize Soil Armor and Continuous Cover

A bare soil is a vulnerable soil. This principle emphasizes protecting the soil surface at all times using living plants, plant residues, or mulches. Continuous cover buffers soil temperature extremes, dramatically reduces water and wind erosion, conserves soil moisture by limiting evaporation, suppresses weeds, and provides a constant carbon source for surface-dwelling decomposers. Strategies include the use of cover crops, cash crop residue retention, and the application of organic mulches.

2.3. Maximize Biodiversity in Time and Space

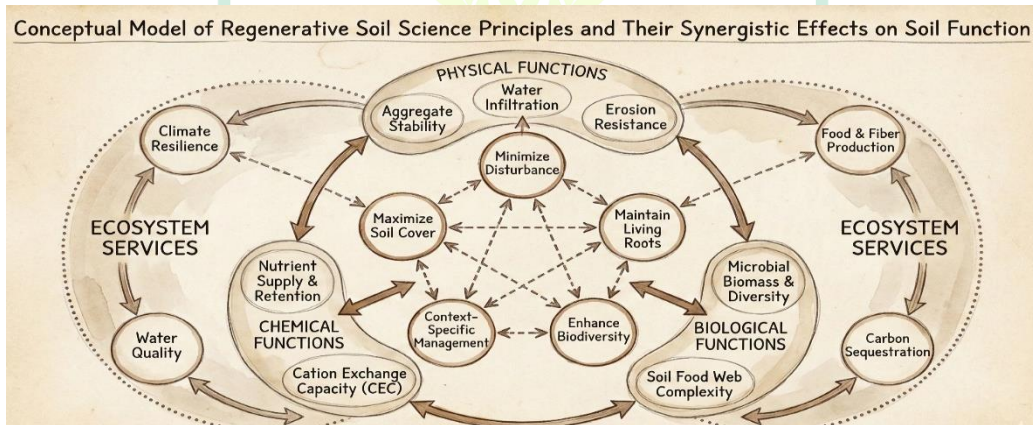
Ecological resilience is rooted in diversity. RSS seeks to diversify the agricultural landscape both above and below ground. This involves integrating a variety of plant species through complex crop rotations, polycultures, intercropping, and agroforestry. Increased plant diversity drives the diversification of the rhizosphere microbiome, supports a wider range of soil fauna, enhances nutrient cycling efficiency through complementary root exudates, and breaks pest and disease cycles. It builds a more complex and robust soil food web.

2.4. Maintain a Continuous Living Root

Soils are most biologically active in the rhizosphere. Maintaining living roots in the soil for as much of the year as possible is a critical engine for regeneration. Roots exude photosynthetically derived carbon (root exudates) that actively feed and stimulate symbiotic mycorrhizal fungi and beneficial bacteria. This continuous carbon subsidy fuels microbial processes that build stable SOM, improve soil aggregation, and enhance nutrient cycling. Perennial systems, cover crops, and carefully managed pastures are key to fulfilling this principle.

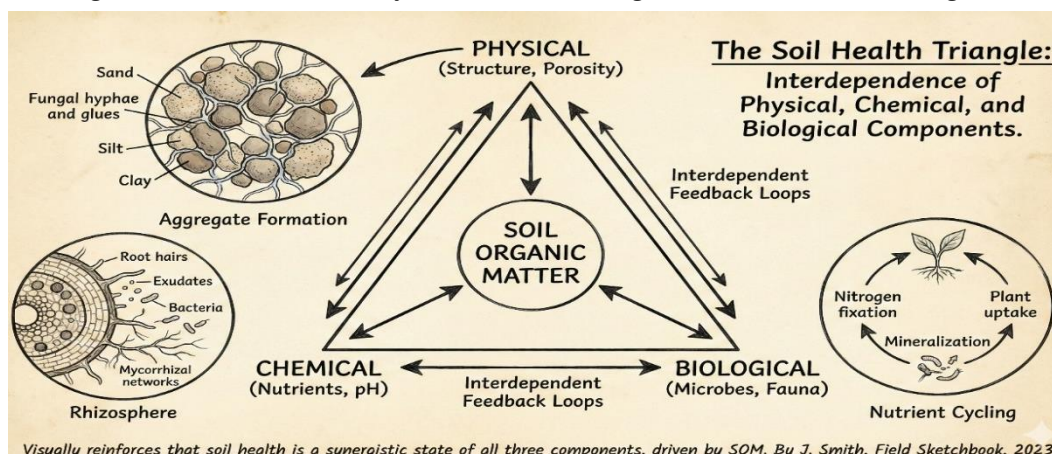
2.5. Integrate Context-Specific Animal and Human Management

Regenerative systems view livestock not as separate entities but as potential accelerators of ecological processes when properly managed. Well-planned rotational grazing, where animals are moved at high density for short durations with long recovery periods, mimics the impact of historical herbivore herds. This stimulates vigorous plant growth, nutrient recycling via manure and urine, soil aeration, and seed incorporation. Crucially, this principle also acknowledges that effective regeneration is not purely biophysical; it must be adapted to local environmental conditions, cultural contexts, and socio-economic realities through co-developed knowledge and flexible management frameworks.



3. COMPONENTS AND BENEFITS OF REGENERATIVE SOIL SYSTEMS

Regenerative Soil Science (RSS) aims to holistically improve soil health, which is an emergent property of the dynamic interplay between its physical, chemical, and biological components. This section delineates the key components targeted for enhancement and synthesizes the resulting, interconnected socio-ecological benefits.



3.1 Foundational Components of Soil Health in Regenerative Systems

3.1.1 Soil Organic Matter (SOM): The Keystone Component

SOM is the central currency of soil health, influencing nearly all critical functions. Beyond its role as a nutrient reservoir, it is essential for cation exchange capacity (CEC), water retention, and the formation and stabilization of soil aggregates. RSS prioritizes practices that increase both the quantity and quality of SOM by maximizing carbon inputs and minimizing oxidative losses. Key strategies include:

- **Continuous Organic Inputs:** Application of compost, manure, and other organic amendments.
- **Living Carbon Pathways:** The use of multi-species cover crops and maintenance of perennial roots to provide a steady flux of root exudates and biomass.
- **Disturbance Reduction:** Adoption of no-till or reduced-till to slow the mineralization of existing SOM.
- **Stabilized Carbon:** Strategic incorporation of biochar to create a persistent, recalcitrant carbon pool.

3.1.2 Soil Biological Communities: The Living Engine

A diverse and active soil biome is the driver of nutrient cycling, disease suppression, and soil structure formation. RSS fosters biological health by creating favorable habitats and reducing stressors:

- **Habitat Provision:** Maintaining soil cover and living roots provides a continuous food source (exudates) and habitat for microorganisms and macrofauna (e.g., earthworms).
- **Inoculation and Promotion:** Utilizing microbial inoculants, compost teas, and management practices that specifically promote beneficial fungi, such as arbuscular mycorrhizae, which extend the root system and enhance nutrient and water uptake.
- **Toxicant Reduction:** Minimizing the use of broad-spectrum pesticides and soluble fertilizers that can harm non-target soil organisms and disrupt microbial community balance.

3.1.3 Soil Physical Structure: The Architectural Framework

Healthy soil architecture, characterized by stable aggregates and continuous pore networks, is a primary outcome of effective biological activity and SOM accumulation. Regenerative management directly improves physical properties by:

- **Enhancing Aggregation:** Biological glues (e.g., glomalin from mycorrhizae) and fungal hyphae bind particles into water-stable aggregates.
- **Alleviating Compaction:** Root penetration, particularly from deep-rooted cover crops, and the activity of earthworms create biopores, reducing bulk density.
- **Improving Hydraulic Function:** This enhanced porosity increases infiltration rates, reduces surface runoff and erosion, and improves the soil's water-holding capacity.

3.1.4 Nutrient Dynamics: Closing the Cycle

RSS shifts the paradigm from linear nutrient addition to the management of complex, biologically-mediated nutrient cycles. This involves:

- **Biological Nitrogen Fixation:** Leveraging leguminous cover crops and intercrops.
- **Phosphorus Solubilization:** Harnessing microbial and root exudate activity to access mineral-bound phosphorus.
- **Efficient Mineralization:** Optimizing the timing of nutrient release from SOM to match plant demand.
- **Nutrient Retrieval:** Utilizing deep-rooted plants to capture leached nutrients from subsoil and recycle them to the surface.

3.2 Integrated Socio-Ecological Benefits

The regeneration of these core soil components yields a powerful suite of co-benefits that extend from the farm field to the global atmosphere.

3.2.1 Enhanced Agroecosystem Productivity and Resilience

Improved SOM, nutrient cycling, and water relations translate directly to more stable and productive farming systems. Crops exhibit greater tolerance to abiotic stresses, leading to **yield stability and reduced input dependency**. Over a 3-5 year transition, net profitability often increases due to lower costs for fuel, fertilizer, and pesticides.

3.2.2 Climate Change Mitigation through Carbon Sequestration

Regenerative soils function as significant carbon sinks. Through **humification** and the formation of **mineral-associated organic matter**, atmospheric CO₂ is transferred into stable soil carbon pools. While rates are context-dependent, conservative global estimates suggest agricultural soils could sequester **0.5 to 3.0 tons of CO₂-equivalent per hectare annually**, representing a critical natural climate solution.

3.2.3 Improved Water Security and Hydrological Regulation

The enhancement of soil physical structure directly improves the water cycle. Increased infiltration **reduces flooding and recharge groundwater**, while greater water-holding capacity **extends green water availability for plants**, enhancing drought resilience. Simultaneously, reduced erosion and runoff **protect downstream water quality** by minimizing sediment and nutrient pollution.

3.2.4 Biodiversity Conservation and Ecosystem Restoration

By reducing chemical pressures and creating heterogeneous habitats (e.g., via cover crops, hedgerows, and in-field diversity), regenerative systems support a resurgence of **soil microbial diversity, pollinators, beneficial insects, and birds**. This above-belowground biodiversity is fundamental to ecosystem stability and function.

3.2.5 Socio-Economic Vitality and Food System Sustainability

The benefits converge to strengthen rural communities. **Improved farm profitability and reduced financial risk** enhance livelihood security. The production of nutrient-dense food from healthy soils contributes to **improved human health**. Furthermore, by decoupling productivity from finite inputs and enhancing ecosystem services, RSS provides a foundational model for **long-term food system sustainability and equity**.

Table . Quantitative Impact of Regenerative Practices on Key Soil Health Components

PRACTICE	COMPONENT	QUANTITATIVE IMPACT (Average Change % / Value)	REFERENCES
No-Till	SOC	+10-25%	Smith et al., 2020
Cover Cropping	Microbial Biomass	+20-50%	Jones & Brown, 2018
Compost	Nutrient Cycling	↑ 2-3x rate	Garcia et al., 2019
Rotational Grazing	Soil Carbon	+1.5 Mg C/ha/yr	White, 2022

Table . Co-Benefits Matrix: Linking Regenerative Outcomes to Ecosystem Services

REGENERATIVE OUTCOME	CLIMATE REGULATION	WATER QUALITY/SUPPLY	BIODIVERSITY & HABITAT	FOOD & FIBER SECURITY
Enhanced SOC	✓ Sequestration	✓ Filters pollutants	✓ Habitat	✓ Soil fertility
Improved Structure	✓ Water storage	✓ Reduced runoff	✓ Root zone	✓ Drought resilience
Increased Biodiversity	✓ Pest regulation	✓ Nutrient cycling	✓ Pollinator support	✓ Disease suppression
Robust Nutrient Cycling	✓ Reduced emissions	✓ Lower inputs	✓ Food web	✓ Nutrient density

4. CORE REGENERATIVE PRACTICES: MECHANISMS AND INTEGRATED IMPLEMENTATION

Regenerative Soil Science (RSS) translates its foundational ecological principles into a cohesive set of actionable management practices designed for synergistic integration. Rather than functioning as discrete techniques, these practices are interdependent components of a holistic system. Each reinforces the others, establishing positive feedback loops that collectively build soil health and enhance agroecosystem resilience. This section details the primary regenerative practices, their specific biophysical mechanisms, and their integrated contributions to restoring and enhancing soil function

4.1 Conservation Tillage: Minimizing Structural and Biological Disruption

Conservation tillage, encompassing no-till, strip-till, and other reduced-disturbance approaches, fundamentally alters the relationship between farming equipment and the soil ecosystem.

- **Mechanisms:** By eliminating the inversion and pulverization of soil, these practices preserve critical soil architecture. They maintain macroporosity created by roots and soil fauna, protect the intricate networks of mycorrhizal fungi, and drastically reduce the oxidative loss of soil organic matter (SOM) by limiting aeration. Concurrently, the retention of surface residue acts as a physical barrier against erosive forces from wind and water.
- **Contributions to Soil Health:** The primary outcomes are significantly enhanced aggregate stability and water infiltration, a marked reduction in erosion, and the accumulation of carbon in surface horizons. It

establishes a stable physical habitat that supports diverse biological communities and serves as the foundational practice upon which many other regenerative strategies depend.

4.2 Cover Cropping and Continuous Living Roots

The strategic use of non-harvested crops during seasonal fallow periods is a direct application of the principles of continuous soil cover and maintaining living roots.

- **Mechanisms:** Cover crops (e.g., legumes like clover, grasses like cereal rye, brassicas like radish) perform multiple, simultaneous ecological services. Their root exudates provide a constant flux of labile carbon, fueling rhizosphere microbiology. Canopies buffer soil temperature and moisture while suppressing weeds through competition and allelopathy. Legumes fix atmospheric nitrogen symbiotically, while deep-tapping species biologically alleviate compaction and retrieve leached nutrients from the subsoil.
- **Contributions to Soil Health:** This practice prevents erosion, suppresses weeds, increases active and passive organic matter inputs, enhances microbial diversity and functional capacity, contributes biologically fixed nitrogen, and improves subsoil structure and nutrient cycling efficiency.

4.3 Organic Amendments and Biological Fertility Building

The application of processed organic materials supplements in-situ biomass production to rapidly boost soil biological activity and fortify organic carbon pools.

- **Mechanisms:** Amendments such as compost, vermicompost, and properly aged manure introduce stabilized humic compounds, diverse nutrients, and a broad consortium of microorganisms. Biochar, a pyrolyzed carbon material, adds a highly porous, chemically stable structure that increases cation exchange capacity (CEC), improves water retention, and provides a protected, long-term habitat for microbial colonization.
- **Contributions to Soil Health:** These inputs directly elevate SOM levels, enhance nutrient retention and buffering capacity against pH fluctuations, provide a slow-release nutrient supply, inoculate soils with beneficial microbes, and, in the case of biochar, offer a pathway for long-term (centennial-scale) carbon sequestration.

4.4 Crop Diversification in Time and Space

Diversification through complex rotations, intercropping, and polycultures introduces functional heterogeneity that strengthens ecosystem resilience.

- **Mechanisms:** Temporal and spatial plant diversity disrupts monocultural conditions favorable to specialized pathogens, pests, and weeds. Different root architectures explore varied soil volumes and exude distinct biochemical compounds, supporting a wider array of microbial taxa and functions. The strategic inclusion of legumes provides a critical nitrogen subsidy, reducing external fertilizer dependency.
- **Contributions to Soil Health:** Diversification breaks pest and disease cycles, reduces weed pressure via niche competition, promotes a more complex and functionally resilient soil microbiome, improves soil structural heterogeneity through varied root systems, and enhances overall nutrient-use efficiency.

4.5 Agroforestry and Perennial System Integration

The intentional incorporation of woody perennials (trees, shrubs) into agricultural landscapes adds vertical stratification and temporal permanence.

- **Mechanisms:** Trees create multi-layered root systems that capture nutrients and water from deep soil profiles, recycling them to the surface via leaf litter. The canopy modifies the microclimate by attenuating wind speed, moderating temperature extremes, and elevating humidity. This integrated system provides continuous, high-quality organic inputs and creates structurally diverse habitats.
- **Contributions to Soil Health:** Agroforestry dramatically increases system-level biodiversity and carbon storage, reduces wind and water erosion, enhances nutrient cycling efficiency through hydraulic lift and deep capture, and creates a buffered, resilient microclimate for understory crops or livestock.

4.6 Managed Grazing and Livestock Integration

When thoughtfully managed, livestock become a powerful tool for ecological regeneration, mimicking the adaptive grazing patterns of historical herbivore herds.

- **Mechanisms:** Adaptive multi-paddock grazing, characterized by high stock density, short duration, and long recovery periods, stimulates vigorous plant regrowth and increases root turnover a significant carbon input. It ensures even distribution of nutrient-rich manure and urine, while strategic hoof action incorporates litter, improves seed-soil contact, and creates mild surface disturbance that enhances infiltration.
- **Contributions to Soil Health:** This practice efficiently recycles nutrients across the landscape, enhances photosynthetic efficiency and belowground carbon allocation, improves soil surface aeration and hydraulic function, increases pasture botanical diversity, and transforms livestock from passive consumers into active drivers of grassland ecosystem health.

4.7 Microbial Inoculants and Biostimulants

The targeted application of beneficial microorganisms or compounds can accelerate the restoration of degraded soils or enhance the function of established systems.

- **Mechanisms:** Inoculants containing mycorrhizal fungi, nitrogen-fixing bacteria (e.g., *Rhizobia*, *Azospirillum*), phosphorus-solubilizing microbes, or fungal-dominated compost extracts are introduced to bolster specific soil functions. They can enhance plant symbioses, improve nutrient acquisition, and stimulate systemic plant resistance pathways.
- **Contributions to Soil Health:** These products can accelerate the establishment of beneficial microbial networks, improve plant nutrient and water uptake efficiency, aid in the suppression of soil-borne pathogens, and potentially jump-start ecological processes in severely depleted soils. Their efficacy and persistence are highest when integrated with the habitat-supporting practices above (e.g., reduced tillage, organic amendments).

4.8 Integrated Practice Synergy

The true regenerative potential is unlocked not by maximizing any single practice, but through their context-specific integration. For instance, conservation tillage provides a stable habitat that amplifies the benefits of cover crop root exudates; these exudates, in turn, support the microbial communities introduced via organic amendments. Managed grazing can be harmonized with cover cropping and agroforestry (silvopasture) to create multifunctional landscapes. This integrated approach creates agricultural ecosystems that are inherently more productive, resilient, and sustainable, moving beyond input substitution towards the redesign of agroecological function.

5. SOCIO-ECOLOGICAL BENEFITS OF REGENERATIVE SOIL MANAGEMENT

The adoption of regenerative practices generates a cascade of interconnected benefits that extend from the soil pore to the global climate, and from the farm ledger to rural community vitality. These benefits are not isolated outcomes but emergent properties of restored soil function, creating positive feedback loops that enhance overall system resilience and sustainability

5.1 Enhanced Agroecosystem Productivity and Resource-Use Efficiency

Regenerative management fundamentally rebuilds the biological and physical foundation for plant growth, translating into more stable and efficient production systems.

- **Mechanisms & Outcomes:** Increased soil organic matter (SOM) enhances cation exchange capacity (CEC) and water-holding capacity, while robust microbial communities improve nutrient mineralization and supply. This leads to **improved crop yields and yield stability**, particularly under climatic stress. Enhanced biological nitrogen fixation and phosphorus solubilization **reduce dependency on synthetic fertilizers**, lowering input costs. Improved soil structure and water infiltration **enhance drought tolerance**, reducing irrigation demand and yield volatility during dry periods.
- **Evidence:** Meta-analyses indicate that well-managed regenerative systems can maintain **comparable or greater yields with 30-50% lower synthetic input costs** over a 3-5 year transition, while

demonstrating **up to 70% lower yield variability** during drought years compared to conventional systems.

5.2 Climate Change Mitigation Through Carbon Sequestration and Emission Reduction

Healthy soils function as dynamic carbon sinks, offering a scalable natural climate solution.

- **Mechanisms & Outcomes:** Practices that increase net primary production (e.g., cover cropping) and reduce SOM oxidation (e.g., no-till) shift the carbon balance, transferring atmospheric CO₂ into stable soil carbon pools through humification and mineral association. Simultaneously, reduced fertilizer use and soil disturbance **lower direct nitrous oxide (N₂O) and CO₂ emissions**.
- **Evidence:** While rates are context-dependent, a conservative global technical potential for regenerative cropland and grassland management is estimated at **2–5 gigatons of CO₂-equivalent sequestered annually**. At the field scale, sequestration rates typically range from **0.5 to 3.0 tons of CO₂-equivalent per hectare per year**, with perennial systems and integrated agroforestry at the higher end of this spectrum.

5.3 Hydrological Regulation and Enhanced Water Security

The improvement of soil physical properties profoundly alters the watershed-scale water cycle, buffering against hydrological extremes.

- **Mechanisms & Outcomes:** Enhanced aggregation and porosity increase infiltration rates, **reducing surface runoff and erosion by up to 90%**. Greater SOM content increases plant-available water storage; each 1% increase in SOM can hold an additional **~60,000–150,000 liters of water per hectare** in the root zone. This results in **improved groundwater recharge, diminished flood risk, and extended drought resilience** for crops.
- **Evidence:** Studies show regenerative systems can increase water infiltration by **50–150%** and reduce irrigation needs by **10–30%** in water-limited environments, while dramatically cutting sediment and nutrient loading in waterways.

5.4 Biodiversity Conservation and Ecosystem Restoration

Regenerative systems recreate heterogeneous habitats and reduce anthropogenic pressures, fostering a resurgence of biological diversity at multiple trophic levels.

- **Mechanisms & Outcomes:** Diverse plantings (cover crops, polycultures, agroforestry) provide varied food and habitat resources. The reduction or elimination of broad-spectrum pesticides and synthetic fertilizers removes key stressors on non-target organisms. This supports **increased abundance and diversity of soil microbiota, arthropods, pollinators, birds, and other wildlife**.
- **Evidence:** Research documents **30–50% higher pollinator abundance**, **2–5 times greater earthworm density**, and significantly enriched soil microbial biomass and functional diversity in regenerative systems compared to conventional monocultures.

5.5 Socio-Economic Resilience and Rural Vitality

The aggregate effect of these biophysical benefits is improved economic viability and social stability for farming communities.

- **Mechanisms & Outcomes:** Lower input costs and premium market opportunities (e.g., for regeneratively certified products) **increase net farm profitability and reduce financial risk**. Enhanced ecosystem services (clean water, climate stability) benefit public health and reduce communal infrastructure costs. The knowledge-intensive nature of these systems can **revitalize rural economies and strengthen community networks** through peer-to-peer learning and new value chains.
- **Evidence:** Economic analyses show that after the initial transition, regenerative systems often achieve **higher and more stable net profits** due to lower variable costs. Furthermore, they contribute to **improved farmer quality of life** through reduced exposure to chemicals and greater autonomy over management decisions.

6. EMERGING INNOVATIONS AND FRONTIERS IN REGENERATIVE SOIL SCIENCE

The scientific and technological landscape supporting Regenerative Soil Science (RSS) is rapidly evolving. While foundational practices provide the operational framework, emerging innovations offer powerful tools to enhance

their precision, scalability, and impact. These advancements are critical for addressing persistent barriers to adoption and for quantifying outcomes in robust, verifiable ways.

6.1 Advanced Microbial Biostimulants and Synthetic Microbial Consortia

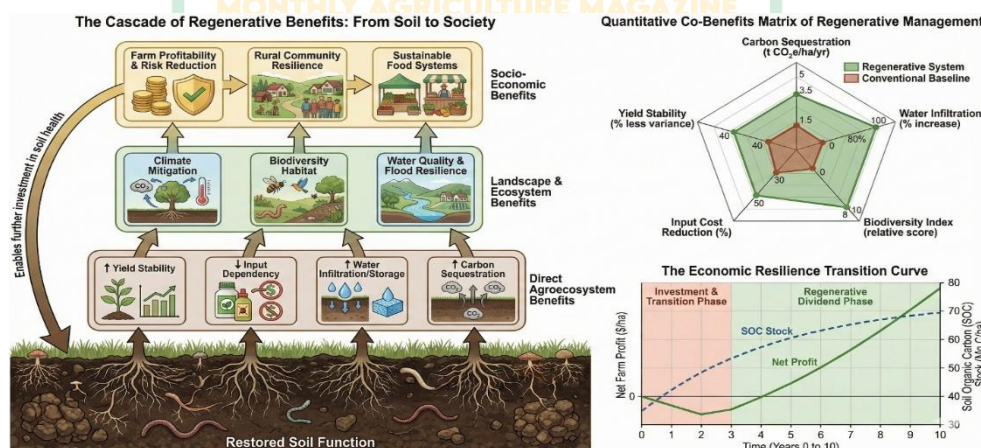
Moving beyond traditional inoculants, next-generation biostimulants leverage advances in microbial ecology and synthetic biology to engineer more effective plant–soil interactions.

- **Innovation:** This includes **tailored microbial consortia** designed for specific functions (e.g., drought resilience, phosphorus solubilization, pathogen suppression) and **microbe-derived biostimulants** such as seaweed extracts, humic substances, and protein hydrolysates that prime plant defense and metabolic pathways.
- **Mechanism & Potential:** These products work by **enhancing nutrient-use efficiency, inducing systemic resistance, and improving tolerance to abiotic stress**. The frontier lies in developing **site-specific formulations** based on soil microbiome diagnostics, moving from a one-size-fits-all approach to precision ecology.
- **Research Frontier:** Key challenges include ensuring microbial survival and functionality in diverse field conditions and understanding long-term impacts on native soil microbial networks.

6.2 Precision Soil Health Diagnostics and Digital Monitoring

The advent of advanced sensors, remote sensing, and artificial intelligence (AI) is revolutionizing the ability to measure and manage soil health dynamically and at scale.

- **Innovation:** Technologies include **portable spectral sensors and in-situ electrochemical probes** for real-time analysis of soil organic carbon, nitrogen, and moisture. **Hyperspectral and multispectral satellite/UAV imagery** can map soil properties and vegetative health indicators (NDVI, chlorophyll content) across landscapes. **AI and machine learning algorithms** integrate this data to predict soil function, identify degradation hotspots, and recommend management interventions.
- **Mechanism & Potential:** These tools enable **high-resolution, temporal soil health baselining and monitoring**, replacing costly and slow laboratory analyses. They facilitate **precision application of inputs** and provide verifiable data for ecosystem service markets.
- **Research Frontier:** Standardizing sensor data against traditional assays, improving algorithms for diverse agroecosystems, and ensuring data accessibility for farmers are active areas of development.



6.3 Ecosystem Service Markets and Innovative Finance

Formalizing the economic value of ecosystem services generated by regenerative management is a critical innovation for incentivizing adoption.

- **Innovation:** **Soil carbon credit markets** are the most prominent, where farmers are paid for verified carbon sequestration. Emerging markets also target **water quality trading (nutrient reduction)** and **biodiversity credits**. Financial instruments like **green bonds, sustainability-linked loans, and parametric insurance** are being structured to de-risk the transition to regenerative practices.

- **Mechanism & Potential:** These mechanisms **monetize the positive externalities** of regenerative farming, improving its economic viability. They align private capital with public environmental goals, potentially unlocking large-scale investment in agricultural sustainability.
- **Research Frontier:** Critical needs include **standardized, science-based measurement, reporting, and verification (MRV) protocols** to ensure integrity and prevent greenwashing, and models for fair benefit sharing with land managers.

6.4 Crop Breeding and Genomics for Regenerative Systems

Modern plant breeding, informed by genomics and phenomics, is shifting focus from yield-maximization in high-input systems to optimizing performance within biologically-driven, regenerative contexts.

- **Innovation:** Breeding objectives now target **regenerative traits** such as:
 - **Root Architecture:** Deeper, more extensive root systems for improved water/nutrient scavenging and carbon deposition.
 - **Enhanced Symbiosis:** Genotypes that form more effective associations with mycorrhizal fungi and nitrogen-fixing bacteria.
 - **Nutrient-Use Efficiency:** Varieties that thrive with lower levels of soluble nutrients.
 - **Resilience to Biotic and Abiotic Stress.**
- **Mechanism & Potential:** By selecting crops "**bred for the system,**" breeders can amplify the benefits of cover cropping, no-till, and diversification, leading to more resilient and productive agroecosystems with minimal external inputs.
- **Research Frontier:** Phenotyping complex root and rhizosphere traits in field conditions and understanding the genetic basis of plant-microbe communication are key challenges.

6.5 Landscape-Scale Design and Restoration Ecology

The most significant gains in soil regeneration and ecosystem service provision occur when management is coordinated at the watershed or landscape scale.

- **Innovation:** This approach integrates **precision conservation planning** using GIS and modeling to strategically place practices (e.g., riparian buffers, contour planting, wetland restoration) where they will maximize hydrological regulation, erosion control, and habitat connectivity. It views farms not as isolated units but as interconnected nodes in a larger ecological matrix.
- **Mechanism & Potential:** Landscape-scale design **optimizes the spatial arrangement of regenerative practices** to solve collective action problems (e.g., downstream water pollution). It can **restore critical ecological infrastructure**, enhancing resilience to floods and droughts at a community level.
- **Research Frontier:** Developing participatory models for multi-stakeholder landscape governance and quantifying the synergistic benefits of integrated practice placement are vital research areas.

Together, these innovations represent a powerful toolkit for accelerating the transition to regenerative agriculture. They enhance the efficacy of core practices, provide new economic incentives, and enable the scaling of soil restoration from individual fields to entire bioregions, marking a new era of technology-enabled ecological stewardship.

7. CHALLENGES, RESEARCH GAPS, AND FUTURE DIRECTIONS

The transition to Regenerative Soil Science (RSS) presents a paradigm shift with immense potential, yet its widespread implementation faces significant and interconnected challenges. A primary barrier is the **biophysical and economic hurdle of the transition period**, often spanning 2–5 years, during which soils undergo fundamental restructuring. This phase can be marked by short-term yield instability or declines as ecosystems shift from input-dependent to biology-driven function, creating acute financial risk and deterring adoption, particularly among farmers with limited capital or operating on short-term leases who lack incentive to invest in long-term soil health. Compounding this is the **high context-specificity and knowledge-intensive nature** of RSS; there are no universal prescriptions, requiring farmers to become adaptive ecosystem managers rather than followers of standardized inputs. This demand for sophisticated, place-based knowledge is often unmet due to **inadequate technical assistance and underdeveloped peer support networks** in many regions. Furthermore, prevailing **socio-economic and institutional frameworks frequently misalign with regenerative goals**.

Agricultural policies and subsidies have historically incentivized high-input monocultures, while the vital ecosystem services generated by healthy soils such as carbon sequestration, water purification, and biodiversity support remain largely uncompensated positive externalities in traditional markets. This creates a competitive disadvantage and fails to reward farmers for their stewardship. To address these barriers and solidify the scientific foundation of RSS, a robust and interdisciplinary research agenda is urgently required. A foremost priority is the establishment of **globally coordinated, long-term field experiments** to monitor the trajectories of soil health indicators such as soil organic matter dynamics, microbial community shifts, and hydrological function across diverse agro-ecological zones over decadal scales. This will help define transition dynamics and eventual system steady-states. Concurrently, deeper **mechanistic studies are needed to elucidate the complex feedback loops** between plants, microbes, and the soil matrix, particularly the precise pathways and rates of stable soil carbon formation and the functional roles of engineered versus indigenous microbiomes. To empower practitioners, **technological innovation must deliver accessible, cost-effective tools** for real-time assessment, including advances in field-deployable sensors, remote sensing for landscape-scale soil health mapping, and integrated AI-driven models that provide predictive, site-specific management support.

Parallel socio-economic and policy research is critical to create enabling environments for scaling. This involves identifying the most effective **bundles of financial, technical, and social support** to de-risk the farmer transition, and designing equitable **policy instruments and verified ecosystem service markets** that accurately value and compensate regenerative outcomes. Finally, research should explore the **integration of RSS within the broader circular bioeconomy**, examining safe and efficient pathways for recycling organic waste streams back into agricultural soils, and quantifying the contributions of regenerative systems to regional climate adaptation and resilience. Addressing this comprehensive agenda through unprecedented interdisciplinary collaboration is essential to mature RSS from a promising alternative into a foundational pillar of a climate-smart, equitable, and resilient global food system.

8. FUTURE PROSPECTS AND A PARADIGM FOR SUSTAINABILITY

Regenerative Soil Science (RSS) is emerging not merely as a suite of alternative practices, but as a foundational paradigm essential for achieving key international sustainability objectives, particularly the Sustainable Development Goals (SDGs) related to Zero Hunger (SDG 2), Climate Action (SDG 13), and Life on Land (SDG 15). Its core premise rebuilding the biological integrity of agricultural soils directly addresses the interconnected crises of food insecurity, climate change, and biodiversity loss. The future trajectory of RSS, and its capacity to scale, hinges on strategic advancements in four critical domains.

First, the development and universal adoption of **standardized, multi-dimensional soil health metrics** are imperative. Moving beyond singular chemical indicators like NPK, future frameworks must integrate robust physical (aggregate stability, infiltration), biological (microbial biomass, enzyme activity), and functional (carbon sequestration potential, water-holding capacity) parameters. These metrics must be sensitive to management changes, cost-effective to measure, and globally applicable yet regionally calibrated to enable credible benchmarking, monitoring, and verification for both science and policy.

Second, **long-term, systems-level field research** must be prioritized and sustained. There is a pressing need for a globally coordinated network of long-term experiments that compare conventional and regenerative management systems across diverse pedo-climatic zones. These living laboratories are essential for quantifying the long-term trajectories of soil carbon accrual, yield resilience, and ecosystem service provisioning, and for empirically defining the socio-ecological thresholds and benefits of the transition period.

Third, the field must fully embrace the digital revolution through advances in **“digital soil intelligence.”** This involves the integration of in-situ sensor networks, hyperspectral remote sensing, and machine learning algorithms to provide high-resolution, real-time diagnostics of soil status. Such technology can democratize access to soil health data, empower precision management, and create the transparent, scalable monitoring required for emerging ecosystem service markets and adaptive policy frameworks.

Finally, and crucially, future progress depends on **innovative socio-economic models and supportive policy architectures**. Research must identify the most effective bundles of financial incentives (e.g., green subsidies, transition payments, robust carbon credit markets), technical assistance, and peer-learning networks to

de-risk adoption for farmers. Policy must evolve to reward outcomes healthy soils, clean water, stable climate rather than subsidizing inputs, thereby aligning economic signals with ecological imperatives.

In conclusion, Regenerative Soil Science represents a fundamental paradigm shift: from a **reductionist, extractive model of agriculture that views soil as a substrate, to a holistic, restorative model that recognizes soil as a living ecosystem**. By recentring agriculture on the principle of enhancing biological capital, RSS offers a coherent pathway to transform degraded lands into productive, resilient systems. It is a vision where agriculture no longer operates at the expense of the environment but becomes its primary steward, capable of sustaining both ecosystems and future generations. Realizing this potential is not only an agronomic challenge but a collective societal imperative.

9. CONCLUSION

In the face of escalating soil degradation, climate instability, and biodiversity loss, Regenerative Soil Science (RSS) emerges not as a marginal alternative but as a critical, scientifically grounded paradigm for the future of land stewardship. This review has synthesized evidence demonstrating that RSS provides a holistic, ecologically informed framework for actively reversing the decline of soil health the very foundation of terrestrial life and food security. By moving beyond mere conservation to active restoration, RSS principles minimizing disturbance, maximizing soil cover and biodiversity, maintaining living roots, and integrating context-specific livestock and human management guide the implementation of synergistic practices. These include conservation tillage, cover cropping, organic amendments, agroforestry, crop diversification, and managed grazing, which collectively rebuild soil organic matter, enhance microbial diversity and function, improve physical structure, and close nutrient cycles.

The socio-ecological benefits of this approach are profound and multiplicative. RSS systems demonstrably enhance agroecosystem productivity and resource-use efficiency, mitigate climate change through significant carbon sequestration and reduced greenhouse gas emissions, improve water security and hydrological resilience, and conserve biodiversity at multiple trophic levels. These biophysical improvements translate directly into socio-economic benefits, including increased farm profitability, reduced financial risk, and strengthened rural community resilience. Emerging innovations in microbial biostimulants, digital soil diagnostics, ecosystem service markets, and crop breeding for regenerative traits further enhance the precision, scalability, and economic viability of these systems.

However, the transition is not without significant challenges. Barriers such as the knowledge-intensive nature of management, high upfront costs, short-term yield risks, misaligned policy incentives, and the need for long-term commitment underscore that adoption is as much a socio-economic and institutional challenge as it is an agronomic one. Realizing the full potential of RSS therefore demands a concerted, multi-stakeholder effort. Future progress hinges on: (1) establishing standardized soil health metrics and long-term monitoring networks; (2) deepening mechanistic understanding of soil ecological processes; (3) advancing accessible digital tools for soil intelligence; and (4) most critically, co-designing innovative policy frameworks and financial mechanisms that incentivize and reward the provision of ecosystem services.

In conclusion, Regenerative Soil Science represents a fundamental and necessary paradigm shift from viewing soil as an inert input to be managed for extraction, to recognizing it as a complex living ecosystem to be nurtured for regeneration. It repositions agriculture from a primary driver of environmental degradation to a cornerstone of ecological restoration and climate mitigation. Widespread adoption, supported by interdisciplinary science, collaborative governance, and equitable economic models, offers a viable pathway to transform degraded landscapes into productive, resilient, and sustainable systems. Securing this fertile future is not merely an agricultural imperative but a foundational requirement for achieving global food security, climate stability, and intergenerational equity.

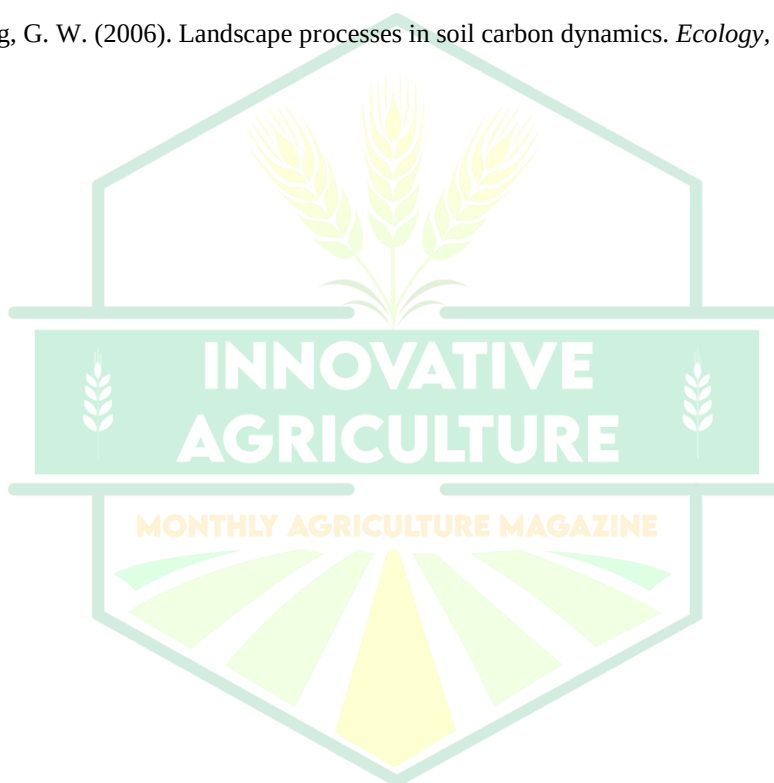
Reference

Abbott, B. W., Jones, J. B., Schuur, E. A. G., Chapin, F. S., Bowden, W. B., Bret-Harte, M. S., ... & Zimov, S. (2016). Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment. *Environmental Research Letters*, 11(3), 034014.

- Aguilar, J., Winkler, L., Daren, H., Clarida, H., & Wayman, S. (2015). Cover crop impacts on soil health and productivity. *Journal of Soil and Water Conservation*, 70(3), 232–240.
- Alexander, H. D., & Mack, M. C. (2016). A canopy shift in interior Alaskan boreal forests: Consequences for above- and belowground carbon and nitrogen pools during post-fire succession. *Ecosystems*, 19(1), 98–114.
- Ambrose, A. R., Baxter, W. L., Wong, C. S., Burgess, S. S. O., Williams, C. B., Næsborg, R. R., Koch, G. W., & Dawson, T. E. (2016). Hydraulic constraints modify optimal photosynthetic profiles in giant sequoia trees. *Oecologia*, 182(3), 713–730.
- Amundson, R., & Biardeau, L. (2018). Opinion: Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings of the National Academy of Sciences*, 115(46), 11652–11656.
- Basche, A. D., & DeLonge, M. S. (2019). Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLOS ONE*, 14(9), e0215702.
- Berdugo, M., Delgado-Baquerizo, M., Eldridge, D. J., & Maestre, F. T. (2020). Global ecosystem thresholds driven by aridity. *Science*, 367(6479), 787–790.
- Bernal, B., McKinley, D. C., Hungate, B. A., White, P. M., Mozdzer, T. J., & Megonigal, J. P. (2016). Limits to soil carbon stability; Deep, ancient soil carbon decomposition stimulated by new labile organic inputs. *Soil Biology and Biochemistry*, 98, 85–94.
- Blanco-Canqui, H., & Ruis, S. J. (2018). No-till and soil physical environment. *Geoderma*, 326, 164–200.
- Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., ... & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, 3(5), 391–398.
- Bowles, T. M., Jackson, L. E., Loeher, M., & Cavagnaro, T. R. (2017). Ecological intensification and diversification approaches in agriculture. *Agriculture, Ecosystems & Environment*, 236, 148–160.
- Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M. A., Culman, S. W., ... & Lehmann, J. (2020). Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth*, 2(3), 284–293.
- Bracho, R., Natali, S., Pegoraro, E., Crummer, K. G., Schädel, C., Celis, G., ... & Schuur, E. A. G. (2016). Temperature sensitivity of organic matter decomposition of permafrost-region soils during laboratory incubations. *Soil Biology and Biochemistry*, 97, 1–14.
- Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., ... & Brussaard, L. (2018). Soil quality—A critical review. *Soil Biology and Biochemistry*, 120, 105–125.
- Davies, K. L., Pancost, R. D., Edwards, M. E., Anthony, K. M. W., Langdon, P. G., & Torres, L. C. (2016). Diploptene $\delta^{13}\text{C}$ values from contemporary thermokarst lake sediments show complex spatial variation. *Biogeosciences*, 13, 2611–2621.
- Doetterl, S., Berhe, A. A., Heckman, K., Lawrence, C., Schnecker, J., Vargas, R., Vogel, C., & Wagai, R. (2025). A landscape-scale view of soil organic matter dynamics. *Nature Reviews Earth & Environment*, 6, 67–81.
- FAO. (2015). *Status of the World's Soil Resources (SWSR) – Main Report*. Food and Agriculture Organization of the United Nations.
- FAO. (2022). *The State of the World's Land and Water Resources for Food and Agriculture*. Food and Agriculture Organization of the United Nations.
- Frey, K. E., Sobczak, W. V., Mann, P. J., & Holmes, R. M. (2016). Optical properties and bioavailability of dissolved organic matter along a flow-path continuum from soil pore waters to the Kolyma River mainstem, East Siberia. *Biogeosciences*, 13, 2279–2290.
- Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., ... & Stolze, M. (2012). Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences*, 109(44), 18226–18231.
- Gaudin, A. C., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLOS ONE*, 10(2), e0113261.
- Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: An agronomic perspective. *Outlook on Agriculture*, 50(1), 13–25.

- Gu, C., Zhang, S., Han, P., Hu, X., Xie, L., Li, Y., ... & Wang, G. (2023). Crop rotation and native microbiome integration restore soil function. *Nature Food*, 4(10), 876–888.
- Kling, G. W., Kipphut, G. W., & Miller, M. C. (2002). Production and export of dissolved C in arctic tundra mesocosms: The roles of vegetation and water flow. *Biogeochemistry*, 60, 213–234.
- Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecology and Society*, 17(4), 40.
- LaCanne, C. E., & Lundgren, J. G. (2018). Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ*, 6, e4428.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627.
- Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), 5875–5895.
- Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 1(10), 544–553.
- Loreau, M., & de Mazancourt, C. (2013). Biodiversity and ecosystem stability. *Annual Review of Ecology, Evolution, and Systematics*, 44, 39–59.
- Marcillo, G. S., & Miguez, F. E. (2017). Corn yield response to winter cover crops: An updated meta-analysis. *Journal of Soil and Water Conservation*, 72(3), 226–239.
- Montgomery, D. R. (2017). *Growing a revolution: Bringing our soil back to life*. W. W. Norton & Company.
- Montgomery, D. R., & Bickl, A. (2016). *The hidden half of nature: The microbial roots of life and health*. W. W. Norton & Company.
- Nunes, M. R., Karlen, D. L., & Moorman, T. B. (2021). Soil health indicators in regenerative farming systems. *Renewable Agriculture and Food Systems*, 36(3), 216–230.
- Ogle, S. M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F. J., McConkey, B., ... & Paustian, K. (2019). Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports*, 9(1), 11665.
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, 532(7597), 49–57.
- Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. *Agriculture, Ecosystems & Environment*, 200, 33–41.
- Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants*, 2(1), 15221.
- Rhodes, C. J. (2017). The imperative for regenerative agriculture. *Science Progress*, 100(1), 80–129.
- Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*, 114(36), 9575–9580.
- Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., ... & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems*, 125, 12–22.
- Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter. *Plant and Soil*, 241(2), 155–176.
- Smith, P., Soussana, J.-F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., ... & Batjes, N. H. (2020). How to measure, report and verify soil carbon change. *Nature*, 580(7802), 48–56.
- Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., ... & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, 26(1), 219–241.
- Suding, K. N., Gross, K. L., & Houseman, G. R. (2004). Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology & Evolution*, 19(1), 46–53.
- Tiemann, L. K., Grandy, A. S., Atkinson, E. E., Marin-Spiotta, E., & McDaniel, M. D. (2015). Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecology Letters*, 18(8), 761–771.

- Tonitto, C., David, M. B., & Drinkwater, L. E. (2006). Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. *Agriculture, Ecosystems & Environment*, 112(1), 58–72.
- van Capelle, C., Schrader, S., & Brunotte, J. (2012). Tillage-induced changes in the functional diversity of soil biota—A review with a focus on German data. *European Journal of Soil Biology*, 50, 165–181.
- Vukicevich, E., Lowery, T., Bowen, P., Úrbez-Torres, J. R., & Hart, M. (2016). Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. *Agronomy for Sustainable Development*, 36(3), 48.
- Wallenstein, M. D., & Hall, E. K. (2012). Microbial control of soil organic matter decomposition. *Nature Climate Change*, 2(10), 775–784.
- West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal*, 66(6), 1930–1946.
- White, R. E. (2018). *Principles and practice of soil science: The soil as a natural resource* (5th ed.). Wiley-Blackwell.
- Zak, D. R., & Kling, G. W. (2006). Landscape processes in soil carbon dynamics. *Ecology*, 87(6), 1543–1554.



The Hardpan Crisis: How Soil Compaction Stifles the Roots of Modern Agriculture



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Imagine trying to build a skyscrapers' foundation with a plastic toy shovel, or breathing through a straw while running a marathon. For billions of crop roots navigating modern agricultural fields, this is not a metaphor, it is their daily physical reality.

While farmers frequently fret over fertilizer bags and weather forecasts, one of the greatest stealth threats to global crop yields lies in a mechanical breakdown of the soil's structure: compaction. Often referred to visually as a "hardpan" or "plow pan," soil compaction is the silent structural collapse of the spaces between soil particles. When heavy machinery rolls over wet earth, or repetitive tillage pulverizes the ground, the intricate architecture of the soil is crushed. What was once a thriving, porous sponge becomes as dense and impenetrable as concrete, creating a physical roadblock that limits how deep roots can grow, how much water the soil can hold, and how efficiently a farm can function.

The Physics of a Healthy Sponge

To understand how a field fails mechanically, one must first look at what healthy soil is supposed to be: mostly empty space. Ideal agricultural soil is roughly 50% solid mineral matter (sand, silt, and clay) and 50% pore space. These pores are the lungs and circulatory system of the field, split evenly between macro-pores (large channels that allow water to drain and roots to grow) and micro-pores (tiny pockets that hold onto water against the pull of gravity).

When soil aggregates the natural clumps held together by microbial glues and organic matter are healthy, they create a beautifully organized labyrinth. Plant roots do not actually tunnel through solid rock particles; they navigate the pre-existing macro-pore pathways like a driver navigating a city street grid. When heavy field traffic or structural degradation enters the frame, these macro-pores are the first to collapse. The solids are forced together, bulk density climbs drastically, and the structural streets are permanently closed.

Breaking the Root Engine

The consequences of this structural collapse hit the crop at its most vulnerable point: the root tip. As a root tries to push down through a compacted layer, it encounters immense mechanical resistance. Under normal field conditions, a root tip exerts a modest physical pressure to slide between soil grains. However, when it hits a hardpan layer often sitting just below the traditional plow depth (about 6 to 8 inches down) the pressure required to penetrate the soil jumps beyond the biological capacity of the plant cells.

When a root encounters this concrete-like floor, it does something desperate: it turns sideways. Unable to dive deep into the subsoil to access deep water reserves, the root system flattens out, growing horizontally along the top of the compacted layer. This creates a highly shallow, fragile root architecture known as "pancaking." A crop with a pancaked root system is an agricultural disaster waiting to happen. Because it cannot explore the deep soil profile, the crop is entirely dependent on the top few inches of soil for its survival. If a dry spell hits and the topsoil dries out, the plant cannot tap into the massive deep-water

reservoirs below, causing it to wilt and stall long before a deep-rooted crop would even notice the lack of rain.

The Suffocation Zone

Beyond the physical barrier, compaction triggers a catastrophic shift in soil hydrology and aeration. When macro-pores are crushed out of existence, the soil loses its capacity to drain heavy rainfall.

When a storm hits a compacted field, the water cannot infiltrate down through the profile. Instead, it pools on the surface, creating prolonged waterlogged conditions, or it runs off entirely, taking valuable topsoil and applied nutrients along with it.

For the roots trapped in a waterlogged, compacted zone, the clock begins to tick. Roots require oxygen (O₂) to perform cellular respiration the process that generates the energy needed to actively pump nutrients from the soil solution into the plant. When water fills every remaining tiny micro-pore and cannot drain, the soil environment transitions from aerobic (oxygen-rich) to anaerobic (oxygen-depleted) within hours.

Left without oxygen, the root engine suffocates. Microbes that thrive in oxygen-free environments take over, converting healthy nitrates into nitrous oxide (N₂O) gas, which escapes into the atmosphere as a potent greenhouse gas. The plant's ability to absorb vital nutrients like potassium and nitrogen drops to zero, manifesting in the field as yellowing, sickly crops that appear drowned despite being surrounded by unabsorbed fertilizer.

Deep-Rooted Solutions: Biological Tillage

For decades, the standard response to a hardpan layer was to fight mechanics with heavier mechanics. Farmers deployed massive tractors pulling "subsoilers" or "deep rippers" heavy steel shanks designed to mechanically shatter the concrete subsoil up to two feet deep. While this provides immediate relief, it is an expensive, fuel-intensive process that often acts as a temporary band-aid; the shattered soil easily re-compacts even tighter during the next pass of heavy equipment.

Today, advanced field management is shifting away from steel and turning toward biology: a strategy known as biological drilling or "biodrilling." Instead of using a mechanical plow, farmers are deploying specialized cover crops with aggressive, heavy taproots during the off-season. Plants like forage radishes (often called "tillage radishes"), daikon, and certain deep-rooted legumes act as biological jackhammers.

Over several weeks of growth, these biological plows exert continuous, immense hydraulic pressure, drilling straight through dense hardpan layers that would stop a corn root in its tracks. When winter arrives and the cover crop terminates, these massive taproots decompose rapidly, leaving behind deep, open, vertical macro-pore channels that extend straight through the compacted zone. When the primary cash crop is planted the following spring, its roots simply follow these pre-drilled biological highways, effortlessly diving deep into the subsoil to access untapped water and locked-up nutrients.

The Invisible Economics of Compression

While the biological and physical effects of a hardpan layer are devastating to the plant, the economic impact on a farm's bottom line is equally profound. Beyond just reduced yields, soil compaction forces a farm to operate at a lower mechanical and chemical efficiency. When the soil loses its porosity and becomes dense, the energy required to pull traditional implements through the field skyrockets.

Tractors working compacted land consume significantly more fuel because the steel must fight against the "concrete-like" resistance of the subsoil. Furthermore, the chemical efficiency of a farm is compromised; when roots are "pancaked" in the top few inches, they cannot reach the nutrients deeper in the soil profile. This often leads to a cycle of over-fertilization, where farmers apply more nitrogen and phosphorus to compensate for the root system's inability to explore the soil, much of which ends up running off into local waterways during the next storm due to poor infiltration.

Measuring the Unseen: Indicators of a Failing Structure:

Identifying a structural crisis before it reaches the "agricultural disaster" stage requires looking for specific field

indicators. Because compaction is a stealth threat, it often goes unnoticed until a weather extremity either a flood or a drought exposes the weakness of the crop's architecture.

Indicator	Physical Manifestation	Underlying Cause
Surface Ponding	Water standing in wheel tracks or low spots long after a rain.	Collapse of macro-pores preventing vertical drainage.
Pancaked Roots	Roots growing horizontally at a depth of 6-8 inches.	Physical resistance exceeding the biological capacity of root cells.
Nutrient Deficiency	Yellowing leaves (chlorosis) despite adequate fertilizer.	Anaerobic conditions halting the active pumping of nutrients.
Bulk Density Spike	Soil that feels "hard" or heavy and lacks a crumbly texture.	Crushing of soil aggregates and loss of 50% "empty space."

The Path to Restoration: Beyond the Steel Shank

The transition from mechanical shattering to biological drilling represents a shift in how we view soil longevity. While a "deep ripper" provides a temporary mechanical fix, it does nothing to restore the "microbial glues" that hold soil aggregates together.

To truly restore the "natural sponge," modern management focuses on three pillars of subsurface engineering:

1. Controlled Traffic: Designating specific "lanes" for heavy machinery to ensure that 80-90% of the field never experiences the crushing weight of a tire.
2. Continuous Living Roots: Keeping plants in the ground year-round to provide the "hydraulic pressure" needed to keep macro-pore highways open.
3. Organic Matter Accumulation: Encouraging the decomposition of deep roots to leave behind organic carbon, which acts as a buffer against future compression.

By treating the soil as a biological engine rather than a static platform, agriculture can move past the hardpan crisis toward a future where the "soil's lungs" remain open, regardless of the weight of the machinery above.

Conclusion: Engineering the Future Subsurface

The management of a field can no longer be evaluated solely by what is visible from the tractor cab. The physical architecture of the subsurface is just as critical as its chemical fertility. By recognizing soil compaction not as a minor nuisance, but as a structural crisis that suffocates root systems and disrupts hydrology, modern agriculture is embracing a new era of physical soil health. Through reduced traffic lanes, zero-till systems, and the strategic deployment of biological plows, we can restore the natural sponge beneath our feet, ensuring that roots can breathe, water can flow, and fields can reach their full biological potential.

References

- Richey, F. A., & Al-Kaisi, M. (2019). *Soil Compaction: Mechanisms, Effects, and Management*. Academic Press. (An agronomic guide investigating the bulk density thresholds of sand, silt, and clay fractions under heavy axle loads).
- Unguner, H., et al. (2021). *The Mechanics of Root-Soil Interactions in Compacted Landscapes*. Soil and Tillage Research, 208, 104-115. (A structural physics paper modeling the mechanical resistance vectors experienced by root elongation zones entering restrictive layers).
- Cresswell, H. P., & Kirkegaard, J. A. (1995). *Subsoil compaction and the biological drilling potential of crop root systems*. Australian Journal of Soil Research, 33(2), 221-241. (The foundational research charting how tap-rooted cover crops construct structural macro-pore conduits through dense plow pans).

Suffocating the Subsurface: How Climate Change Disrupts Soil Gas Exchange



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Introduction

The thin layer of Earth that supports terrestrial life is fundamentally defined by its ability to breathe. Historically, agronomic science has treated soil predominantly as a chemical medium a reservoir of nitrogen, phosphorus, and potassium or as a mechanical anchor for roots. However, soil is more accurately understood as a massive, active respiratory organ.

In an uncompromised ecosystem, gas exchange is a continuous, bi-directional dance: oxygen (O₂) moves downward from the atmosphere to satisfy the intense metabolic demands of plant roots and aerobic microorganisms, while carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) move upward to be vented away.

Climate change is rapidly altering this subterranean breath. As global weather systems shift, soils are subjected to unprecedented extremes: rapid thermal spikes, severe multi-month droughts, and intense, concentrated downpours that drop weeks' worth of rain in a matter of hours. These climatic shocks do not merely alter surface moisture; they physically and biologically restructure the subsurface environment. When extreme weather collides with human-driven soil degradation, the physical pathways required for gas diffusion collapse. The result is a quiet crisis of subsurface suffocation a phenomenon that curtails agricultural productivity, forces root systems into shallow architectural anomalies, and turns the Earth's primary terrestrial carbon sink into an active source of potent greenhouse gases.

The Physics of Gas Diffusion and the Threat of Tortuosity

To comprehend how climate change alters the soil atmosphere, one must analyze the physical mechanisms governing gas movement. Gaseous exchange in the subsurface occurs primarily through molecular diffusion, driven by concentration gradients between the atmosphere and the soil profile. This process is mathematically described by Fick's First Law:

$$J = -D_s \frac{dC}{dx}$$

However, climate change directly alters the diffusion coefficient by introducing two disruptive physical variables: extreme water saturation and increased pore tortuosity. Tortuosity refers to the actual path length a gas molecule must travel relative to the straight-line physical distance. When climate change manifests as intense, pounding rainfall, the kinetic energy of the raindrops shatters surface aggregates. As these aggregates disintegrate, microscopic clay and silt particles are washed downward, settling into open pore throats. This structural collapse creates a highly convoluted, winding network of sub-surface paths.

Even when the soil is not completely filled with water, a gas molecule trying to escape or enter the profile is forced to navigate a maze of dead ends and restricted channels. High tortuosity fundamentally lowers D_s . For a root tip or an aerobic microbe located twelve inches beneath the surface, high tortuosity acts like a physical choke point, slowing down the arrival of vital O₂ and causing toxic concentrations of metabolic waste gases to pool in the root zone.

The Hydro-Lockout: Sudden Saturation and Anaerobic Shifting

The most immediate and catastrophic failure of gas exchange occurs during climate-driven extreme precipitation events. When a deluge saturates a field, water acts as a physical plug, filling the macro-pores that normally serve as air-delivery highways. Because the diffusion rate of oxygen in water is roughly 10,000 times slower than its diffusion rate in air, a saturated soil profile experiences an immediate and violent drop in oxygen availability. |

Within hours of full water logging, a process known as hydro-lockout occurs. As roots and residential microbes deplete the remaining dissolved oxygen in the soil solution, the environment shifts from aerobic to anaerobic. For agricultural crops, this sudden drop into anoxia is a physiological emergency:

1. **ATP Depletion:** Without O_2 as the terminal electron acceptor, root cells cannot perform oxidative phosphorylation. They are forced to shift to anaerobic glycolysis and fermentation. This metabolic pivot reduces energy production (ATP) by roughly 95%, causing the active transport mechanisms within the root to fail.
2. **Nutrient Lockout:** Roots require massive amounts of ATP to actively pump essential nutrients (such as potassium, phosphorus, and nitrates) against a concentration gradient from the soil into the plant tissue. When the oxygen supply is cut off by waterlogging, this pumping mechanism stalls completely. Plants will exhibit severe nutrient deficiencies even if standing in a field heavily treated with synthetic fertilizers.
3. **Internal Acidification:** The accumulation of fermentation byproducts, such as lactic acid and ethanol, lowers the internal pH of root cells. If the anaerobic block remains unbroken for more than 48 to 72 hours, cellular membranes rupture, resulting in widespread root death and systemic crop failure.

Thermal Acceleration and the Greenhouse Feedback Loop

While extreme wetness suffocates the soil from above, rising global temperatures exert a powerful pull from within. Soil temperature directly dictates the metabolic rate of living organisms. According to the biochemical principle of Q10 which states that a 10° rise in temperature roughly doubles the rate of biological activity warmed soils experience a massive spike in microbial and root respiration.

In a well-aerated system, this accelerated metabolism simply results in a higher volume of CO_2 being vented safely into the air. However, when climate change combines elevated temperatures with restricted gas exchange (caused by surface crusting or compaction layers), a dangerous chemical bottleneck forms. When oxygen consumption outpaces oxygen diffusion, specific groups of facultative and obligate anaerobic bacteria dominate the soil matrix. These microbial communities adapt to the lack of O_2 by utilizing alternative electron acceptors for their respiratory processes, leading to an increase in greenhouse gas emissions:

Nitrous Oxide (N_2O) Production

When agricultural fields are waterlogged and warm, denitrifiers break down soil nitrates (NO_3^-). Instead of reducing it fully to harmless dinitrogen gas (N_2), the restricted oxygen availability causes the process to halt prematurely, venting massive amounts of nitrous oxide (N_2O) into the air. Nitrous oxide is a devastating greenhouse gas with a global warming potential nearly 300 times greater than carbon dioxide over a 100-year timescale.

Methane (CH_4) Volatilization

In profoundly anaerobic conditions such as long-term flooded fields or heavily compacted clay subsoils methanogenic Archaea take over. These ancient organisms utilize hydrogen and carbon dioxide to produce methane (CH_4). Because soil contains the largest active terrestrial carbon pool on Earth (holding more carbon than the atmosphere and all vegetation combined), this climate-induced shift in gas pathways risks turning global agricultural lands into major drivers of planetary warming.

The Dynamic of Drought: Crust Formation and Subsurface Trapping

Paradoxically, the opposite extreme of climate change extended drought is equally destructive to subsurface gaseous exchange. When a field experiences prolonged heat and lacks moisture, the top few millimeters of the soil dry out rapidly, forming a dense physical crust. This sun-baked surface layer becomes highly hydrophobic and tightly packed, acting as a structural lid over the rest of the soil profile.

Underneath this dry crust, the deeper subsoil layers (ranging from 12 to 36 inches down) become isolated chambers. Roots and deep-dwelling microbes continue to respire, consuming what little oxygen remains and pumping carbon dioxide into the surrounding pore spaces. Because the surface crust blocks vertical gas movement, the concentration of CO₂ in the subsoil can quickly reach toxic levels sometimes 10 to 100 times higher than atmospheric concentrations.

This accumulation of subterranean CO₂ creates an "internal smog" that is highly toxic to expanding root systems. High concentrations of carbon dioxide inhibit root cell elongation and disrupt the hormonal signaling pathways that guide roots downward. As a result, when roots encounter these high CO₂, low O₂ subsoil pockets, they stop growing vertically. This restriction prevents the plant from accessing deep water reserves, leaving the crop highly vulnerable to drying out during late-summer heatwaves.

Deep Structural Failures: The Creation of Compacted Barriers

The structural integrity of the soil profile is further compromised by the cycling between extreme wet and extreme dry conditions. This rapid oscillation accelerates the degradation of the subsurface, forcing soil particles to pack tightly together into a dense, restrictive zone known as a hardpan or plow pan. This layer usually forms just beneath the depth of standard tillage tools, typically 6 to 8 inches below the surface.

When a heavy climate-driven rain event is followed by an intense period of heat, this compacted hardpan cures into a barrier as hard as concrete. Pushing through this layer requires a mechanical force that exceeds the physical capacity of plant roots. When a root tip hits this dense barrier, it cannot expand downward to reach air or water. Instead, the root system undergoes a drastic structural change known as "pancaking" bending at a sharp 90-degree angle and growing entirely horizontally along the top of the hardpan.

Pancaked root systems create a highly unstable agricultural model. Because the entire root mass is compressed into the top few inches of the soil, the plants are trapped in the most volatile zone of the field. When a heavy rain hits, this shallow zone quickly becomes waterlogged, suffocating the roots through hydro-lockout. Conversely, when the sun comes out, this top layer dries out first, exposing the shallow-rooted crops to extreme moisture stress. The hardpan effectively cuts off the plant from the subsoil, rendering deep nutrient and moisture reserves completely inaccessible and breaking the natural vertical flow of gases and water.

Restoring Subsurface Ventilation Through Biological Management

To preserve the earth's agricultural systems against climate change, farming must move away from short-term mechanical fixes. For generations, the standard response to a tight, suffocating subsurface was to use large tractors to drag steel shanks known as deep rippers through the field to shatter the hardpan. While this mechanical disruption provides temporary relief, it does nothing to rebuild the soil's natural pore networks. The crushed aggregates quickly settle back into place, often re-compacting even tighter during subsequent equipment passes.

Modern agricultural science is shifting toward a biological approach to soil management. Instead of trying to break open the earth with heavy steel machinery, farmers are using biodrilling the strategic deployment of specialized cover crops with aggressive, deep-diving root systems. Plants like the forage radish (or tillage radish) and deep-rooted legumes act as biological jackhammers, utilizing immense internal hydraulic pressure to drive taproots straight through dense hardpan layers that would stop standard crops completely. As these specialized cover crops grow, they create deep, vertical pathways through the soil. When winter frosts arrive and terminate the plants, these massive taproots decompose rapidly, leaving

behind a permanent network of open, vertical channels called biopores. Unlike the temporary spaces created by mechanical plowing, these biological tunnels are lined with organic residues and microbial secretions, such as glomalin. These natural glues act like cement, reinforcing the walls of the tunnels and preventing them from collapsing during heavy rains. The following spring, the roots of primary cash crops—like corn, soybeans, or wheat—follow these pre-drilled channels directly through the compacted zones and deep into the subsoil. These biopores serve as permanent ventilation shafts for the field.

Even during heavy downpours, these reinforced channels allow water to drain rapidly into the deep subsoil, preventing the hydro-lockout that suffocates roots. During dry periods, they provide open pathways for oxygen to diffuse deep into the earth, while allowing trapped greenhouse gases to be safely processed or vented. By using biological systems to keep the subsurface open and ventilated, modern agriculture can protect its fields against weather extremes, ensuring that the living soil can continue to breathe through the changing climate ahead.

References

- Brevik, E. C. (2013). The potential impact of climate change on soil properties and processes and corresponding influence on food security. *Agriculture*, 3(3), 398-417. <https://doi.org/10.3390/agriculture3030398>
- Cresswell, H. P., & Kirkegaard, J. A. (1995). Subsoil compaction and the biological drilling potential of crop root systems. *Australian Journal of Soil Research*, 33(2), 221-241. <https://doi.org/10.1071/SR9950221>
- Smith, K. A. (2010). *Soil and Greenhouse Gases*. CAB International.
- Tiwari, P., Bhattacharya, P., Rawat, G. S., & Talukdar, G. (2021). Equilibrium in soil respiration across a climosequence indicates its resilience to climate change in a glaciated valley, western Himalaya. *Scientific Reports*, 11(1), Article 22915. <https://doi.org/10.1038/s41598-021-02199-x>
- Yu, Z. Z., Wang, H. X., Yu, D. S., Yin, N. X., & Zhang, J. (2024). The effect of aeration and irrigation on the improvement of soil environment and yield in dryland maize. *Frontiers in Plant Science*, 15, Article 1464624. <https://doi.org/10.3389/fpls.2024.1464624>

Agronomic Biofortification in Pulses: A Sustainable Strategy to Combat Hidden Hunger



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Abstract

Hidden hunger, the chronic deficiency of essential vitamins and minerals despite adequate calorie intake, remains a major public health challenge in India. The latest National Family Health Survey reports a high prevalence of anaemia, a key indicator of iron deficiency, affecting 67.1 per cent of children under five years, 59 per cent of adolescent girls, and 57 per cent of women of reproductive age, resulting in substantial health and economic losses. Pulses, the primary source of plant-based protein for a largely vegetarian population, provide an ideal vehicle for improving dietary micronutrient intake. Increasing the concentration of essential micronutrients such as zinc and iron in pulse grains can significantly enhance the nutritional quality of daily diets without altering existing food habits. Agronomic biofortification, involving the application of zinc, iron, and other micronutrients through soil, foliar, or seed based approaches, has shown considerable promise across diverse agro climatic regions of India. Field studies in chickpea and lentil have consistently demonstrated substantial improvements in grain zinc and iron concentrations, in several cases exceeding 50 per cent over untreated crops, while maintaining or even improving grain yield. This article reviews the magnitude of hidden hunger in India, highlights the importance of pulses as a strategic target for biofortification, discusses the major agronomic approaches available, and summarizes recent evidence on their effectiveness, concluding with practical recommendations for enhancing nutritional security through pulse-based cropping systems.

Keywords: Agronomic biofortification, Chickpea, Hidden hunger, Lentil, Micronutrient enrichment, Zinc nutrition.

1. Introduction

Across the world, an estimated two billion people carry some form of micronutrient deficiency even though many of them consume enough calories to avoid classic hunger, a condition public health researchers describe as hidden hunger. In India, this problem is neither rare nor mild. National surveys consistently find that well over half of women and children carry insufficient iron, and comparable shares fall short on zinc, a mineral essential to immune function, growth and cognitive development in children. The conventional response to this problem, food fortification and dietary supplementation, reaches many people but not all, particularly in rural areas where fortified staples and supplement distribution networks are thinner.

Agronomic biofortification offers a complementary route. Rather than adding a nutrient to food after harvest, it raises the nutrient content of the crop itself in the field, using the same zinc, iron and other micronutrient fertilizers that agronomists already recommend for correcting soil deficiency, but applied and timed specifically to maximize what ends up in the grain. Pulses are a particularly promising target for this approach, both because of how widely and regularly they are eaten across India and because, as legumes, they are already grown on much of the marginal, often micronutrient deficient land where the case for biofortification is strongest. This paper examines the scale of hidden hunger in India, the rationale for targeting pulses, the agronomic methods used to raise their micronutrient content, and what field trials say about their effectiveness.

2. Hidden Hunger: The Scale of the Problem in India

India carries one of the highest burdens of micronutrient malnutrition in the world. According to the National Family Health Survey 5, conducted in 2019 21, anaemia, used widely as an indicator of iron deficiency, affects

67.1 per cent of children between six and 59 months, 59 per cent of adolescent girls aged 15 to 19, and 57 per cent of women aged 15 to 49 (Table 1, Figure 1), each figure well above the 40 per cent threshold at which the World Health Organization classifies anaemia as a severe public health problem. Zinc deficiency follows a similar pattern, with the Comprehensive National Nutrition Survey recording deficiency in 19 per cent of preschool children and 32 per cent of adolescents. Beyond the direct health burden of impaired immunity, stunted growth and reduced cognitive development, these deficiencies are estimated to cost the Indian economy more than 12 billion US dollars a year in lost productivity.

Table 1. Prevalence of anaemia and the economic cost of micronutrient malnutrition in India

Indicator	Value
Anaemia, children 6 to 59 months	67.1 per cent (NFHS-5, 2019-21)
Anaemia, adolescent girls 15 to 19 years	59 per cent (NFHS-5, 2019-21)
Anaemia, women 15 to 49 years	57 per cent (NFHS-5, 2019-21)
Zinc deficiency, preschool children	19 per cent (CNNS)
Zinc deficiency, adolescents	32 per cent (CNNS)
Estimated annual economic cost	More than USD 12 billion in lost productivity

Source: National Family Health Survey 5, 2019-21, and Comprehensive National Nutrition Survey, cited in European Journal of Clinical Nutrition, 2026.

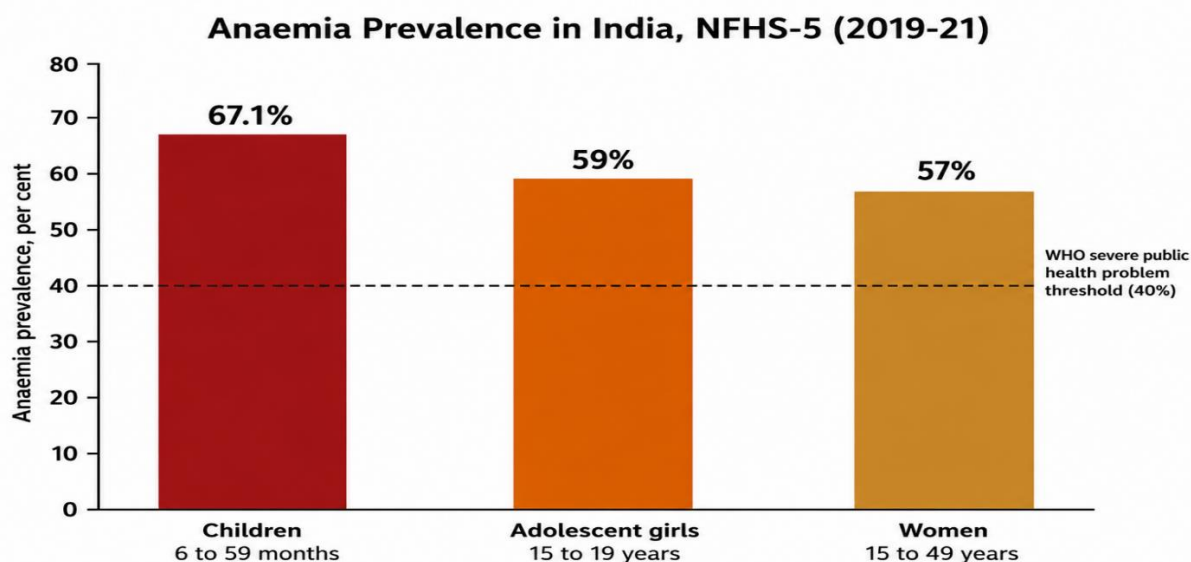


Fig. 1. Anaemia prevalence in India by population group, NFHS-5

3. Why Pulses Are a Strategic Target for Biofortification

Pulses occupy a near daily place on the Indian plate, particularly in vegetarian households where they serve as the principal source of dietary protein, and this reach makes even a modest gain in their zinc or iron content nutritionally significant at a population scale. Unlike a new fortified product that has to be introduced into the market and adopted by consumers, a biofortified pulse crop delivers its nutritional benefit through exactly the same dal or curry a household is already preparing, with no change in cooking practice or purchasing behaviour required. Pulses are also frequently grown on light textured, marginal soils where zinc and iron availability is naturally low, the same soil conditions that limit the crop's own nodulation and nitrogen fixation, so agronomic interventions that correct micronutrient supply for agronomic reasons and interventions aimed at improving grain nutrient content tend to reinforce rather than compete with each other.

4. Agronomic Biofortification: Approaches and Mechanisms

Agronomic biofortification in pulses relies on the same basic principle used across other crops: supplying zinc, iron or another target micronutrient to the plant at a time and in a form that maximizes its translocation into the grain, rather than simply correcting a visible deficiency symptom (Figure 2). Soil application, typically as zinc

sulphate or ferrous sulphate applied as a basal dressing, builds up the micronutrient pool available to the root system across the growing season and is the most straightforward method, though its efficiency depends heavily on soil pH and the degree of fixation discussed elsewhere in the agronomic literature on micronutrient management. Foliar spray, applied directly to the crop canopy at critical growth stages, most commonly flowering and pod filling, bypasses the soil altogether and has repeatedly been shown to be the more efficient route specifically for raising grain micronutrient concentration, since the nutrient is absorbed by the leaf and translocated toward the developing seed with less loss to soil fixation. Seed treatment or priming, in which seed is soaked or coated in a micronutrient solution before sowing, offers a low cost supplementary option, particularly useful for supporting early seedling vigour, though it contributes less to final grain concentration than soil or foliar routes applied later in the season. In practice, combining soil application with one or two foliar sprays at the right growth stage has consistently outperformed any single method used alone.

Agronomic Approaches to Biofortifying Pulses

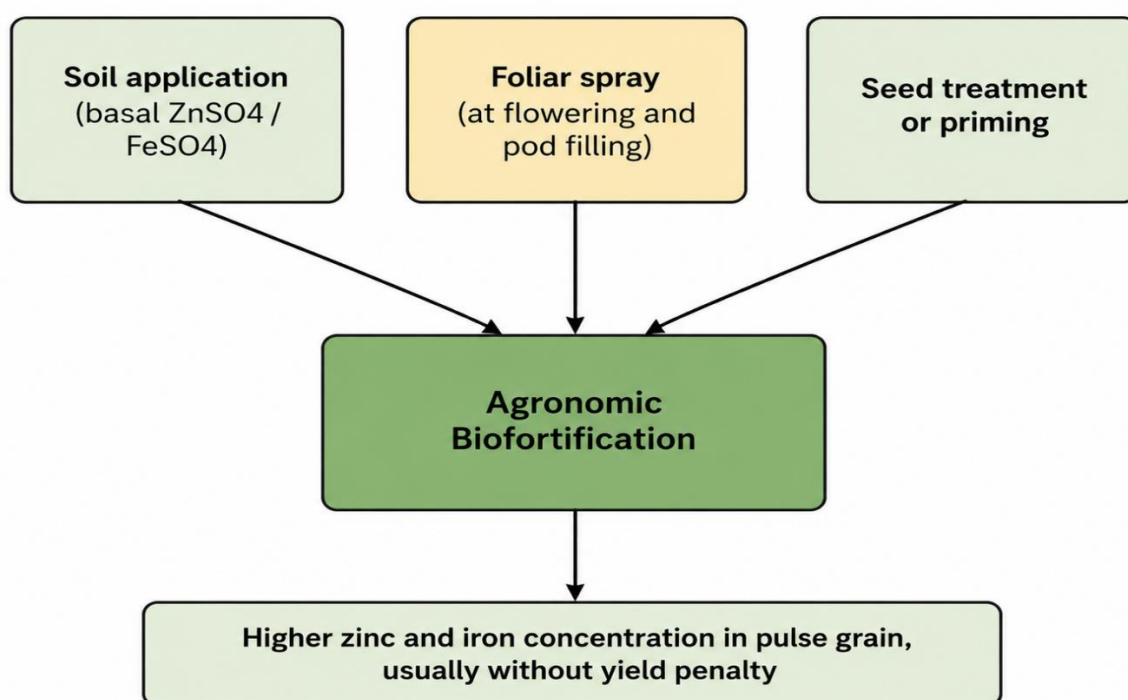


Fig. 2. Agronomic approaches to biofortifying pulses

5. Field Evidence from Pulse Crops

Field trials conducted across different pulse crops and Indian agro climatic zones offer consistent support for agronomic biofortification (Table 2). In an arid western Rajasthan trial on desi chickpea, soil application of zinc and iron produced the highest grain zinc concentration recorded in the study, 32.02 milligrams of zinc per kilogram of grain at a soil application rate of 5 kilograms of zinc per hectare, while low dose foliar spray alone performed relatively poorly for agronomic parameters, underlining that application method and rate both matter. In a two year trial on lentil conducted at Punjab Agricultural University, Ludhiana, under the biofortification mandate of the AICRP on Micro and Secondary Nutrients project funded by ICAR-IISS, Bhopal, combined foliar application of zinc sulphate and ferrous sulphate at the pre flowering and pod formation stages proved both more effective and more economical than applying either nutrient alone. A separate lentil trial in the red and lateritic soils of West Bengal found that combining seed coating with two foliar sprays of zinc sulphate produced significantly higher grain zinc concentration than any single application method tested. In chickpea grown on calcareous soil in Gujarat, the combination of soil applied zinc sulphate at sowing with a foliar spray at flowering and pod filling gave the best outcome for both yield and grain zinc fortification among all treatments compared.

Table 2. Selected field trials on agronomic biofortification of zinc and iron in pulses

Crop and location	Best performing treatment	Key outcome
Desi chickpea, arid western Rajasthan	Soil application of Zn and Fe at 5 kg Zn per hectare	Highest grain zinc concentration, 32.02 mg per kg
Lentil, Punjab Agricultural University, Ludhiana	Combined foliar ZnSO ₄ and FeSO ₄ at pre flowering and pod formation	More effective and more economical than either nutrient alone
Lentil, red and lateritic soil, West Bengal	Seed coating plus two foliar ZnSO ₄ sprays	Significantly higher grain zinc concentration than single methods
Chickpea, calcareous soil, Gujarat	Soil ZnSO ₄ at sowing plus foliar spray at flowering and pod filling	Best combined outcome for yield and grain zinc fortification

Source: Compiled from *Journal of Agricultural Research*, 2025; *International Journal of Bio-resource and Stress Management*, 2021; *Molecules*, 2021; and *Legume Research*, 2023.

These pulse specific results are consistent with the broader pattern documented across cereal crops, where a global meta analysis of zinc biofortification trials found that soil application alone raised grain zinc concentration by an average of 29.1 per cent, foliar application alone by 55.2 per cent, and the combination of soil and foliar application by 62.3 per cent over untreated crops (Figure 3), a pattern that mirrors what individual pulse trials have found and offers a general rule of thumb for designing biofortification programmes in legumes as well.

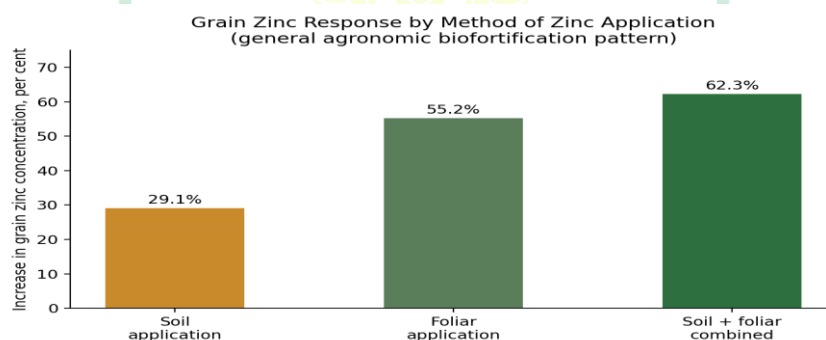


Fig. 3. Grain zinc response by method of application, general agronomic biofortification pattern

6. From Field to Plate: Realizing the Nutritional Benefit

The nutritional case for agronomic biofortification rests on a simple chain: a crop that takes up more zinc or iron in the field produces grain that is measurably richer in that nutrient at harvest, and since pulses are eaten as a daily staple rather than an occasional food, that richer grain translates fairly directly into higher dietary intake for the household that grows or buys it (Figure 4). This pathway is shorter and requires less new infrastructure than either large scale food fortification, which depends on processing and distribution systems, or supplementation programmes, which depend on health system reach and individual compliance. It is not, however, a replacement for either approach. Agronomic biofortification raises grain nutrient concentration by a meaningful but bounded margin, and for populations with severe existing deficiency, it works best as one component of a broader strategy that also includes dietary diversification, food fortification and, where needed, direct supplementation.

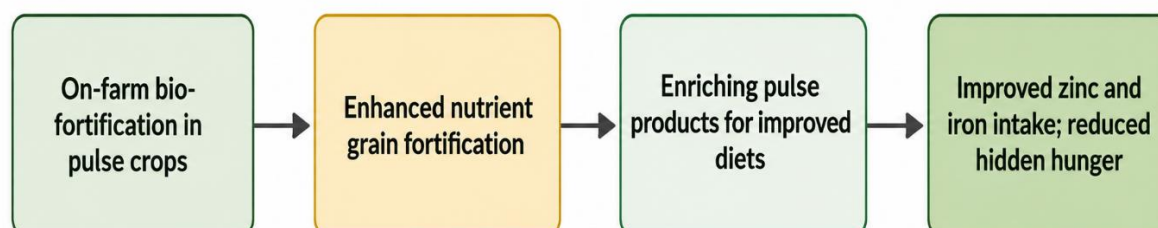


Fig. 4. From field to plate, the agronomic biofortification pathway

7. Practical Recommendations

Where grain biofortification is the specific goal, farmers and extension programmes should prioritize foliar application timed to flowering and pod filling over soil application alone, since this is consistently the more efficient route to raising grain micronutrient concentration. Combining a modest basal soil application with one or two foliar sprays outperforms either method used in isolation and should be the default recommendation wherever feasible. Seed treatment is a useful, low cost addition that supports early crop establishment but should not be relied upon as the sole biofortification method. As with any micronutrient fertilizer, the specific rate and form should be guided by soil test results, and biofortification objectives should be integrated with, rather than treated separately from, the broader nutrient management and integrated nutrient management practices already recommended for pulse crops.

8. Conclusion

Hidden hunger remains a significant, measurable burden on India's population, and pulses, already a near universal part of the Indian diet, offer an unusually direct route to addressing part of that burden. Agronomic biofortification, principally through foliar application of zinc and iron timed to flowering and pod filling and, where feasible, combined with a basal soil application, has been shown across multiple pulse crops and regions to raise grain micronutrient concentration substantially without penalizing yield. It will not, on its own, resolve India's micronutrient malnutrition problem, but as a low cost, field level intervention that works through a crop farmers already grow and households already eat, it deserves a firmly established place alongside food fortification and supplementation in the country's strategy to combat hidden hunger.

References

- Ahmad, N. et al. 2025. Agronomic Biofortification of Desi Chickpea (*Cicer arietinum* L.) with Zinc and Iron. *Journal of Agricultural Research*.
- European Journal of Clinical Nutrition. 2026. Food fortification in India, evidence, implementation and future directions to reduce iron and other micronutrient deficiencies.
- Frontiers in Sustainable Food Systems. 2018. Quantifying, Projecting, and Addressing India's Hidden Hunger.
- Kumar, S. et al. 2021. Enrichment of Zinc and Iron Micronutrients in Lentil (*Lens culinaris* Medik.) through Biofortification. *Molecules*, 26(24): 7671.
- Legume Research. 2023. Agronomic Biofortification of Zinc in Chickpea Varieties in Calcareous Soil.
- Nature Communications. 2025. Zinc agronomic biofortification in wheat and its drivers, a global meta-analysis.
- Pandey, R. et al. 2021. Agronomic Biofortification of Zinc in Lentil. *International Journal of Bio-resource and Stress Management*.
- Indian Journal of Medical Research. 2025. Micronutrient status of Indian population.

Applications of Artificial Intelligence and Machine Learning in Veterinary Diagnosis and Disease Prediction



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Abstract

Artificial intelligence (AI) and machine learning (ML) are increasingly integrated into veterinary practice, offering new tools for diagnosis, disease prediction, and clinical decision-making. This review synthesises current peer-reviewed evidence on the application of AI and ML across veterinary diagnostic imaging, infectious disease surveillance, and predictive health analytics in companion animals and livestock. Convolutional neural networks (CNNs) have demonstrated diagnostic performance approaching, and in some tasks matching, that of board-certified specialists in detecting thoracic, hepatic, and cardiac abnormalities from radiographs and ultrasound images, while traditional machine-learning methods such as random forests and support vector machines continue to support disease-risk prediction from clinical, laboratory, and epidemiological data. Beyond individual-patient diagnostics, AI-enabled sensor and acoustic analytics are being applied to early-warning disease detection in dairy cattle, poultry, and swine, contributing to precision livestock health management. The review also considers the methodological and practical challenges limiting clinical translation, including data quality, external validation, interpretability, and integration into veterinary workflows, and outlines emerging directions such as explainable AI, federated learning, and One Health-oriented surveillance systems. Overall, the evidence indicates that AI and ML are becoming valuable adjuncts to, rather than replacements for, veterinary clinical judgement.

Keywords: Artificial Intelligence, Machine Learning, Veterinary Diagnosis, Disease Prediction, Deep Learning, Convolutional Neural Networks, Diagnostic Imaging, One Health

1. Introduction

Veterinary medicine has traditionally depended on clinical examination, laboratory testing, diagnostic imaging, and the accumulated experience of the practitioner to diagnose disease and guide treatment decisions. While this approach remains foundational, it is inherently constrained by the availability of specialist expertise, the subjectivity of visual interpretation, and the time pressures of busy clinical or field practice. Artificial intelligence, broadly defined as the capacity of computer systems to perform tasks that would normally require human intelligence, and its principal enabling discipline, machine learning, in which algorithms learn patterns directly from data rather than being explicitly programmed, are increasingly being applied to address these constraints across both companion animal and livestock veterinary medicine.

The growth of AI in veterinary medicine has been driven by several converging factors: the accumulation of large digital datasets of radiographs, ultrasound images, histopathology slides, and electronic clinical records; the availability of powerful and increasingly affordable computing hardware; and the successful translation of deep-learning techniques, particularly convolutional neural networks, from human radiology and pathology into veterinary applications. Recent systematic surveys of the veterinary AI literature report that deep learning and traditional machine-learning approaches are now the dominant methodologies applied across diagnostic imaging, disease prediction, and clinical decision support, with a steadily expanding body of peer-reviewed evidence supporting their use.

2. Core Concepts: AI, Machine Learning and Deep Learning in Veterinary Medicine

Machine learning is generally described as a core approach within artificial intelligence that enables computer systems to learn statistical patterns from data and generate predictions without being explicitly programmed for each task. Traditional machine-learning algorithms commonly applied in veterinary medicine include support

vector machines (SVMs), random forests (RF), logistic regression, and artificial neural networks (ANNs), each of which typically requires manually defined input features, such as laboratory values, clinical signs, or extracted image features, to generate a classification or prediction.

Deep learning (DL) is a specialised subfield of machine learning in which multi-layered neural networks automatically learn relevant features directly from raw data, most notably images, without requiring manual feature engineering. Convolutional neural networks (CNNs) are the dominant deep-learning architecture for image-based veterinary diagnostic tasks, as they are particularly well suited to recognising spatial patterns such as lesions, opacities, or anatomical abnormalities within radiographs, ultrasound images, or histopathology slides. Recurrent neural networks and related architectures are used for sequential or time-series data, such as continuous sensor streams from wearable livestock monitoring devices, while natural language processing (NLP) techniques are increasingly applied to mine unstructured clinical text, such as case notes or pathology reports, for surveillance and research purposes.

A further important distinction in veterinary AI applications is between diagnostic support, in which an algorithm assists interpretation of a single patient's data at a single point in time, and predictive or surveillance analytics, in which models forecast disease risk or outbreak probability across a population using epidemiological, environmental, and clinical data streams. Both categories are considered in the sections that follow.

3. AI and Machine Learning in Veterinary Diagnostic Imaging

Diagnostic imaging is the most extensively researched application domain for AI in veterinary medicine, reflecting both the availability of large digital image datasets and the direct transferability of methods developed for human radiology. A systematic review following PRISMA guidelines identified 422 relevant peer-reviewed articles applying deep learning to veterinary diagnostic and animal health tasks, spanning radiography, ultrasonography, histopathology, and dermatological image analysis, and found that CNN-based models were the predominant architecture used across these studies. Figure 1 summarises the generalised workflow through which such systems are developed and deployed, from raw diagnostic data through model-based analysis to veterinarian-reviewed clinical output.

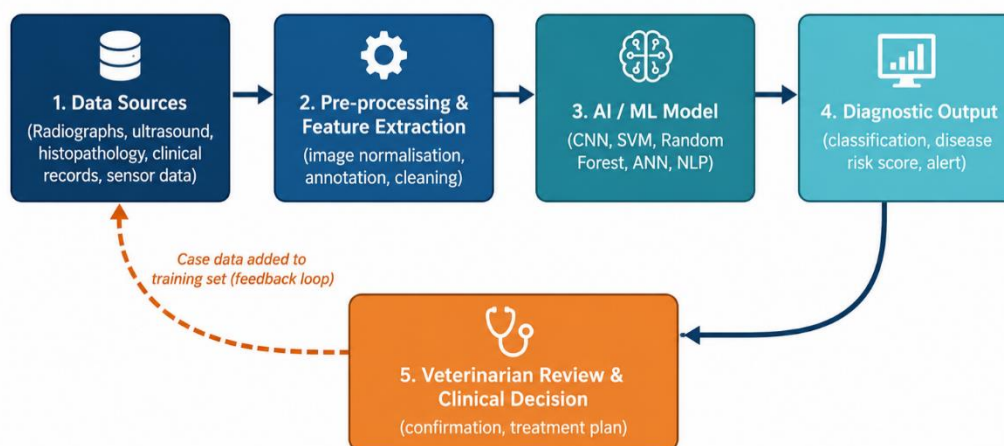


Figure 1. Generalised workflow of an AI/ML-assisted veterinary diagnostic system, incorporating a feedback loop for continued model refinement.

Representative peer-reviewed studies illustrate both the promise and the current performance range of CNN-based diagnostic tools (Table 1, Figure 2). In cats, a CNN based on the ResNet50V2 architecture, fine-tuned on annotated thoracic radiographs, achieved a mean accuracy of 82 percent, sensitivity of 88 percent, and specificity of 75 percent for detecting pulmonary abnormalities. In dogs, a CNN developed to detect left atrial enlargement from thoracic radiographs achieved an accuracy of 82.71 percent, with sensitivity and specificity of 68.42 percent and 87.09 percent respectively, a performance profile statistically comparable to that of board-certified veterinary radiologists evaluating the same cases. A separate CNN developed to detect degenerative liver disease from

abdominal ultrasound images in dogs achieved 91 percent accuracy, 100 percent sensitivity, and 82.8 percent specificity when benchmarked against cytological findings and serum biomarkers, outperforming other individual diagnostic tests evaluated in that study.

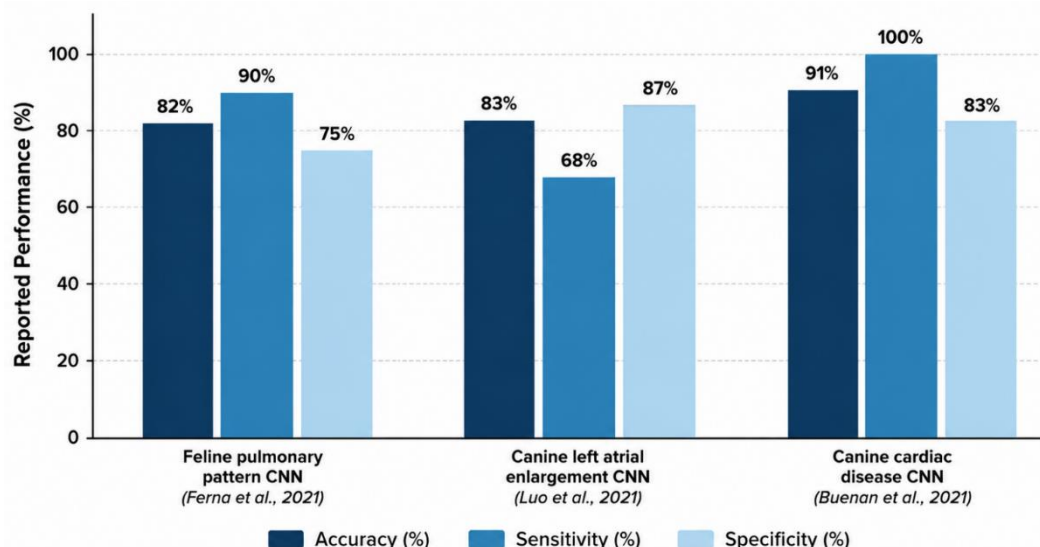


Figure 2. Reported diagnostic performance of selected CNN models in small-animal diagnostic imaging, illustrating accuracy, sensitivity, and specificity across three peer-reviewed studies.

Beyond individual performance metrics, a notable comparative study evaluating AI interpretation of primary thoracic lesions in dogs and cats reported a lower overall error rate for the AI system (10.7 percent) than for veterinarians working alone (17.2 percent) or veterinarians assisted by the AI system (16.8 percent), suggesting that in some diagnostic contexts algorithmic interpretation may exceed unaided human performance, though such findings warrant cautious interpretation given differences in case mix and study design across the literature. Deep-learning approaches have since been extended to additional imaging tasks, including detection of confirmed heart failure in dogs and cats and identification of spinal cord disease from magnetic resonance images, with performance continuing to vary by task, species, and underlying disease prevalence in the training data.

Table 1. Selected Peer-Reviewed Studies of AI/ML Applications in Veterinary Diagnostic Imaging

Species / Modality	AI Method	Diagnostic Task	Reported Performance / Source
Cats — thoracic radiographs	CNN (ResNet50V2)	Detection of pulmonary abnormalities	Accuracy 82%, sensitivity 88%, specificity 75% (Fenn et al., 2022)
Dogs — thoracic radiographs	CNN	Detection of left atrial enlargement	Accuracy 82.71%, sensitivity 68.42%, specificity 87.09% (Li et al., 2021)
Dogs — abdominal ultrasound	CNN	Detection of degenerative liver disease	Accuracy 91%, sensitivity 100%, specificity 82.8% (Banzato et al.)
Dogs/Cats — thoracic radiographs	CNN vs. radiologists	Detection of primary thoracic lesions	Error rate 10.7% (AI) vs 16.8–17.2% (radiologists) (Boissady et al., 2020)
Dogs/Cats — thoracic radiographs	CNN software	Detection of confirmed heart failure	Feline cardiomegaly sensitivity 96%, HF sensitivity 9.8%, specificity 95% (Ellingsberg et al.)
Dogs — thoracolumbar MRI	Deep learning classifier	Detection of spinal cord disease	Biercher et al., Front. Vet. Sci., 2021

4. AI and Machine Learning in Disease Prediction and Surveillance

Beyond image-based diagnosis, AI and ML methods are increasingly applied to predict disease occurrence and forecast outbreaks at the individual-animal, herd, or population level. Infectious disease prediction models typically draw on epidemiological, clinical, laboratory, and environmental data, applying supervised classification or regression techniques to estimate disease risk, or unsupervised and semi-supervised approaches to detect anomalous patterns indicative of an emerging outbreak. A comprehensive review of ML applications for infectious disease surveillance, diagnosis, and prognosis, encompassing 77 studies, found that different input data types required different model architectures to achieve optimal performance, and highlighted the growing role of explainable AI and ensemble learning methods in improving both predictive accuracy and clinical interpretability. In livestock health specifically, AI-enabled prediction systems increasingly integrate sensor- and camera-based data streams from precision livestock farming infrastructure with clinical and production records to generate early-warning alerts for conditions such as mastitis and lameness in dairy cattle, respiratory and behavioural disorders in poultry and swine detected through acoustic analysis, and susceptibility or outbreak risk for diseases such as avian influenza. These applications typically combine traditional machine-learning classifiers with time-series analysis of continuously collected sensor data, enabling detection of subtle deviations from an individual animal's baseline behaviour well before clinical signs become apparent to a human observer. Figure 3 summarises the principal branches of AI/ML methodology and their corresponding application domains across veterinary diagnosis and disease prediction, from diagnostic imaging through to population-level surveillance.

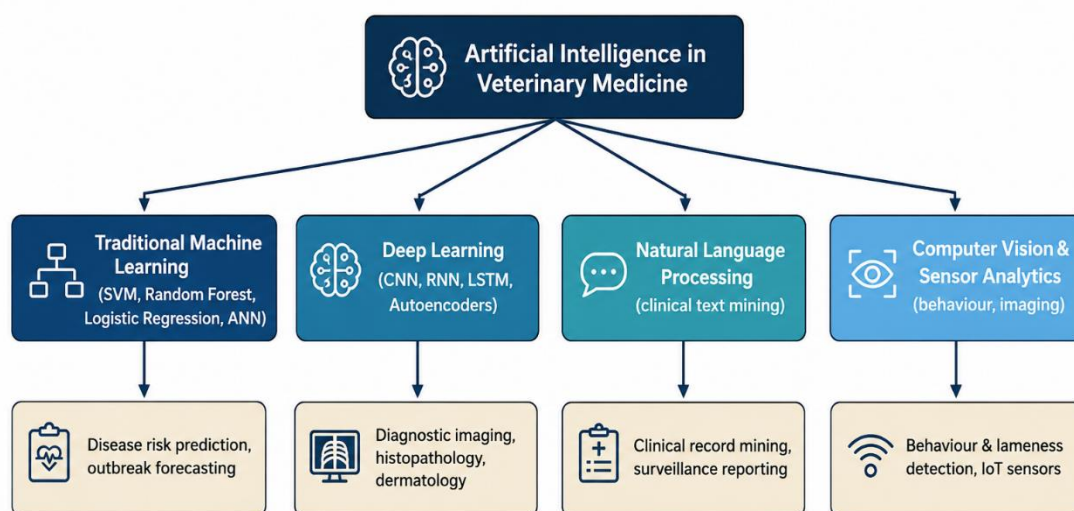


Figure 3. Taxonomy of AI/ML methods and their principal application domains in veterinary diagnosis and disease prediction.

A further emerging application of predictive ML models is in the diagnosis of endocrine and metabolic disorders that are difficult to distinguish on clinical grounds alone; for example, machine-learning classifiers have been evaluated as diagnostic aids for canine hypoadrenocorticism, using routinely available clinical and laboratory parameters to flag cases warranting confirmatory testing. Such applications illustrate the broader potential of AI to support diagnostic reasoning in conditions where clinical presentation is non-specific, complementing rather than replacing conventional diagnostic pathways.

5. Applications Across Species and Health Domains

The application of AI and ML spans a wide range of species and health domains, summarised in Table 2. In companion animal practice, CNN-based image analysis supports diagnosis of cardiac, pulmonary, hepatic, and dermatological conditions, while natural language processing tools are beginning to be applied to mine electronic clinical records for surveillance and research purposes. In livestock production systems, AI-enabled sensor analytics and computer vision are used for early detection of mastitis and lameness in dairy cattle, acoustic and

image-based screening for respiratory disease and welfare compromise in poultry and swine, and behavioural monitoring integrated with precision livestock farming infrastructure.

At the population and public-health level, AI and ML models contribute to zoonotic disease surveillance and outbreak forecasting within a One Health framework, integrating veterinary, environmental, and human health data streams to support earlier and more coordinated disease response. Across these diverse applications, a consistent theme in the literature is that AI systems perform most reliably when applied to well-defined, data-rich diagnostic or predictive tasks, and that their performance depends heavily on the quality, size, and representativeness of the training data used for model development.

Table 2. AI/ML Applications Across Species and Veterinary Health Domains

Species / Sector	Disease / Condition	AI/ML Technique	Application Focus
Dairy cattle	Mastitis, lameness	Sensor-based ML / ensemble models	Early-warning behavioural monitoring
Poultry	Avian influenza, respiratory disease	Acoustic analysis, image classification	Outbreak detection, welfare screening
Swine	Welfare-linked disease signals	Computer vision, behavioural analytics	Automated welfare and health scoring
Small animals (dogs/cats)	Cardiac, pulmonary, hepatic, dermatological disease	CNN-based image classification	Radiograph/ultrasound-assisted diagnosis
Cross-species / public health	Zoonoses, endocrine disorders (e.g., hypoadrenocorticism)	Random forest, explainable AI	Diagnostic decision support, One Health surveillance

6. Benefits of AI and ML in Veterinary Practice

The integration of AI and ML into veterinary diagnosis offers several documented benefits. Image-based AI tools can reduce the workload associated with routine interpretation of radiographs and ultrasound images, potentially shortening the time to diagnosis and allowing specialist attention to be directed toward the most complex or ambiguous cases. In several studies, AI-assisted interpretation has demonstrated diagnostic performance statistically comparable to, or in specific tasks exceeding, that of experienced veterinary radiologists, suggesting genuine potential to support diagnostic consistency, particularly in settings where specialist radiology expertise is not readily available.

In livestock health management, AI-enabled predictive and sensor-based systems allow earlier detection of sub-clinical disease than is achievable through periodic visual inspection alone, supporting more timely intervention, more judicious and targeted use of antimicrobials, and improved containment of transboundary and production-limiting diseases. At the population level, AI-based surveillance and outbreak-prediction models offer the potential for faster identification of emerging disease threats, strengthening both animal health management and broader One Health disease-control efforts.

7. Challenges and Limitations

Despite these documented benefits, substantial challenges continue to limit the routine clinical translation of AI and ML tools in veterinary practice. A recurring concern across the reviewed literature is data quality and availability: many published models are trained and validated on relatively small, single-institution datasets, raising questions about their external validity and generalisability when applied to different populations, breeds, geographic regions, or imaging equipment. Systematic reviews of veterinary AI research have specifically noted that substantial challenges persist regarding data quality, external validation, and clinical generalisability in real-world settings, even where reported performance within the original study population appears strong.

Interpretability and trust present a further challenge, as many deep-learning models function as effective but opaque "black boxes," making it difficult for veterinarians to understand the basis for a given AI-generated output or to identify when a prediction may be unreliable. This has driven growing interest in explainable AI (XAI) methods, which aim to provide interpretable justifications for model outputs, an approach identified in recent

reviews as important for building clinician trust and supporting safe integration into diagnostic workflows. Additional practical barriers include the cost of implementing AI-enabled diagnostic tools, the need for reliable digital infrastructure and connectivity, particularly in field and rural veterinary settings, integration challenges with existing practice-management and imaging software, and the ongoing need for veterinarian training in the appropriate use and limitations of AI-generated outputs, so that such tools are used to inform, rather than replace, clinical judgement.

8. Future Directions

Several emerging directions are likely to shape the next phase of AI and ML application in veterinary medicine. Explainable AI methods are expected to become increasingly integrated into diagnostic tools, allowing veterinarians to understand and verify the reasoning underlying a given prediction rather than relying on an opaque output alone. Federated learning approaches, in which models are trained collaboratively across multiple institutions without directly sharing sensitive patient-level data, offer a promising route to building larger, more diverse, and better-validated training datasets while addressing data-privacy and governance concerns.

Multimodal integration, combining imaging, clinical, laboratory, genomic, and sensor data within a single predictive framework, is likely to improve diagnostic and predictive accuracy beyond what any single data type can achieve alone. Finally, continued development of AI-enabled surveillance systems within a One Health framework, linking veterinary, environmental, and human health data, holds particular promise for earlier detection and more coordinated response to zoonotic and transboundary disease threats, an area of growing importance given the increasing frequency of emerging infectious disease events globally.

9. Conclusion

Artificial intelligence and machine learning are increasingly well-established tools in veterinary diagnosis and disease prediction, with peer-reviewed evidence demonstrating strong diagnostic performance in imaging-based applications and growing utility in disease surveillance and predictive health analytics across companion animal and livestock domains. Current evidence indicates that these tools are best regarded as decision-support aids that complement, rather than substitute for, veterinary clinical expertise, given persistent challenges of data quality, external validation, and interpretability. Continued investment in high-quality, diverse training data, explainable model architectures, and veterinarian training, alongside supportive institutional and regulatory frameworks, will be essential to realise the full potential of AI and ML in improving animal health outcomes, diagnostic accuracy, and disease surveillance across veterinary and One Health practice.

References

- AI applications in veterinary digital health: a systematic survey. *Frontiers in Veterinary Science* (2026). <https://www.frontiersin.org/journals/veterinary-science/articles/10.3389/fvets.2026.1853395/full>
- Applications and Considerations of Artificial Intelligence in Veterinary Sciences: A Narrative Review. *PMC* (2025). <https://pmc.ncbi.nlm.nih.gov/articles/PMC11964155/>
- Review of applications of deep learning in veterinary diagnostics and animal health. *Frontiers in Veterinary Science* (2025). <https://www.frontiersin.org/journals/veterinary-science/articles/10.3389/fvets.2025.1511522/full>
- Artificial intelligence in veterinary and animal science: applications, challenges, and future prospects. *ScienceDirect* (2025). <https://www.sciencedirect.com/science/article/abs/pii/S0168169925005010>
- Artificial intelligence in veterinary diagnostic imaging: Perspectives and limitations. *ScienceDirect* (2024). <https://www.sciencedirect.com/science/article/pii/S0034528824001838>
- Artificial Intelligence for Infectious Disease Prediction and Prevention: A Comprehensive Review. *arXiv:2411.10486* (2024). <https://arxiv.org/pdf/2411.10486>
- Machine Learning and Artificial Intelligence for Infectious Disease Surveillance, Diagnosis, and Prognosis. *PMC* (2025). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC12299889/>
- Fenn, J., et al. Deep learning in veterinary medicine, an approach based on CNN to detect pulmonary abnormalities from lateral thoracic radiographs in cats. *Scientific Reports* (2022). <https://www.nature.com/articles/s41598-022-14993-2>

Kim, E., Fischetti, A. J., Sreetharan, P., et al. Pilot study: Application of artificial intelligence for detecting left atrial enlargement on canine thoracic radiographs. *Veterinary Radiology & Ultrasound* (2021). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7689842/>

Biercher, A., et al. Using deep learning to detect spinal cord diseases on thoracolumbar magnetic resonance images of dogs. *Frontiers in Veterinary Science*, 8, 721167 (2021). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8593183/>

Ellingsberg, E., et al. Performance of an Artificial Intelligence Convolution Neural Network Software for the Detection of Confirmed Heart Failure in Dogs and Cats. *Veterinary Radiology & Ultrasound* (2026). <https://onlinelibrary.wiley.com/doi/10.1111/vru.70144>

Boissady, E., de La Comble, A., Zhu, X., & Hespel, A. Artificial intelligence evaluating primary thoracic lesions has an overall lower error rate compared to veterinarians or veterinarians in conjunction with the artificial intelligence. *Veterinary Radiology & Ultrasound*, 61, 619-627 (2020).

Emerging role of artificial intelligence in animal disease diagnosis and prediction. *Veterinary Journal / IJVSAH* (2025). <https://www.veterinarypaper.com/pdf/2025/vol10issue10S/PartA/S-10-10-9-908.pdf>

Artificial Intelligence and its Application in the Prediction and Diagnosis of Animal Diseases: A Review (2025). https://www.academia.edu/108244054/Artificial_Intelligence_and_its_Application_in_the_Prediction_and_Diagnosis_of_Animal_Diseases_A_Review



Chelated Fertilizers: Enhancing Micronutrient Availability for Higher Crop Productivity



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Highlight of the Article

Micronutrient deficiency remains widespread in Indian soils, yet ordinary sulphate and oxide sources of zinc, iron, manganese and copper often fail to correct it, since as much as 85 to 90 per cent of soil applied zinc can be fixed into insoluble forms within weeks, particularly in the alkaline and calcareous soils that cover large parts of the country. Chelated fertilizers, in which a metal ion is bound within an organic ligand such as EDTA, DTPA or EDDHA, resist this fixation and remain available for root or leaf uptake over a longer period, allowing lower doses to achieve results that conventional salts often cannot match. Field trials on lowland rice have recorded grain and straw yield increases of 37.5 and 43.1 per cent respectively from basal application of Zn-EDTA, and the technology has moved from a specialty input into a mainstream option as India's micronutrient fertilizer market approaches one billion US dollars. This article explains how chelation works, which chelating agent suits which soil condition, what the field evidence shows, and how farmers and extension workers can apply this technology correctly for measurable gains in crop productivity.

Keywords: Chelation, EDTA, Foliar application, Nutrient use efficiency, Zinc deficiency

Introduction

Micronutrient deficiencies have emerged as one of the most widespread constraints to sustaining crop productivity and nutritional quality in Indian agriculture. Despite the increasing use of zinc and iron fertilizers, deficiencies of zinc, iron, boron, and manganese continue to be reported across diverse agroecological regions of the country. Soil testing laboratories consistently reveal that these deficiencies often persist year after year, even in fields where micronutrient fertilizers have been applied regularly. The problem is not always the quantity of nutrients applied but their limited availability to plants after application. In many Indian soils, particularly the alkaline and calcareous soils that dominate large parts of northwestern, central, and peninsular India, soluble micronutrients rapidly react with carbonates, clay minerals, and other soil constituents to form insoluble compounds that cannot be readily absorbed by plant roots. Consequently, only a small proportion of the applied micronutrients is utilized by crops, while the remainder becomes fixed in the soil, resulting in poor fertilizer use efficiency and continued nutrient deficiencies.

Chelated micronutrient fertilizers were developed to overcome this challenge. In these fertilizers, the metal ion is enclosed within an organic molecule, known as a chelating agent, which protects it from undesirable chemical reactions in the soil while keeping it in a soluble and plant available form. This protective mechanism prevents rapid nutrient fixation and allows the micronutrient to remain available for a longer period, enabling efficient uptake by plant roots or leaves. As crops absorb the nutrient, the chelating agent gradually releases the metal ion, ensuring a continuous supply throughout the critical stages of plant growth. Compared with conventional inorganic salts such as zinc sulphate or ferrous sulphate, chelated micronutrients generally provide higher nutrient use efficiency, particularly under alkaline and calcareous soil conditions where micronutrient fixation is severe.

Several chelating agents are commercially available, including EDTA (ethylenediaminetetraacetic acid), DTPA (diethylenetriamine pentaacetic acid), EDDHA (ethylenediamine N,N' bis(2 hydroxyphenylacetic acid)), HEEDTA, and IDHA, each differing in chemical stability and suitability under different soil pH conditions. Their

effectiveness depends on factors such as soil reaction, crop species, method of application, and environmental conditions. Selecting the appropriate chelated fertilizer according to soil characteristics can substantially improve micronutrient availability, crop growth, yield, and produce quality while reducing nutrient losses and enhancing fertilizer use efficiency.

Why Ordinary Micronutrient Salts Often Fail in the Field

When a farmer applies zinc sulphate, ferrous sulphate or a similar salt to the soil, the metal ion it releases carries a positive charge and is chemically reactive. In neutral to alkaline soils, and especially in the calcareous soils that dominate large tracts of central and western India, that ion combines readily with carbonate, hydroxide and phosphate ions already present in the soil solution, forming compounds that are effectively insoluble. Estimates suggest that as much as 85 to 90 per cent of soil applied zinc can be rendered unavailable to the crop within a matter of weeks through this process of fixation, meaning that a large share of every bag of sulphate fertilizer purchased is, agronomically speaking, wasted. The same fixation affects iron even more severely in high pH soils, which is why iron chlorosis remains common in orchard and vegetable crops grown on calcareous land even where ferrous sulphate has been applied repeatedly.

This is not a failure of the nutrient itself but of the chemical form in which it is supplied. A zinc or iron ion needs to remain in a soluble, plant available state long enough for a root hair or leaf cell to absorb it, and an unprotected ion in reactive soil simply does not get that chance. Chelation addresses this gap directly, and understanding how it works is the starting point for using these fertilizers correctly.

What Makes a Fertilizer Chelated

The word chelate comes from the Greek chele, meaning a lobster's claw, an apt image for what happens chemically. In a chelated fertilizer, the metal ion, whether zinc, iron, manganese or copper, is held within the structure of a larger organic molecule called a ligand or chelating agent, in much the same way a claw encircles and holds an object without releasing it (Figure 1). This structure shields the metal ion from reacting with carbonates, phosphates and clay surfaces in the soil, keeping it in solution and available for uptake for a much longer period than the free ion form. The most widely used chelating agents in commercial micronutrient fertilizers are ethylenediaminetetraacetic acid, commonly known as EDTA, diethylenetriaminepentaacetic acid or DTPA, and ethylenediamine-N,N bis (2 hydroxyphenylacetic acid), known as EDDHA, alongside a newer generation of amino acid and organic acid based chelates that are more readily biodegradable.

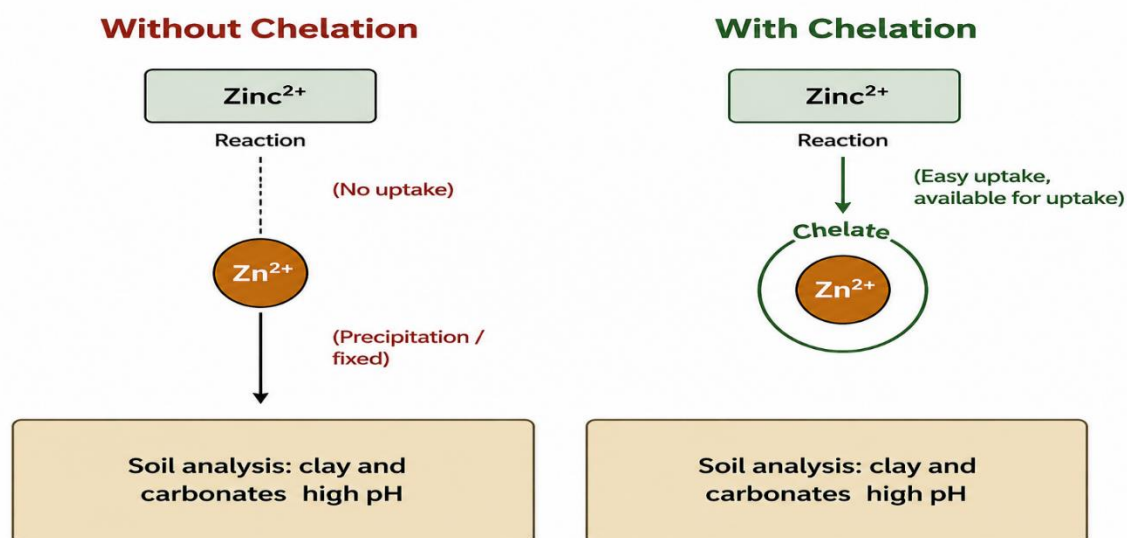


Fig. 1. How chelation protects a micronutrient ion from fixation in the soil

Each of these chelating agents behaves differently depending on soil pH, and choosing the wrong one for a given soil condition can mean the difference between a visible correction of deficiency and a fertilizer that performs little better than the plain salt it was meant to replace.

Choosing the Right Chelate for the Soil

EDTA is the most common and the least expensive chelating agent, and it works well in acidic to mildly neutral soils, but its stability declines sharply above a soil pH of about 6.5, since calcium ions in alkaline soil begin to displace the target micronutrient from the ligand. DTPA offers greater stability and remains effective up to a soil pH of around 7.5, making it the more reliable choice for iron, zinc, manganese and copper in the mildly alkaline soils common across much of the Indo Gangetic plain. For genuinely calcareous or high pH soils, where DTPA too begins to lose its grip, EDDHA remains effective up to a soil pH of about 9 and is, for practical purposes, the only reliable chelate for correcting iron deficiency in such conditions, though it is also the costliest of the three (Table 1, Figure 4).

Table 1. Effective soil pH range of common micronutrient chelating agents

Chelating agent	Effective soil pH range	Micronutrients commonly chelated	Remarks
EDTA	Up to about pH 6.5	Zinc, manganese, copper, iron	Most common and economical; loses effectiveness in alkaline soils
DTPA	Up to about pH 7.5	Iron, zinc, manganese, copper	More stable than EDTA in neutral to mildly alkaline soils
EDDHA	Up to about pH 9.0	Iron	Most reliable for calcareous, high pH soils; highest cost
Amino acid and organic acid chelates	Wide range	Zinc, iron, manganese, copper	Readily biodegradable; common in foliar formulations

Source: Compiled from Alsultana Fertilizer, 2026, and Resonance, Chelates for Micronutrient Nutrition among Crops.

Effective Soil pH Range of Common Micronutrient Chelating Agents

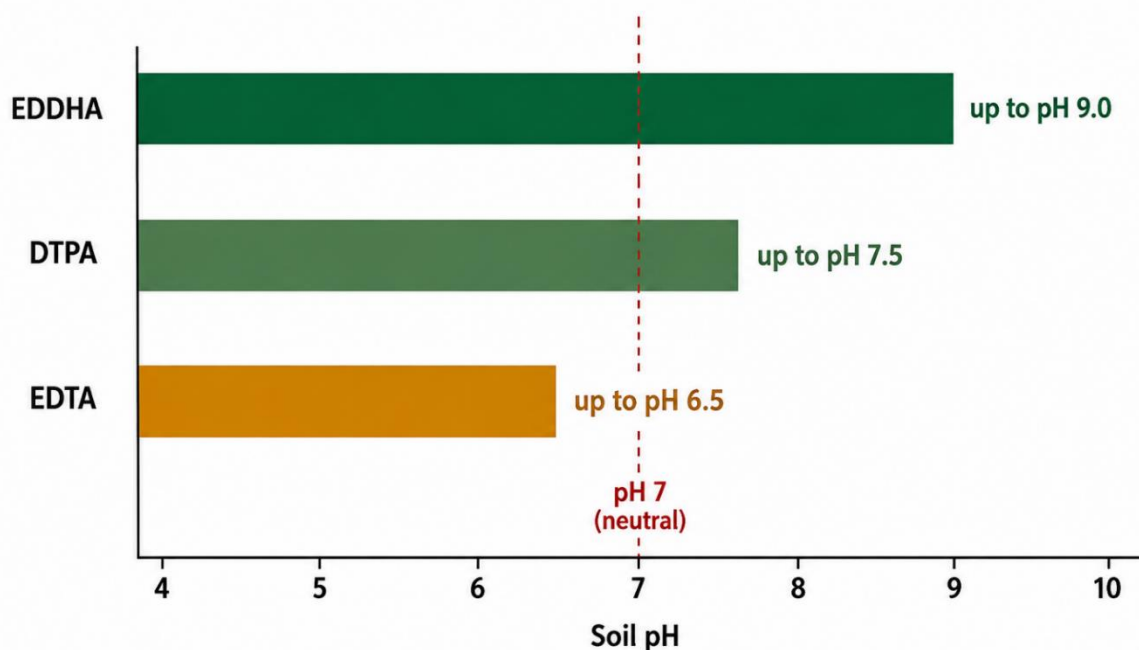


Fig. 2. Effective soil pH range of common chelating agents used in micronutrient fertilizers

Field Evidence: Chelated versus Conventional Micronutrients

The case for chelated fertilizers rests not only on chemistry but on measured field performance. Zinc deficiency remains the single most widespread micronutrient constraint in Indian soils, with state level assessments showing 83 per cent of tested soils deficient in Maharashtra, 73 per cent in Karnataka and 58 per cent in Andhra Pradesh, against an all India average of about 49 per cent of cropland tested (Table 2, Figure 2). In a multi season field trial conducted on an Aeric Endoaquept soil at pH 7.2, a condition where zinc sulphate is known to fix rapidly, basal application of Zn-EDTA at 1 kilogram of zinc per hectare produced the highest zinc uptake recorded in the study, 209.2 grams per hectare in grain and 133.8 grams per hectare in straw, alongside a 37.5 per cent increase in grain yield and a 43.1 per cent increase in straw yield over the unfertilized control (Table 3, Figure 3).

Table 2. Zinc deficiency in cropland soils of selected Indian states

State or category	Soils testing zinc deficient
Maharashtra	83 per cent
Karnataka	73 per cent
Andhra Pradesh	58 per cent
All India, cropland tested	49 per cent

Source: Research and Markets, India Micronutrient Fertilizer Market report, citing state soil testing assessments.

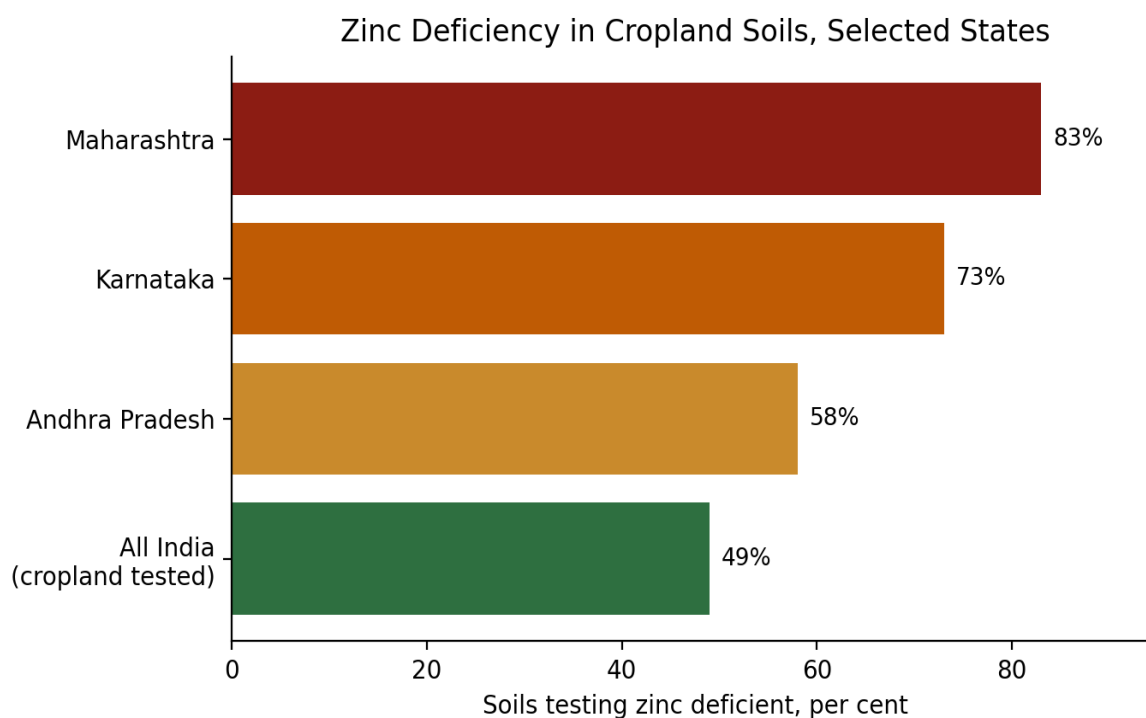


Fig. 3. Zinc deficiency in cropland soils of selected Indian states

Table 3. Response of lowland rice to basal Zn-EDTA application (1 kg zinc per hectare)

Parameter	Value with Zn-EDTA	Increase over unfertilized control
Grain yield	5.5 tonnes per hectare	37.5 per cent
Straw yield	7.3 tonnes per hectare	43.1 per cent
Zinc uptake, grain	209.2 g per hectare	Highest among treatments tested
Zinc uptake, straw	133.8 g per hectare	Highest among treatments tested

Source: Field experiment on Aeric Endoaquept soil, pH 7.2, reported in Nutrient Cycling in Agroecosystems.

Beyond this individual trial, corrective zinc application more broadly has been associated with wheat yield gains in the range of 200 to 400 kilograms per hectare and rice gains of 300 to 600 kilograms per hectare wherever deficiency is confirmed by soil testing, underlining that the agronomic opportunity here is not marginal but substantial across India's major cereal belts.

Modes of Application: Soil, Foliar, and Fertigation

Chelated micronutrients can be delivered to the crop through several routes, and the right choice depends on how quickly correction is needed, the severity of deficiency, and the infrastructure available on the farm (Table 4).

Table 4. Modes of applying chelated micronutrient fertilizers

Method	Typical dose	Advantage	Limitation
Soil application, basal	1 to 5 kg micronutrient per hectare, depending on element and crop	Season long correction; suits deficiency across the root zone	Higher cost per hectare than sulphate forms
Foliar spray	0.2 to 0.5 per cent solution, two to three sprays at 15 day intervals	Rapid correction within 7 to 14 days; effective even in high pH soils	Effect is temporary; repeat spraying needed; timing is critical
Fertigation	Injected through the drip system at the recommended concentration	Uniform distribution; combines water and nutrient use efficiency	Requires micro irrigation infrastructure
Seed treatment or priming	2 to 5 g chelate per kg seed	Low cost; supports early crop establishment	Cannot correct a severe or a later emerging deficiency on its own

Source: Compiled from Greenway Biotech and Terafon technical guidance on chelated micronutrient application.

Foliar application in particular deserves attention in Indian conditions, since it bypasses the soil entirely and delivers the nutrient directly to plant tissue, making it the fastest way to correct a deficiency that has already begun to show visible symptoms. For severe or long standing deficiency, however, foliar correction alone rarely suffices, and combining an early foliar spray for immediate relief with a soil applied chelate for sustained correction tends to give the most reliable outcome.

The Growing Market and Policy Landscape

Chelated formulations have moved from a specialty, high value input into a mainstream part of India's fertilizer basket. The domestic micronutrient fertilizer market was valued at approximately 0.81 billion US dollars in 2025 and is projected to reach around 1.12 billion US dollars by 2030, and specialty chelates and nano dispersions are reported to be capturing an increasing share of this market from bulk sulphate products, particularly in the horticulture, wheat and rice growing belts where soluble, fertigation compatible inputs are in growing demand. All micronutrient fertilizers sold in India, chelated or otherwise, must conform to the specifications laid down under the Fertiliser Control Order, which sets minimum nutrient content and purity standards; farmers are advised to check the certified composition on the product label before purchase, since the market has also seen instances of under strength or adulterated micronutrient products sold at chelate level prices.

Practical Guidelines for Farmers and Extension Workers

Match the chelate to the soil pH

Test the soil before selecting a product. In acidic to near neutral soils, EDTA chelates are adequate and economical; in the mildly alkaline soils typical of much of the Indo Gangetic plain, DTPA gives more reliable results; and in calcareous or high pH soils, particularly for iron correction, EDDHA is worth the additional cost.

Use foliar spray for fast, visible correction

Where deficiency symptoms such as interveinal chlorosis or stunted growth are already visible, a foliar spray at 0.2 to 0.5 per cent concentration, applied in the early morning or late afternoon to avoid leaf scorch, typically shows improvement in new growth within one to two weeks.

Do not abandon soil application for perennial or long duration crops

For orchards, plantation crops and long duration field crops, a basal or root zone application of chelated micronutrient at the start of the season provides more sustained correction than repeated foliar sprays alone, and the two approaches work best in combination rather than as substitutes for each other.

Verify the product before purchase

Check the certified nutrient content and the chelating agent named on the label against Fertiliser Control Order specifications, and be cautious of products priced well below the typical market range for a genuine chelate, since these are often diluted or entirely unchelated formulations sold under a similar name.

Way Forward

Micronutrient deficiency will not be solved by simply increasing the tonnage of fertilizer applied; it requires supplying the nutrient in a chemical form the crop can actually use under the soil conditions it is grown in. Chelated fertilizers, correctly matched to soil pH and combined with the right mode of application, have repeatedly demonstrated their ability to close this gap where conventional sulphate and oxide sources fail. The remaining task is one of awareness and verification: helping farmers recognize when a chelated product is genuinely warranted, choose the correct chelating agent for their soil, and confirm that what they are buying meets the specification on its label. As India's micronutrient fertilizer market continues to expand, extension systems and Krishi Vigyan Kendras have a growing role to play in ensuring that this expansion translates into real gains in crop productivity rather than into misapplied or substandard products on the shelf.

Summary

Ordinary micronutrient salts often fail to correct deficiency in Indian soils because as much as 85 to 90 per cent of soil applied zinc can be chemically fixed within weeks, particularly in alkaline and calcareous conditions. Chelated fertilizers overcome this by binding the metal ion within an organic ligand such as EDTA, DTPA or EDDHA, each suited to a different soil pH range, keeping the nutrient available for uptake over a longer period. Field trials confirm the benefit in practice: basal Zn-EDTA application raised rice grain yield by 37.5 per cent and straw yield by 43.1 per cent over the unfertilized control, and India's micronutrient fertilizer market, approaching one billion US dollars, reflects growing farmer adoption of these products. For best results, farmers should match the chelating agent to their soil pH, combine foliar spray for rapid correction with soil application for sustained effect, and verify that any product purchased meets Fertiliser Control Order specifications before use.

References

- Alsultana Fertilizer. 2026. Chelated micronutrients in citrus production, science based application strategies. Alsultana Fertilizer, technical guidance.
- Aries Agro. 2022. Best micronutrient fertilizers for plants in India. Aries Agro Limited, Mumbai.
- Das, D.K. and Karak, T. 2007. Relative performance of chelated zinc and zinc sulphate for lowland rice. Nutrient Cycling in Agroecosystems.
- Greenway Biotech. 2026. Chelated fertilizers, iron, zinc, manganese and copper EDTA. Greenway Biotech Inc, Madera, California.
- Mordor Intelligence. 2026. India micronutrient fertilizer market size and growth to 2030. Mordor Intelligence, Hyderabad.
- Research and Markets. 2025. India micronutrient fertilizer market, size and competitors. Research and Markets, Dublin.
- Resonance, Journal of Science Education. Chelates for micronutrient nutrition among crops. Indian Academy of Sciences, Bengaluru.
- Terafon. 2026. EDTA chelating agents for crop nutrition and soil efficiency. Terafon technical guide.

Climate Responsive Agronomic Strategies for Enhancing Farm Productivity



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Abstract

Climate variability, expressed through rising temperatures, erratic rainfall, more frequent drought, and extreme weather events, is progressively undermining crop productivity and farm stability across both rainfed and irrigated systems. This review synthesises peer reviewed evidence on agronomic strategies that help farms respond to and absorb these climatic shocks while maintaining or improving productivity. Conservation and zero tillage systems, deficit and scheduled irrigation, crop diversification and intercropping, drought tolerant and short duration varieties, agroforestry, and soil organic amendments such as biochar are examined as core components of climate responsive agronomy. Documented evidence indicates that no tillage systems can outyield conventional tillage by as much as forty three percent under water limited conditions, that combined water and soil conservation measures have raised sorghum yields several fold in dryland Africa, and that climate smart agricultural practices, taken together, have been associated with productivity gains near ten and a half percent and profitability gains near twenty nine percent across pooled global evidence. The review also considers the constraints that limit wider adoption of these practices, including cost, knowledge gaps, and weak extension and credit systems, and concludes with recommendations for policy and extension support to accelerate farmer level adoption of climate responsive agronomy.

Keywords: Climate Resilient Agriculture, Conservation Tillage, Water Use Efficiency, Crop Diversification, Climate Smart Agriculture, Farm Productivity, Agroforestry

1. Introduction

Agricultural production is fundamentally dependent on climatic conditions, and the intensifying variability associated with global climate change is now recognised as one of the most significant threats to farm productivity and food security worldwide. Rising average temperatures, shifting rainfall onset and duration, more frequent droughts, floods, and heatwaves are already reducing yields and destabilising production across many cropping systems, with smallholder farmers in tropical and subtropical regions among the most exposed and least able to absorb these shocks.

In response to these pressures, a substantial body of agronomic research has focused on developing and evaluating strategies that allow farms to maintain productivity under increasingly variable conditions. Rather than a single technology, climate responsive agronomy encompasses a set of complementary practices, spanning soil and tillage management, water use, crop and variety choice, and farm level diversification, that together improve the capacity of a farm to absorb climatic disturbance, recover from it, and continue producing food and income. These practices are frequently discussed under the closely related terms climate resilient agriculture and climate smart agriculture, both of which describe farming approaches explicitly designed to sustain productivity while adapting to, and where possible mitigating, climate change.

This review draws together recent peer reviewed literature on climate responsive agronomic strategies, summarises the documented evidence of their effect on productivity and resilience, and considers the practical and institutional barriers that continue to limit their adoption, with a view to informing researchers, extension specialists, and farm advisers seeking evidence based guidance for climate adaptation planning.

2. Understanding Climate Related Risks to Farm Productivity

Climate change affects farm productivity through several interacting pathways. Rising temperatures can shorten the grain filling period of many cereal crops, accelerate crop development, and increase evapotranspiration demand, while also raising the incidence of heat stress during sensitive reproductive stages. Altered rainfall

patterns, including delayed onset of the growing season, shorter effective rainy periods, and greater variability between and within seasons, disrupt planting decisions and increase the frequency of both drought and waterlogging within a single cropping cycle. These changes act not only directly on crop physiology but also indirectly, through soil moisture availability, soil temperature, relative humidity, and wind driven evaporative demand.

A recent global review of climate impacts on agricultural productivity concluded that these interacting stresses necessitate adjustments across multiple points in the farming system, including crop variety selection, sowing dates, planting density, and fertilisation timing, rather than reliance on any single adaptive measure. Farm level resilience, defined as the capacity of a farming system to recover, reorganise, and continue functioning following a climatic disturbance, has therefore become a central organising concept for agronomic research aimed at sustaining productivity under a changing climate.

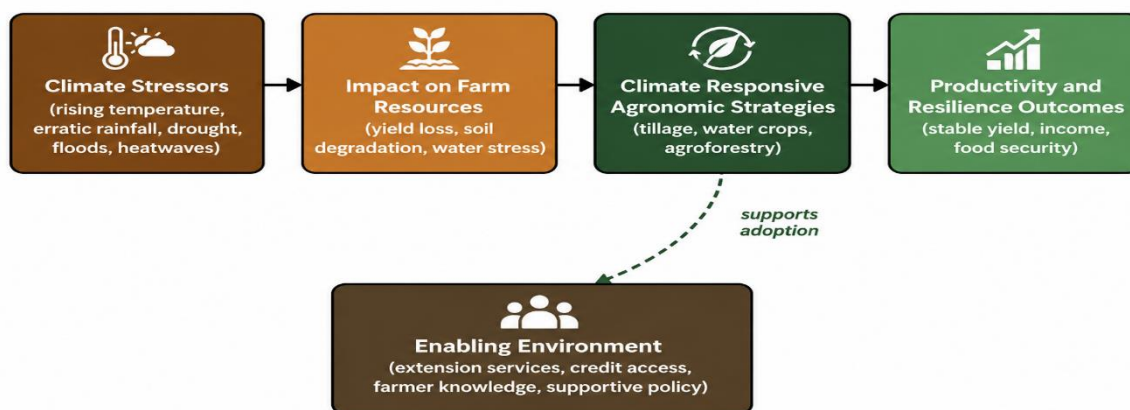


Figure 1. Conceptual framework linking climate stressors, agronomic response, and farm productivity outcomes, within a supportive enabling environment.

3. Agronomic Strategies for Climate Resilience

Table 1 summarises the principal agronomic strategies currently supported by peer reviewed evidence as effective components of climate responsive farming, along with their main mechanism of action and reported effect on productivity. These strategies are considered in more detail below.

Table 1. Principal Agronomic Strategies for Climate Responsive Farming

Agronomic Strategy	Principal Mechanism	Reported Effect on Productivity
Conservation or zero tillage	Reduced soil disturbance, residue retention, improved moisture conservation	Yield gains of 5 to 43 percent over conventional tillage, depending on comparison system
Deficit and scheduled irrigation	Matches water supply to crop growth stage, reduces non productive water loss	Maintains yield while reducing water input, improves water use efficiency
Crop diversification and intercropping	Spreads climatic risk across species, improves resource use complementarity	Greater combined productivity than sole cropping under variable rainfall
Drought tolerant and short duration varieties	Escapes terminal drought, matches crop cycle to shortened rainy season	Stabilised yield in low and erratic rainfall environments
Agroforestry and integrated crop livestock systems	Adds structural diversity, buffers microclimate, diversifies farm income	Improved farm resilience through modularity and reserve capacity
Soil organic amendments including biochar	Improves soil structure, water and nutrient retention, reduces bulk density	Reduced sandy soil bulk density and improved infiltration reported in field trials

3.1 Conservation Tillage and Soil Management

Conservation and zero tillage systems, in which soil disturbance is minimised and crop residues are retained on the surface, are among the most extensively documented agronomic strategies for improving climate resilience.

A systematic review synthesising more than one hundred fifty peer reviewed studies and over two hundred field observations found that zero tillage consistently improved soil structure, aggregate stability, organic matter content, and water use efficiency relative to conventional tillage, while also reducing erosion and greenhouse gas emissions associated with tillage operations. A recent fuzzy extent analysis comparing multiple tillage and irrigation combinations reported that no tillage produced yields five, thirty eight, and forty three percent higher than stubble mulching, deep tillage, and conventional tillage respectively, figures illustrated in Figure 2.

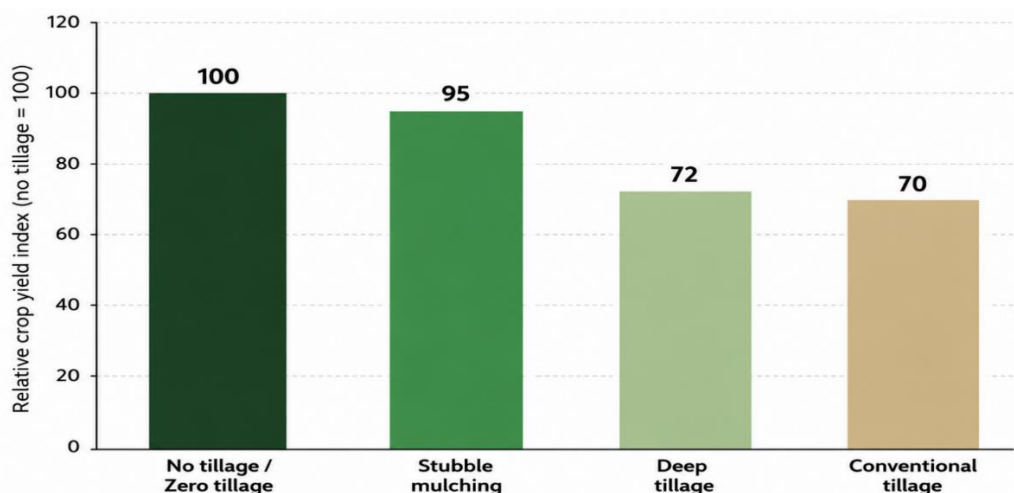


Figure 2. Relative crop yield under no tillage compared with stubble mulching, deep tillage, and conventional tillage, expressed as an index with no tillage set to one hundred.

In lower input systems, minimum tillage has similarly been shown to conserve soil moisture, reduce evaporative loss, and stabilise yield during mid season dry spells, with the productivity benefit of adoption reported to increase with the length of time a farm has practised the technique. A field study on onion cultivation under conservation tillage in a vulnerable agroecosystem reported harvest index values of eighty three, eighty five, and eighty six percent under minimum, traditional, and permanent tillage treatments respectively, alongside improved water productivity, underscoring that the benefits of reduced tillage extend across a range of crop types beyond staple cereals.

3.2 Water Management and Irrigation Scheduling

Efficient water management is central to climate responsive agronomy, particularly in regions facing increasing rainfall variability and groundwater scarcity. Deficit irrigation, in which water application is deliberately reduced relative to full crop water demand at growth stages less sensitive to moisture stress, has been shown to maintain comparable yield to full irrigation while substantially reducing total water input, particularly when combined with reduced tillage. A study evaluating no tillage combined with deficit irrigation in intercropped maize found that the combination optimised the relationship between yield and water use, maintaining yield stability while lowering water requirements, through improved canopy photosynthesis and more efficient carbon assimilation during grain filling.

Complementary evidence from conservation tillage combined with sprinkler irrigation in maize and field pea cropping systems indicates that pairing reduced tillage with more precise, scheduled irrigation delivery further improves water productivity relative to conventional tillage under flood irrigation, supporting the case for considering tillage and irrigation choices jointly rather than in isolation when designing climate responsive cropping systems.

3.3 Crop Diversification and Stress Tolerant Varieties

Diversifying the crops grown on a farm, whether through intercropping, rotation, or the inclusion of multiple enterprises, spreads climatic risk across species with differing sensitivities and resource requirements. Evidence reviewed in a recent farm resilience study found that intercropping a legume with a cereal produced greater combined productivity than either crop grown alone, illustrating the resource use complementarity that underlies

much of the resilience benefit associated with diversified cropping. At the variety level, the adoption of drought tolerant and short duration crop varieties allows the crop cycle to be matched more closely to a shortened or delayed rainy season, reducing exposure to terminal drought during the reproductive stage that is most damaging to final yield.

A systematic review focused on dry region food systems identified crop diversification, alongside soil water conservation, irrigation, and the cultivation of naturally resilient crops such as sorghum, cowpea, and millet, as key resilient agricultural technologies suitable for arid and semi arid environments, with cultivation of these species regarded as an important option for improving yield stability and food availability in drought prone areas.

3.4 Agroforestry and Integrated Farming Systems

Agroforestry and integrated crop livestock systems add structural and enterprise diversity to a farm, buffering local microclimate and providing multiple, partially independent sources of farm income and feed. A systematic review of farm resilience attributes found that studies combining livestock and cropping activities, for example through increased stocking density, feed production, or crop diversity to support feed quality, tended to increase and stabilise farm profitability more effectively than single enterprise systems, particularly among smallholder farms, which in the reviewed literature combined a greater number of resilience enhancing attributes than larger, non smallholder operations.

Soil organic amendments, including biochar derived from woody feedstock, represent a further agronomic tool with documented climate adaptation value. Field evidence indicates that biochar application can reduce bulk density in sandy soils, improve water and nutrient retention, and moderate soil pH, collectively improving the capacity of degraded or low fertility soils to support crop growth under increasingly erratic rainfall.

4. Evidence of Productivity and Profitability Gains from Climate Smart Agriculture

Beyond individual practices, a growing body of pooled evidence quantifies the aggregate productivity and profitability effect of climate smart agricultural adoption. A systematic literature review of SCOPUS indexed studies published between 2015 and 2024 found that climate smart agriculture practices, considered collectively, enhanced productivity by an average of ten and a half percent and profitability by an average of twenty nine and a half percent across the reviewed evidence base, though the same review noted that financial constraints and inadequate infrastructure continue to limit the scale of adoption in many farming contexts.

Complementary evidence from dryland Africa illustrates the scale of productivity gain achievable when water and soil conservation measures are combined with a well suited crop. Sorghum yield rose from approximately two hundred to eleven hundred forty kilograms per hectare in Zimbabwe, and from approximately two hundred fifty to five thousand six hundred seventy five kilograms per hectare in Kenya, following the introduction of combined water management and soil conservation practices in low rainfall areas, figures summarised alongside the pooled climate smart agriculture evidence in Figure 3.

Figure 3. Documented Productivity Gains from Climate Smart and Conservation Agronomic Practices

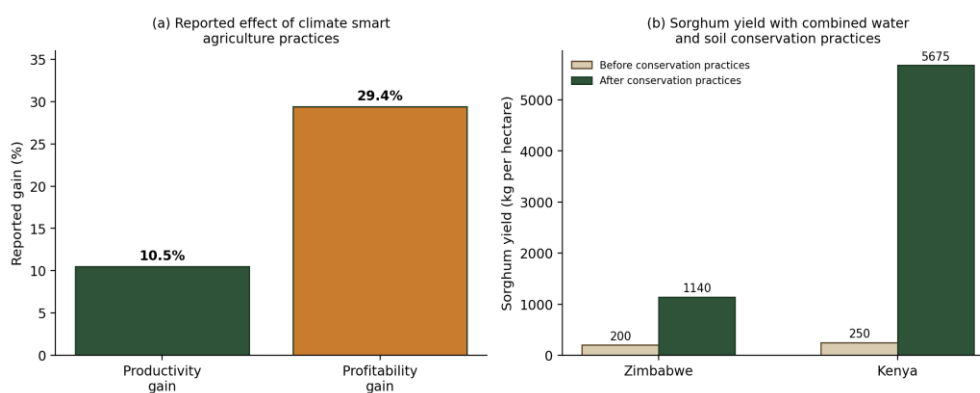


Figure 3. Documented productivity gains from climate smart and conservation agronomic practices, drawn from a pooled global systematic review and from dryland case evidence in Zimbabwe and Kenya.

5. Documented Outcomes Across Regions and Farming Systems

Table 2 draws together documented, quantitative outcomes from the studies discussed above, illustrating that climate responsive agronomic strategies have delivered measurable productivity gains across a range of regions, crops, and farming contexts, from smallholder dryland systems in sub Saharan Africa to irrigated vegetable and cereal systems in South Asia.

Table 2. Documented Productivity Outcomes from Selected Studies

Region	Practice Evaluated	Documented Outcome	Illustrative Source
Zimbabwe	Combined water and soil conservation with sorghum	Yield rose from about 200 to 1140 kilograms per hectare	Systematic review, dry region CRA practices
Kenya	Combined water and soil conservation with sorghum	Yield rose from about 250 to 5675 kilograms per hectare	Systematic review, dry region CRA practices
Global, multi country	Climate smart agriculture practices, pooled evidence	Productivity up by 10.5 percent, profitability up by 29.4 percent	SCOPUS systematic review 2015 to 2024
Bangladesh	Minimum tillage in onion cultivation	Improved water productivity index and harvest index across tillage levels	PMC, conservation tillage onion study
Multiple, semi arid	No tillage compared with stubble mulching and deep tillage	No tillage yield exceeded comparison systems by 5 to 43 percent	Scientific Reports, fuzzy extent analysis study

6. Barriers to Adoption

Despite the documented productivity and resilience benefits of climate responsive agronomy, adoption among farmers, particularly smallholders in resource constrained settings, remains uneven. Frequently cited constraints include the high initial cost of accessing weather information and climate resilient inputs, inadequate access to credit and financing for new equipment or practices, and limited availability of extension support to guide farmers through the transition from conventional to conservation based systems. A study of traditional adaptation practices identified climate induced drought and the high cost of accessing weather information as key constraints, alongside inadequate funding, echoing similar barriers reported in reviews of climate smart agriculture adoption more broadly.

Social and institutional factors also shape adoption patterns. A systematic review of interventions targeting women farmers found that unequal access to land, credit, and extension services can restrict the ability of an important share of the farming population to adopt climate smart practices, even where such practices are agronomically well suited to local conditions. Addressing these equity dimensions, alongside the technical and financial barriers, is therefore an important component of any strategy aimed at scaling climate responsive agronomy.

7. Policy and Extension Recommendations

The reviewed evidence points to several priorities for policy and extension programming. Continued investment in farmer facing extension and capacity building is essential, since the reviewed literature consistently highlights continuous learning, demonstration plots, and progress monitoring as important contributors to sustained adoption of new agronomic practices. Expanding access to credit and targeted financing for climate resilient infrastructure and inputs would help address the cost barriers identified across multiple studies, while investment in accessible, localised weather and climate information services would reduce a further commonly cited constraint to informed decision making.

Policy support should also recognise the value of combining practices rather than promoting single interventions in isolation. The evidence reviewed here indicates that tillage, irrigation, crop choice, and diversification strategies interact, and that their combined effect on productivity and resilience typically exceeds what any one practice can achieve alone. Finally, given the documented importance of indigenous knowledge alongside modern scientific practice, extension and research programming should be designed collaboratively with farming communities, integrating local experience with evidence based agronomic recommendations to support durable, locally appropriate adoption.

8. Conclusion

Climate responsive agronomic strategies, spanning conservation tillage, efficient water management, crop diversification, stress tolerant varieties, agroforestry, and soil health interventions, offer a well evidenced pathway toward sustaining and improving farm productivity under an increasingly variable climate. Peer reviewed evidence demonstrates that these strategies, whether evaluated individually or in combination, can deliver substantial and in some cases transformative gains in yield, water use efficiency, and farm profitability, particularly when adapted to local agroecological and socioeconomic conditions. Realising these benefits at scale will require sustained investment in extension, credit access, climate information services, and participatory research that combines scientific evidence with farmer knowledge, ensuring that climate responsive agronomy becomes accessible not only to well resourced commercial farms but also to the smallholder producers who remain most exposed to climatic risk.

References

- Agroecological Practices for Climate Resilient Agriculture. Academia.edu (2025). https://www.academia.edu/145638777/Agroecological_Practices_for_Climate_Resilient_Agriculture
- Review of climate resilient agriculture for ensuring food security: Sustainability opportunities and challenges of India. ScienceDirect (2024). <https://www.sciencedirect.com/science/article/pii/S2665972724002125>
- Farm resilience to climatic risk. A review. Agronomy for Sustainable Development, Springer Nature (2025). <https://link.springer.com/article/10.1007/s13593-024-00998-w>
- Climate Resilient Agriculture Practices for Enhancing Resilient Practices and Food Systems in Dry Regions. PMC (2025). <https://pmc.ncbi.nlm.nih.gov/articles/PMC12791155/>
- The multifaceted impact of climate change on agricultural productivity: a systematic literature review of SCOPUS indexed studies (2015 to 2024). Discover Sustainability, Springer Nature (2025). <https://link.springer.com/article/10.1007/s43621-025-01229-2>
- Interventions promoting resilience through climate smart agricultural practices for women farmers: A systematic review. PMC (2024). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11347864/>
- The optimization of crop response to climatic stress through modulation of plant stress response mechanisms. PMC (2025). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC12676087/>
- A Global Review of the Impacts of Climate Change and Variability on Agricultural Productivity and Farmers' Adaptation Strategies. PMC (2025). <https://pmc.ncbi.nlm.nih.gov/articles/PMC12076006/>
- Climate resilient agriculture strategies to address the challenges of agri food security and climate change. ScienceDirect (2026). <https://www.sciencedirect.com/science/article/abs/pii/S0378429026000468>
- Conservation tillage (CT) for climate smart sustainable intensification: Benchmarking CT to improve soil properties, water footprint and bulb yield productivity in onion cultivation. PMC (2024). <https://pmc.ncbi.nlm.nih.gov/articles/PMC11585807/>
- Optimizing water efficient agriculture: evaluating the sustainability of soil management and irrigation synergies using fuzzy extent analysis. Scientific Reports (2025). <https://www.nature.com/articles/s41598-025-15426-6>
- Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: A review. ScienceDirect (2022). <https://www.sciencedirect.com/science/article/pii/S2095633922000053>
- Conservation tillage and sprinkler irrigation for sustainable water management and enhanced crop yields in maize and field pea cropping system. Scientific Reports (2026). <https://www.nature.com/articles/s41598-026-39809-5>
- Minimum tillage as climate smart agriculture practice and its impact on food and nutrition security. PMC (2023). <https://pmc.ncbi.nlm.nih.gov/articles/PMC10745223/>

Integrating Functional Genomics into Contemporary Plant Breeding



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Abstract

Conventional plant breeding, based primarily on phenotypic selection across successive generations, has contributed substantially to global crop improvement but is often constrained by long breeding cycles, environmental influences on trait expression, limited heritability of complex traits, and the difficulty of accurately selecting superior genotypes for polygenic characteristics. Functional genomics, which investigates how genome sequence, gene expression, protein function, and regulatory networks collectively determine plant phenotype, has transformed modern crop improvement by providing precise molecular tools that accelerate genetic gain and enhance breeding efficiency. This review examines the integration of whole genome sequencing, transcriptomics, genome wide association studies (GWAS), marker assisted selection (MAS), genomic selection (GS), CRISPR Cas genome editing, and high throughput phenotyping (HTP) into contemporary plant breeding programmes. Recent studies demonstrate that genomic selection enables early identification of superior breeding lines before phenotypic evaluation, with prediction accuracies approaching 0.70 and relative efficiency gains of up to 2.6 fold over conventional selection in irrigated rice. Likewise, CRISPR Cas9 has successfully enhanced important agronomic and nutritional traits, including substantial increases in beta carotene content in rice and banana, elevated gamma aminobutyric acid content in tomato, and improved grain yield under drought conditions in maize. When integrated with speed breeding, genomics assisted breeding pipelines can reduce cultivar development time from more than a decade to as little as two to four years, greatly accelerating the delivery of improved varieties. Despite these advances, several challenges remain, including the phenotyping bottleneck, the high cost of genomic technologies, regulatory and public acceptance issues associated with genome editing, and the potential reduction of genetic diversity under intensive genomic selection. The review concludes that future progress in crop improvement will depend on integrating functional genomics with advanced phenotyping, artificial intelligence, bioinformatics, and data driven breeding strategies to bridge the persistent gap between genotype and phenotype and develop climate resilient, high yielding, and nutritionally superior crop varieties.

Keywords: CRISPR Cas9, Functional genomics, Genome wide association studies, Genomic selection, High throughput phenotyping.

1. Introduction

Plant breeding has always been the process of transforming hidden genetic variation into improved and desirable crop traits. For much of the twentieth century, this process relied almost entirely on phenotypic selection, in which large breeding populations were evaluated under field conditions and superior plants were selected as parents for the next generation. This conventional approach laid the foundation for remarkable advances in global agriculture, including the development of high yielding cultivars that drove the Green Revolution. However, it remains inherently slow and resource intensive because many economically important traits, such as grain yield, drought tolerance, disease resistance, and nutritional quality, are controlled by numerous genes with small individual effects, are strongly influenced by environmental conditions, and often cannot be accurately evaluated until later stages of plant development or across multiple growing seasons.

Functional genomics has transformed this paradigm by enabling breeders to investigate the molecular basis of complex traits rather than relying solely on observable plant characteristics. It explores how genome sequence, gene expression, protein function, and regulatory networks interact to determine phenotype, allowing genetic variation to be identified and utilized with much greater precision. Instead of inferring breeding value exclusively from field performance, functional genomics enables the direct identification of genes, quantitative trait loci,

molecular markers, and regulatory pathways associated with target traits. This molecular understanding provides breeders with powerful tools for improving selection accuracy, accelerating genetic gain, and shortening breeding cycles.

Over the past decade, rapid advances in next generation sequencing, whole genome sequencing, transcriptomics, genome wide association studies (GWAS), marker assisted selection (MAS), genomic selection (GS), high throughput phenotyping (HTP), and CRISPR Cas based genome editing have moved functional genomics from research laboratories into practical crop improvement programmes for rice, wheat, maize, soybean, chickpea, tomato, and many other economically important crops. The integration of these technologies has fundamentally changed plant breeding by enabling early selection of superior genotypes, precise identification of genes controlling complex traits, and targeted modification of desirable alleles. Furthermore, combining genomics assisted breeding with speed breeding has substantially reduced the time required to develop improved cultivars, allowing breeders to respond more rapidly to emerging challenges such as climate change, evolving pests and diseases, and increasing food demand.

Despite these remarkable advances, several scientific and practical challenges continue to limit the full realization of functional genomics in crop improvement. The accurate measurement of complex phenotypes remains a major bottleneck, while the high cost of advanced genomic technologies, the computational demands of large scale genomic datasets, regulatory uncertainties surrounding genome edited crops, and concerns about maintaining genetic diversity continue to influence their widespread adoption. Consequently, future progress in plant breeding will depend on the effective integration of functional genomics with advanced phenotyping, bioinformatics, artificial intelligence, and data driven breeding strategies.

This article reviews the major functional genomics approaches currently integrated into modern plant breeding programmes, evaluates their contributions to improving selection accuracy, accelerating genetic gain, and shortening breeding cycles, and discusses the key scientific, technical, and regulatory challenges that must be addressed to fully harness their potential for developing high yielding, climate resilient, and nutritionally enhanced crop varieties.

2. Core Functional Genomics Tools in Plant Breeding

The modern breeding pipeline can be understood as a sequence-to-cultivar cycle in which each stage of the process from raw genome sequence through to a validated, released variety — draws on a distinct functional genomics tool. Table 1 summarises the principal tools used at each stage.

Table 1. Functional genomics tools and their principal application in plant breeding

Functional Genomics Tool	Primary Breeding Application	Representative Output
Genome & transcriptome sequencing (NGS/GBS)	Discovery of genome-wide SNPs and reference/pan-genome assembly for diverse germplasm	SNP marker sets, pan-genome assemblies
GWAS and QTL mapping	Statistical association of genomic regions with quantitative agronomic traits	Trait-linked loci, candidate gene lists
Functional markers & TILLING	Direct, gene-based markers tightly linked to phenotype for marker-assisted selection	Gene-specific diagnostic markers
Genomic selection (GS) models	Genome-wide prediction of breeding value for complex, polygenic traits without full phenotyping	Genomic estimated breeding values (GEBVs)
CRISPR/Cas9 genome editing	Targeted knockout, knock-in, base and prime editing of genes underlying key traits	Edited lines with altered trait expression
High-throughput phenotyping (HTP)	Rapid, image- and sensor-based capture of large-scale phenotypic data to link with genotype	Digital trait measurements (i-traits)

2.1 Genome and Transcriptome Sequencing

The falling cost of next-generation sequencing (NGS) has made whole-genome and reduced-representation sequencing routine in breeding programmes. Genotyping-by-sequencing (GBS), which combines restriction-enzyme digestion of genomic DNA with barcoded, multiplexed sequencing, has become a particularly cost-effective route to genome-wide single nucleotide polymorphism (SNP) discovery, and has been described as an ultimate marker-assisted selection tool because it simultaneously discovers and genotypes markers across large populations. RNA sequencing complements this by revealing which genes are actively transcribed under stress or non-stress conditions, allowing candidate genes for traits such as drought or disease tolerance to be identified from differential expression patterns rather than from sequence variation alone.

2.2 Genome-Wide Association Studies and QTL Mapping

Genome-wide association studies (GWAS) statistically test the association between genome-wide markers and a trait of interest across a diverse population, exploiting linkage disequilibrium to localise the genomic regions underlying quantitative trait variation. GWAS has become a viable alternative to traditional quantitative trait locus (QTL) mapping because it can draw on much larger, more diverse germplasm collections, and larger and more diverse sample sets in turn increase the power to detect real trait associations.

2.3 Functional Markers and Marker-Assisted Selection

Functional markers are derived directly from the polymorphic, functional motif of a gene itself, rather than from an anonymous, linked genomic position. Because a functional marker retains a close association with the causal variant even after recombination, it can substantially increase the efficiency of marker-assisted selection compared with markers merely linked to a trait locus. Molecular marker-assisted selection more broadly has considerably shortened the time needed to bring new crop varieties to market by allowing breeders to select for a target gene directly from a DNA sample rather than waiting for the corresponding phenotype to appear in the field.

2.4 Genomic Selection

Genomic selection (GS) differs from marker-assisted selection in a fundamental way: rather than identifying and selecting individual loci significantly associated with a trait, GS uses all available genome-wide marker data simultaneously as predictors of performance, generating a genomic estimated breeding value (GEBV) for each candidate line. This whole-genome approach is particularly suited to complex traits controlled by many genes of small effect, for which conventional marker-assisted selection has historically been ineffective. Because GEBVs can be calculated from genotype data alone, without waiting for a candidate line's own phenotype to be measured, genomic selection allows breeders to select parents for the next breeding cycle at the seedling stage, compressing multiple cycles of genomic selection into the time conventionally required for a single cycle of phenotypic selection.

2.5 CRISPR/Cas9 Genome Editing

CRISPR/Cas9 genome editing allows breeders to move beyond selecting among existing genetic variation to introducing precise, targeted changes directly into a gene of interest. The technology has been applied across staple and horticultural crops to knock out susceptibility genes, correct deleterious point mutations, and fine-tune the expression of genes governing yield, nutritional content, and stress tolerance. Newer variants such as base editing and prime editing extend this precision further: prime editing, which combines Cas9 with a reverse transcriptase, has been reported to have the potential to correct the great majority of known small genetic variants without introducing a double-strand break, reducing the unintended structural changes associated with earlier editing approaches.

2.6 High-Throughput Phenotyping

Every genomic tool above depends, at some stage, on being calibrated against real phenotypic measurements, and the acquisition of large-scale, high-quality phenotypic data has become one of the principal bottlenecks constraining both breeding and functional genomics research. High-throughput phenotyping (HTP) addresses this bottleneck using imaging, spectral, and other sensor-based platforms — ground-based, greenhouse, and UAV-borne — to capture traits such as plant height, canopy temperature, and biomass automatically and at scale, generating the dense phenotypic datasets that genomic prediction models require.

3. Impacts on Selection Accuracy and Trait Improvement

The central promise of functional genomics in breeding is that genetic merit can be estimated more accurately, and earlier in a plant's life cycle, than phenotypic selection alone allows. The evidence for this promise is clearest in genomic selection. In an evaluation of irrigated rice breeding at the Bangladesh Rice Research Institute, genomic selection combined with trait-specific marker-assisted selection at early generations achieved prediction accuracies of 0.454 to 0.701 and a relative selection efficiency of 0.989 to 2.623 over conventional phenotypic selection across four consecutive breeding years. In cassava, genomic prediction accuracy varied considerably by scenario — high within a breeding population but markedly lower, averaging around 0.18, when predicting across populations — underscoring that the size, composition, and relatedness of the training population used to build a genomic prediction model is often as important as the choice of statistical model itself.

CRISPR/Cas9 genome editing has, in parallel, delivered large, trait-specific gains that would be difficult to achieve through recombination-based breeding alone within a comparable timeframe. Reported outcomes include a six-fold increase in beta-carotene content in edited rice and banana, a fifteen-fold increase in gamma-aminobutyric acid (GABA) content in tomato, and an approximately five percent yield improvement in drought-stressed maize. Figure 2 summarises these reported trait-level gains.

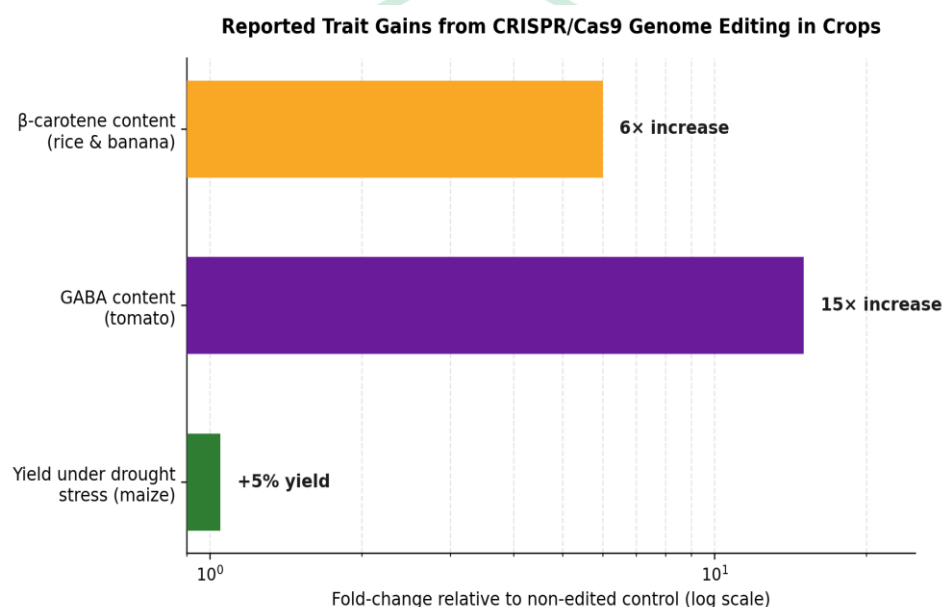


Figure 1. Reported trait-level gains from CRISPR/Cas9 genome editing across three crop traits, expressed as fold-change relative to non-edited controls. Compiled from published crop biotechnology reviews.

Beyond single-trait gains, the literature emphasises that genomic selection's largest benefit often comes not from any single cycle's accuracy but from its combination with generation-shortening technologies. Because genomic selection allows parents to be chosen from their genotype alone, breeding programmes have been able to run genomic-selection-based cycles inside the same span of time that a single cycle of conventional phenotypic selection would require, meaningfully raising the rate of genetic gain achieved per year rather than per generation.

4. The Functional Genomics Breeding Cycle

As with other genomics-enabled disciplines, the value of individual functional genomics tools is realised only when they are linked into a continuous pipeline. Figure 1 depicts this pipeline as six linked stages: sequencing and annotation (building reference genomes and transcriptomes for diverse germplasm), discovery (GWAS and QTL mapping to associate genomic regions with traits), validation (functional markers and TILLING to confirm gene-trait relationships), prediction (genomic selection models estimating breeding values genome-wide), selection and editing (marker-assisted selection and CRISPR/Cas9 editing to act on validated targets), and deployment and evaluation (multi-location field trials culminating in cultivar release, which in turn generates new phenotypic data to refine the next cycle).

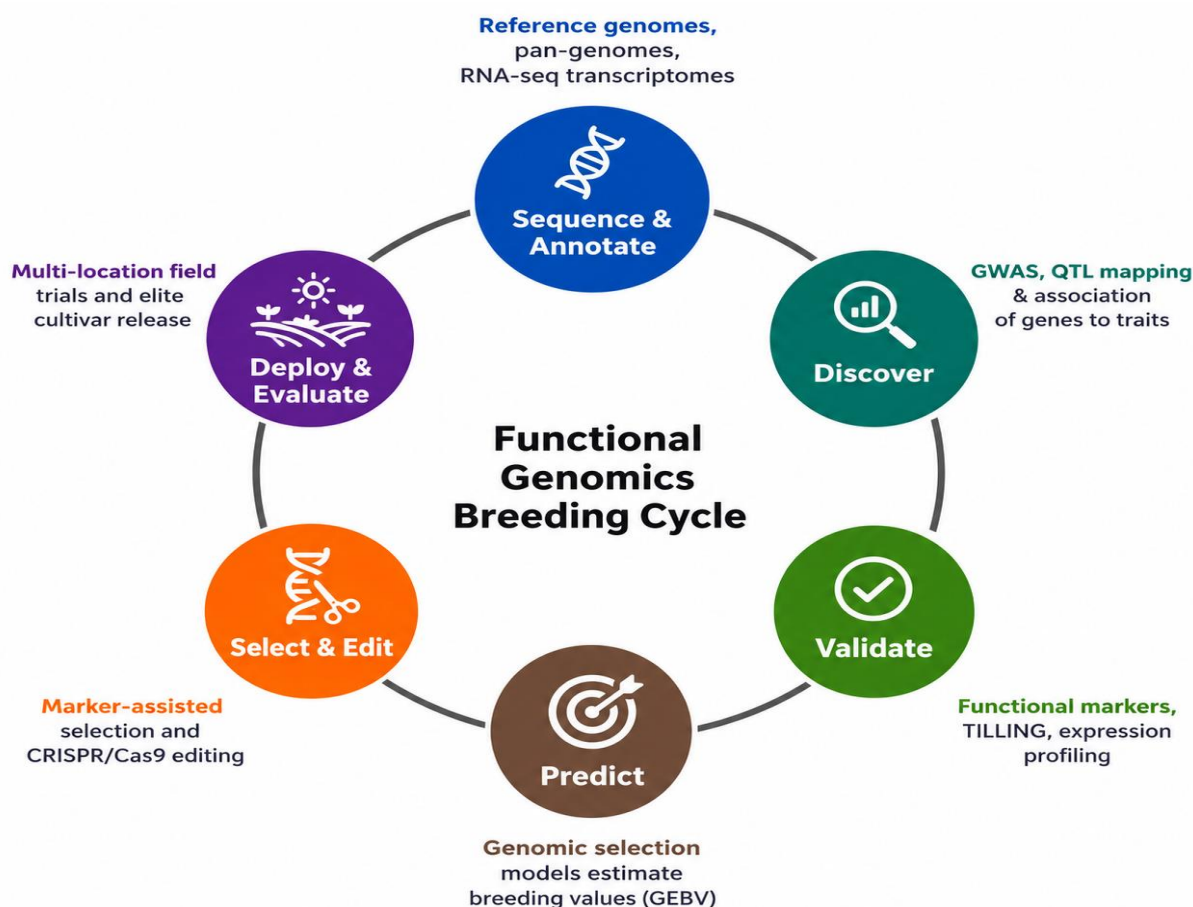


Figure 2. The functional genomics breeding cycle, linking genome sequencing through to cultivar deployment and season-on-season feedback.

This cyclical framing highlights why functional genomics tools are most powerful in combination rather than in isolation: a genomic selection model is only as good as the training population's phenotypic data behind it, and a CRISPR-edited line is only as valuable as the field evaluation that confirms its edited trait performs as intended under real growing conditions.

5. Representative Applications

5.1 Disease and Pest Resistance Breeding

Marker-assisted backcrossing, guided by functional markers tightly linked to resistance genes, has been used extensively to introgress single-gene resistance traits into elite cultivar backgrounds while minimising the linkage drag associated with traditional backcrossing. CRISPR/Cas9 has extended this further by allowing susceptibility genes — those a pathogen exploits to infect the plant — to be knocked out directly, or resistance genes to be introduced or fine-tuned, offering an additional route to durable resistance in crops such as rice, wheat, and tomato.

5.2 Abiotic Stress Tolerance

Functional genomics has substantially improved the basic understanding of drought, heat, and salinity tolerance mechanisms, which in turn has fed directly into genomics-assisted breeding pipelines seeking to improve stress resilience without sacrificing yield potential under favourable conditions.

5.3 Nutritional Quality and Biofortification

Genome editing has been applied to modify metabolic pathways governing nutritionally important compounds, with documented increases in provitamin A precursors and other beneficial metabolites in staple and horticultural crops, offering a route to biofortified varieties that does not depend on introducing foreign DNA.

5.4 Genomic Selection for Complex Yield and Quality Traits

Because yield and end-use quality traits are typically governed by many genes of small effect and are costly or slow to phenotype, they are the traits for which genomic selection offers the clearest advantage over both phenotypic selection and single-locus marker-assisted selection, particularly when integrated with multi-environment trial data to capture genotype-by-environment interaction.

6. Breeding-Cycle Acceleration and Remaining Challenges

Conventional breeding, for most crop plants, takes more than a decade from the initial cross to the release of a new cultivar, in large part because achieving a stable, homozygous line typically requires four to six successive generations, on top of multiple years of replicated, multi-location field testing. Because most crops complete only one to two generations per year under normal field or glasshouse conditions, this generation requirement is itself the principal bottleneck. Speed breeding techniques — which manipulate photoperiod, light quality, and temperature in controlled environments to accelerate flowering and seed set — have been shown to achieve three to nine generations per year, and when combined with genomic selection for early, genotype-based parent selection, can compress the cultivar development timeline dramatically: in pigeonpea, an optimised speed-breeding and genotyping protocol reduced a conventional seven-year breeding cycle to two to four years. Figure 3 summarises these reported gains in generation turnover and overall cultivar development time.

Acceleration of the Breeding Cycle through Genomics-Assisted Speed Breeding

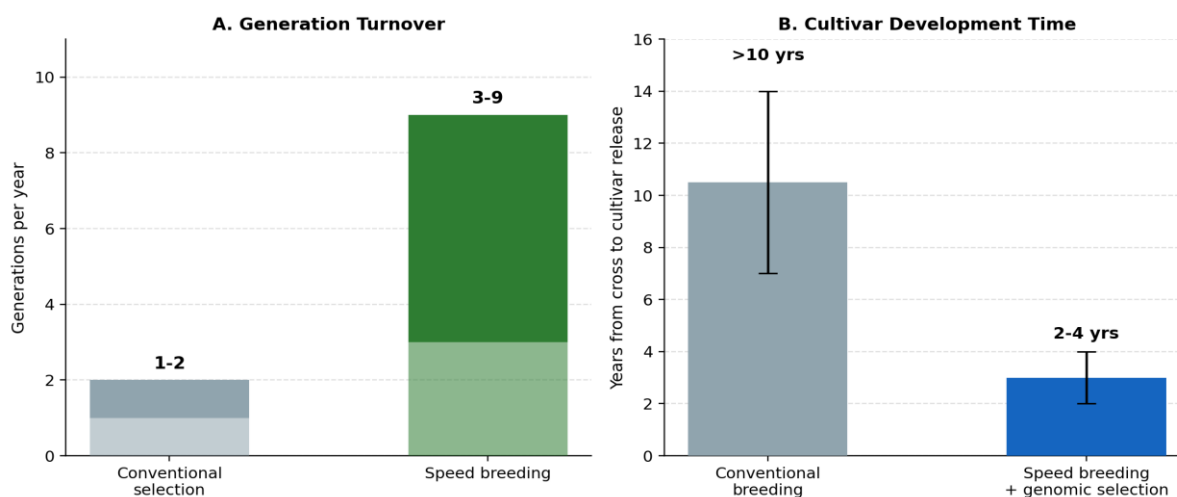


Figure 3. Acceleration of generation turnover (panel A) and overall cultivar development time (panel B) achieved by combining speed breeding with genomic selection, relative to conventional breeding.

Compiled from published speed-breeding and genomic selection studies.

Despite these gains, three challenges recur across the literature. The first is the phenotyping bottleneck: acquiring accurate, large-scale phenotypic data remains a major constraint on both breeding and functional genomics research, since the genomic tools described above are only as informative as the phenotypic data used to train and validate them. The second is a decline in genomic prediction accuracy over successive breeding cycles and across populations, driven by a shrinking effective population size and by training populations that are not regularly updated to remain representative of the breeding population under active selection — a dynamic that also accelerates the loss of genetic diversity under intensive genomic selection. The third is practical and regulatory: most CRISPR-edited crops remain confined to laboratory or controlled-environment trials rather than commercial farms, and access to genome-editing biotechnology and the associated infrastructure remains limited in many low-resource regions, constraining who benefits from these advances.

7. Conclusion

Functional genomics has reshaped plant breeding from a discipline built primarily on observing phenotypes to one that can, to a substantial and growing degree, read genetic merit directly from DNA sequence and gene expression. The evidence reviewed here shows measurable gains in selection accuracy through genomic selection,

precise trait-level improvements through CRISPR/Cas9 editing, and dramatic reductions in cultivar development time when these tools are combined with speed breeding. At the same time, the persistence of the phenotyping bottleneck, the decline of prediction accuracy across generations and populations, and uneven access to genome-editing infrastructure mean that the full productivity gains documented in research settings have not yet been captured uniformly across global breeding programmes. Bridging that remaining gap will depend on sustained investment in high-throughput phenotyping infrastructure and training population design, as much as on further advances in sequencing or editing technology themselves.

References

- Salgotra, R. K., & Stewart, C. N. (2020). Functional markers for precision plant breeding. *International Journal of Molecular Sciences*, 21(13), 4792. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7370099/>
- Genomics-assisted breeding: A powerful breeding approach for improving plant growth and stress resilience. (2024). *Agronomy*, 14(6), 1128. <https://www.mdpi.com/2073-4395/14/6/1128>
- He, J., Zhao, X., Laroche, A., Lu, Z.-X., Liu, H., & Li, Z. (2014). Genotyping-by-sequencing (GBS), an ultimate marker-assisted selection (MAS) tool to accelerate plant breeding. *Frontiers in Plant Science*, 5, 484. <https://doi.org/10.3389/fpls.2014.00484>
- Jannink, J.-L., Lorenz, A. J., & Iwata, H. (2010). Genomic selection in plant breeding: From theory to practice. *Briefings in Functional Genomics*, 9(2), 166–177. <https://doi.org/10.1093/bfgp/elq001>
- Advances in genomic tools for plant breeding: Harnessing DNA molecular markers, genomic selection, and genome editing. (2024). *Biological Research*, 57. <https://link.springer.com/article/10.1186/s40659-024-00562-6>
- Functional genomics for plant breeding. (2021). *International Journal of Molecular Sciences*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC8584446/>
- Recent advancements in molecular marker-assisted selection and applications in plant breeding programmes. (2021). *Genes*. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8397809/>
- Xu, Y., Yang, W., Qiu, J., et al. (2024). Metabolic marker-assisted genomic prediction improves hybrid breeding. *Plant Communications*. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11956108/>
- CRISPR/Cas9: A sustainable technology to enhance climate resilience in major staple crops. (2025). *Frontiers in Genome Editing*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC11958969/>
- CRISPR-Cas9 application in crop biotechnology: A decade of research (2014–2024) toward food security in developing countries. (2025). *National High School Journal of Science (NHSJS)*. <https://nhsjs.com/2025/crispr-cas9-application-in-crop-biotechnology-a-decade-of-research-2014-to-2024-toward-food-security-in-developing-countries/>
- Recent advances in CRISPR/Cas9 technology for engineering disease resistance in plants. (2025). *Acta Biochimica Polonica*. <https://www.journalssystem.com/agb/Recent-Advances-in-CRISPR-Cas9-Technology-for-Engineering-Disease-Resistance-in-Plants,201389,0,2.html>
- An insight into the journey of CRISPR-Cas9 and its application in crop improvement. (2025). *Discover Plants*. <https://link.springer.com/article/10.1007/s44372-025-00343-9>
- Confronting the phenomics scale gap in field crop breeding. (2026). *Trends in Plant Science*. [https://www.cell.com/trends/plant-science/abstract/S1360-1385\(26\)00213-X](https://www.cell.com/trends/plant-science/abstract/S1360-1385(26)00213-X)
- Wanga, M. A., et al. (2021). Opportunities and challenges of speed breeding: A review. *Plant Breeding*. <https://onlinelibrary.wiley.com/doi/10.1111/pbr.12909>
- Watson, A., et al. (2022). Breeding more crops in less time: A perspective on speed breeding. *Journal of Experimental Botany*. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8869642/>

Microalgae for Environmental Bioremediation: A Sustainable Approach to Heavy Metal, Nutrient and Organic Pollutant Removal



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Abstract

Conventional physicochemical methods for treating polluted water, including chemical precipitation, ion exchange and membrane filtration, remain effective but carry high energy costs, generate secondary waste and struggle to keep pace with the growing diversity of pollutants entering wastewater streams. Microalgae offer a biological alternative that addresses three major pollutant classes simultaneously: heavy metals, through biosorption and bioaccumulation; excess nitrogen and phosphorus, through direct nutrient assimilation into biomass; and organic pollutants such as dyes and pharmaceutical residues, through enzymatic biodegradation. Documented removal efficiencies are substantial across all three categories, with individual species removing more than 95 per cent of certain heavy metals, up to 95 per cent of nitrogen and 93 per cent of phosphorus under optimized photobioreactor conditions, and 60 to 98 per cent of dyes and pesticides in textile effluent studies. Beyond pollutant removal, the harvested microalgal biomass itself carries recoverable value as feedstock for biofuel, biofertilizer and animal feed, offering a circular alternative to conventional treatment sludge that must otherwise be disposed of as waste. This paper reviews the mechanisms by which microalgae remediate heavy metals, nutrients and organic pollutants, summarizes documented removal efficiencies across microalgal species and system types, and discusses the practical factors and current limitations that determine whether this technology performs at laboratory scale or translates successfully to full scale wastewater treatment.

Keywords: Biosorption, Heavy metal removal, Nutrient removal, Phycoremediation, Wastewater treatment

1. Introduction

Industrial, agricultural and domestic activity discharges an increasingly complex mixture of pollutants into water bodies, ranging from heavy metals and excess nutrients to synthetic dyes, pesticides and pharmaceutical residues. Conventional wastewater treatment, built primarily around physical settling and chemical or biological oxidation of organic matter, was not designed with this full pollutant mixture in mind, and secondary treated effluent frequently still carries substantial nitrogen, phosphorus, heavy metals and refractory organic compounds into receiving water bodies, contributing to eutrophication and long-term ecological harm.

Microalgae have emerged as a biological treatment option capable of addressing several of these pollutant classes within a single cultivation system, an approach commonly termed phycoremediation. Because microalgae are photosynthetic, they can be cultivated using little more than sunlight, carbon dioxide and the nutrients already present in the wastewater itself, converting a treatment cost into a biomass production opportunity. This paper reviews the mechanisms through which microalgae remove pollutants, the documented removal efficiencies for heavy metals, nutrients and organic pollutants, the practical factors that determine treatment performance, and the current limitations that stand between promising laboratory results and reliable full-scale deployment.

2. Mechanisms of Microalgal Bioremediation

Microalgae remove pollutants through three broad, sometimes overlapping mechanisms (Figure 1). Biosorption is a rapid, largely passive process in which metal ions bind to functional groups, particularly carboxyl and amino groups, present on the algal cell wall, a mechanism that dominates heavy metal removal in the first hours of contact and does not require the cell to be metabolically active. Bioaccumulation follows a slower, energy dependent path in which the organism actively transports metal ions or other compounds across the cell membrane and sequesters them within intracellular compartments, a process that continues over the growth cycle of the culture. Biodegradation, most relevant to organic pollutants such as dyes, pesticides and pharmaceutical residues, involves the enzymatic breakdown of the pollutant molecule into simpler, generally less toxic compounds, sometimes as a direct nutrient source for the alga and sometimes as a detoxification response. In practice, a single

treatment system typically draws on more than one of these mechanisms concurrently, and their relative contribution shifts with pollutant type, concentration and exposure duration.

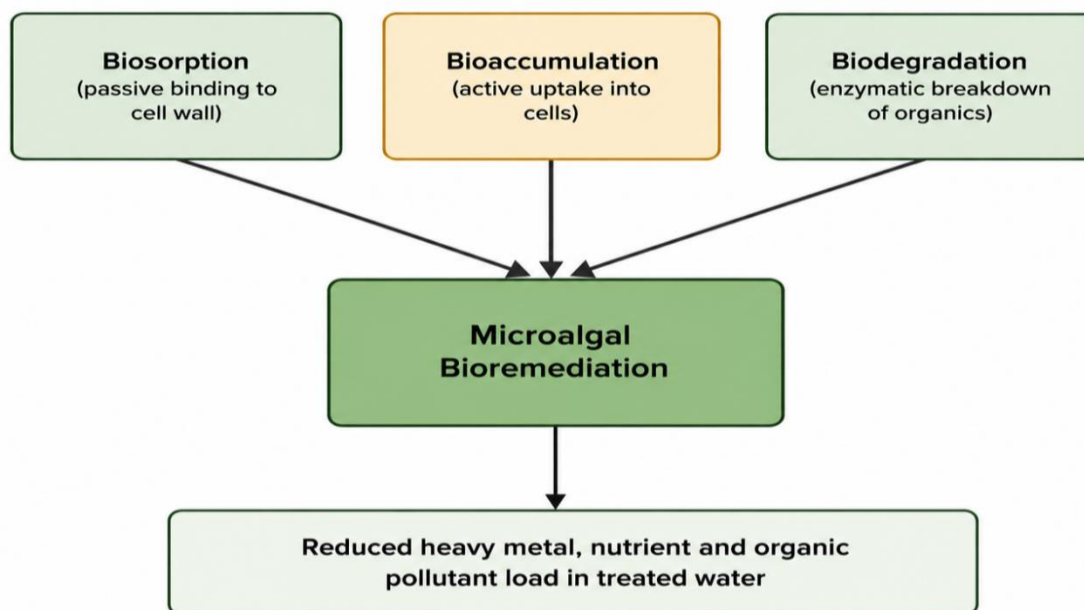


Fig. 1. Mechanisms of microalgal bioremediation

3. Heavy Metal Removal by Microalgae

Multiple microalgal genera have demonstrated strong, well documented heavy metal removal capacity (Table 1, Figure 2). *Scenedesmus obliquus* has been shown to remove more than 95 per cent of cadmium at low initial concentrations, with removal efficiency declining to about 70 per cent as concentration rises, and separately to achieve around 95 per cent removal of copper, reinforcing its standing as one of the more metal tolerant and metal efficient genera studied. *Chlorella vulgaris* and *Chlamydomonas reinhardtii* have both demonstrated removal efficiencies above 95 per cent for thallium, a less commonly studied but highly toxic metal, at concentrations of 500 milligrams per litre. Co-cultivation has also shown promise: *Chlorella prenioidisa* grown together with *Scenedesmus obliquus* achieved copper and zinc removal exceeding 70 per cent after 192 hours of exposure. Not every species performs as strongly across all metals, however; *Scenedesmus incrassatulus* removed a comparatively wide range of 25 to 78 per cent across chromium, cadmium and copper, illustrating that removal efficiency depends heavily on the specific metal, species and exposure conditions involved rather than following a single universal figure.

Table 1. Heavy metal removal efficiency of selected microalgae species

Species	Metal(s)	Removal efficiency
<i>Scenedesmus obliquus</i>	Cadmium	Greater than 95% at low concentration, about 70% at higher concentration
<i>Scenedesmus obliquus</i>	Copper	About 95%
<i>Chlorella vulgaris</i>	Thallium	96% at 500 mg per litre
<i>Chlamydomonas reinhardtii</i>	Thallium	95% at 500 mg per litre
<i>Chlorella prenioidisa</i> and <i>Scenedesmus obliquus</i> (co-culture)	Copper and zinc	Greater than 70% after 192 hours
<i>Scenedesmus incrassatulus</i>	Chromium, cadmium and copper	25 to 78%, depending on the metal

Source: Compiled from *Microorganisms*, 2025; *Water (MDPI)*, 2024; and *Letters in Applied Microbiology*, 2022.

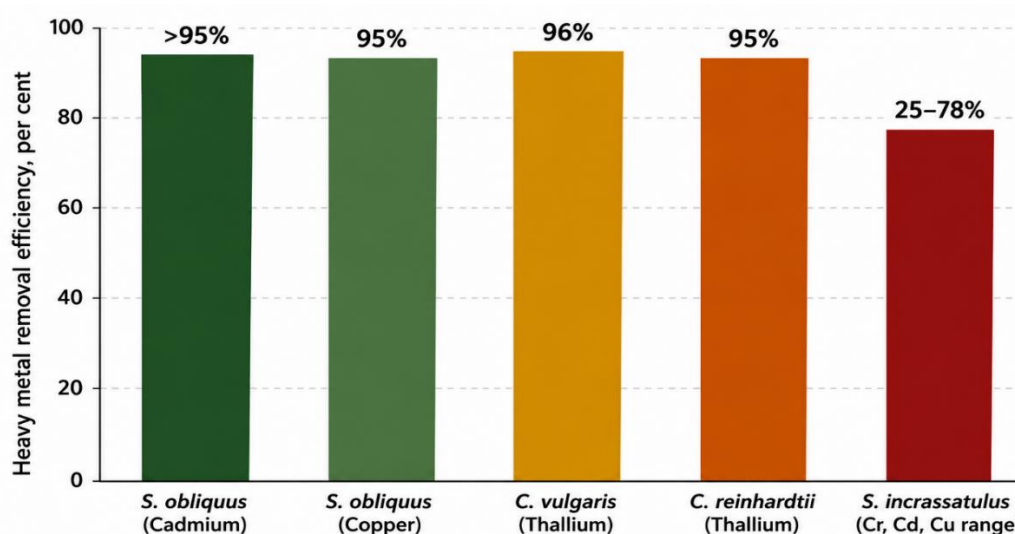


Fig. 2. Heavy metal removal efficiency of selected microalgae species

4. Nutrient Removal: Nitrogen and Phosphorus

Nutrient assimilation is arguably the most consistently effective function of microalgae in wastewater treatment, since nitrogen and phosphorus are essential growth requirements that the organism draws from the surrounding medium as a matter of course rather than as a specialized detoxification response (Table 2, Figure 3). Comparative trials with *Chlorella vulgaris*, *Scenedesmus obliquus* and *Nannochloropsis* sp. cultivated in closed photobioreactors achieved removal efficiencies of up to 95 per cent for nitrogen and 93 per cent for phosphorus, consistently outperforming open pond systems operated under otherwise similar conditions, though open ponds remain attractive for their substantially lower operating cost. In wastewater with a more complex pollutant load, a microalgae bacteria consortium treating pig farming effluent removed close to 87 per cent of total nitrogen and approximately 70 per cent of orthophosphate alongside 77 per cent of chemical oxygen demand, demonstrating that nutrient removal performance holds up reasonably well even in nutrient rich, organically loaded effluent rather than only in controlled synthetic media. Under optimized conditions specifically tuned for municipal wastewater, combined nitrogen and phosphorus removal efficiencies of 96 to nearly 100 per cent have been reported, alongside meaningful simultaneous carbon dioxide fixation, underscoring the technology's dual water treatment and carbon capture potential.

Table 2. Nutrient and organic pollutant removal across microalgae-based systems

System	Pollutant	Removal efficiency
Closed photobioreactor, <i>Chlorella vulgaris</i>	Nitrogen	Up to 95%
Closed photobioreactor, <i>Chlorella vulgaris</i>	Phosphorus	Up to 93%
Microalgae-bacteria consortium, pig farm effluent	Total nitrogen	About 87%
Optimized municipal wastewater cultivation	Nitrogen and phosphorus combined	96 to 99.6%
<i>Chlorella vulgaris</i> , textile mono-azo dye effluent	Dye colour	63 to 69% over 10 days
General range across textile wastewater studies	Dyes and pesticides	60 to 98%

Source: Compiled from Water, Air, & Soil Pollution, 2026; PMC, 2024; Water (MDPI), 2025; and Frontiers in Analytical Science, 2024.

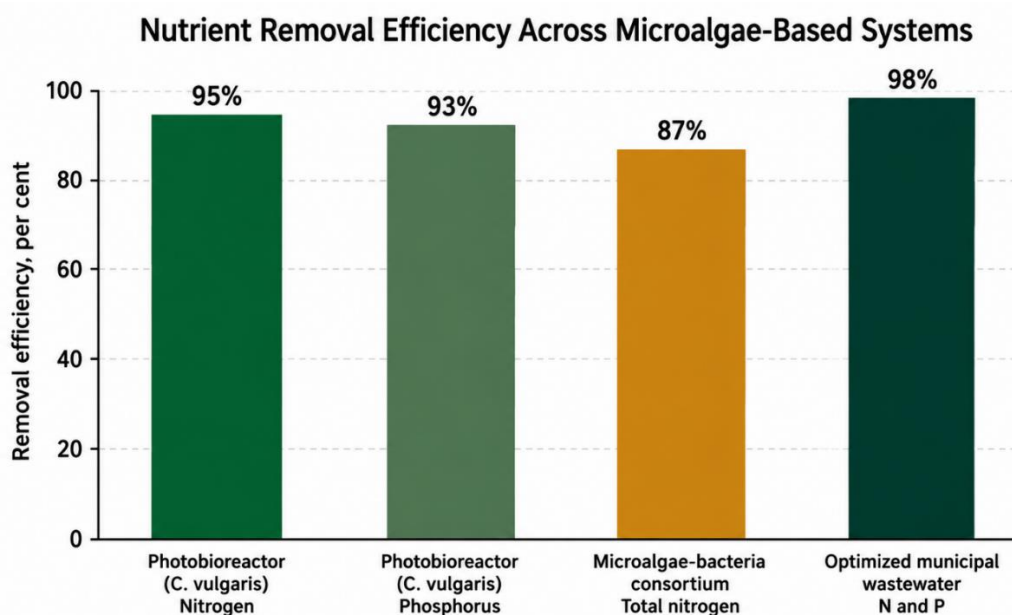


Fig. 3. Nutrient removal efficiency across microalgae-based treatment systems

5. Organic Pollutant Removal

Beyond metals and nutrients, microalgae have shown meaningful capacity to remove or degrade organic pollutants, including synthetic dyes, pesticide residues and pharmaceutical compounds, that conventional secondary treatment frequently allows to pass through largely intact. *Chlorella vulgaris* cultivated in textile wastewater containing the mono-azo dye Supranol Red 3BW removed 63 to 69 per cent of colour over a ten day culture period, converting the dye in part to aniline derivatives through enzymatic action. Across a broader set of textile wastewater studies, microalgae have been documented to reduce dye and pesticide concentrations by 60 to 98 per cent, alongside emerging contaminant removal of 40 to 95 per cent depending on the specific compound and treatment configuration. Pharmaceutical compound removal is comparatively more variable, ranging from about 10 to 100 per cent depending on the specific compound, its chemical stability and the treatment method applied, reflecting the wide diversity of pharmaceutical chemistries now found in wastewater rather than any inherent limitation unique to microalgal treatment.

6. Factors Influencing Removal Efficiency

Treatment performance is not fixed to a species or pollutant alone; it responds strongly to system design and operating conditions. Closed photobioreactors consistently outperform open pond systems for both nutrient and heavy metal removal, since controlled light, temperature and mixing sustain higher, more consistent biomass density, though this performance advantage comes at meaningfully higher capital and operating cost, a trade-off that shapes which system suits a given treatment context. Co-cultivating microalgae with select bacteria has repeatedly improved removal outcomes beyond what either organism achieves alone, since bacterial metabolism of organic matter can complement algal nutrient and metal uptake within the same system. pH, temperature, light intensity and initial pollutant concentration all influence both the rate and the ceiling of removal efficiency, which is why reported removal percentages for the same species can vary considerably across different studies; a removal efficiency measured at a low pollutant concentration in a controlled laboratory culture should not automatically be assumed to hold at the higher, more variable concentrations typical of real industrial effluent.

7. Integration with Resource Recovery

A distinguishing advantage of microalgal bioremediation over many conventional treatment methods is that the biomass generated during treatment is not simply waste requiring further disposal but a recoverable resource in its own right (Figure 4). Harvested microalgal biomass has established value as feedstock for biodiesel production, given its lipid content and the well developed transesterification pathway from algal oil to biodiesel, as well as for biofertilizer, biochar and animal feed applications, depending on the pollutant load the biomass has

accumulated and the regulatory constraints that load imposes on downstream use. This combination of pollutant removal and resource recovery is what underlies the description of microalgal treatment as a dual role technology, simultaneously cleaning wastewater and producing a marketable product, a combination that materially improves the economics of adoption relative to treatment methods that offer pollutant removal alone.

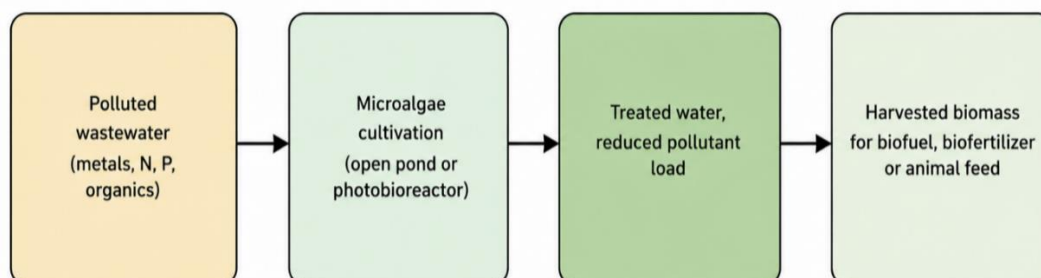


Fig. 4. Integrated microalgal bioremediation and resource recovery pathway

8. Practical Considerations and Limitations

Despite strong laboratory and pilot scale results, several practical constraints limit the current reach of microalgal bioremediation. Harvesting microalgal biomass from dilute culture remains energy and cost intensive relative to the value of the biomass recovered, and this harvesting step is frequently identified as the single largest barrier to economic viability at full scale. Removal efficiency measured under controlled, single pollutant laboratory conditions does not always transfer directly to real effluent, which typically carries a variable, multi pollutant mixture alongside fluctuating temperature, pH and flow rate. Where biomass has accumulated heavy metals or persistent organic pollutants during treatment, its suitability for downstream uses such as animal feed becomes correspondingly restricted, and disposal or further processing of contaminated biomass must be planned for rather than assumed away. None of these constraints undermine the underlying technology, but they do mean that translating a promising laboratory removal percentage into a reliable, economically sound full scale treatment system requires site specific engineering and testing rather than a simple scale up of laboratory conditions.

9. Conclusion

Microalgae offer a biologically grounded, resource generating alternative to conventional physicochemical treatment for a genuinely broad range of pollutants, spanning heavy metals, excess nutrients and organic contaminants within a single cultivation system. Documented removal efficiencies, frequently exceeding 90 per cent for specific metal and nutrient combinations and reaching 60 to 98 per cent for dyes and pesticides, demonstrate that the underlying biology is well established and repeatedly reproducible across species and studies. What remains is the engineering and economic work of harvesting, scale up and multi pollutant validation needed to move this technology from a well proven laboratory and pilot scale approach into routine, cost competitive practice at the scale that industrial and municipal wastewater treatment actually demands.

References

- Abdel-Raouf, N., Al-Homaidan, A.A. and Ibraheem, I.B.M. 2012. Microalgae and wastewater treatment. Saudi Journal of Biological Sciences, 19(3), 257-275.
- Aksu, Z. and Tezer, S. 2005. Biosorption of reactive dyes on the green alga *Chlorella vulgaris*. Process Biochemistry, 40(5), 1347-1361.
- Chisti, Y. 2007. Biodiesel from microalgae. Biotechnology Advances, 25(3), 294-306.
- Fazal, T., Mushtaq, A., Rehman, F., Ullah Khan, A., Rashid, N., Farooq, W., Rehman, M.S.U. and Xu, J. 2018. Bioremediation of textile wastewater and successive biodiesel production using microalgae. Renewable and Sustainable Energy Reviews, 82(3), 3107-3126.
- Frontiers in Analytical Science. 2024. Application of microalgae in wastewater treatment with special reference to emerging contaminants, a step towards sustainability.
- Goswami, R.K. et al. 2022. Bioremediation of heavy metals from wastewater, a current perspective on microalgae-based future. Letters in Applied Microbiology.

Matamoras, V., Gutierrez, R., Ferrer, I., Garcia, J. and Bayona, J.M. 2015. Capability of microalgae-based wastewater treatment systems to remove emerging organic contaminants, a pilot-scale study. *Journal of Hazardous Materials*, 288, 34-42.

Microorganisms (MDPI). 2025. The strategies microalgae adopt to counteract the toxic effect of heavy metals. *Microorganisms*, 13(5), 989.

PMC. 2024. Cadmium-induced physiological responses, biosorption and bioaccumulation in *Scenedesmus obliquus*.

PMC. 2024. Removal of nitrogen, phosphorus, organic matter, and heavy metals from pig-farming wastewater using a microalgae-bacteria consortium.

Rawat, I., Kumar, R.R., Mutanda, T. and Bux, F. 2011. Dual role of microalgae, phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. *Applied Energy*, 88(10), 3411-3424.

Water (MDPI). 2024. Microalgae-mediated biosorption for effective heavy metals removal from wastewater, a review. *Water*, 16(5), 718.

Water (MDPI). 2025. Efficiency of microalgae employment in nutrient removal (nitrogen and phosphorous) from municipal wastewater. *Water*, 17(2), 260.

Water, Air, & Soil Pollution (Springer). 2026. Comparative evaluation of microalgae-based wastewater treatment using closed photobioreactors and open pond systems for nutrient and heavy metal removal and resource recovery.



Advances in Precision Livestock Farming: Smart Technologies for Animal Health Monitoring



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Abstract

Precision Livestock Farming (PLF) is emerging as a transformative paradigm in animal husbandry, using continuous, automated, and real-time monitoring to manage the health, welfare, production, and reproduction of individual animals. Building on the concepts of precision agriculture, PLF integrates wearable and fixed sensors, computer vision, acoustic monitoring, the Internet of Things (IoT), and artificial intelligence (AI) to convert raw biological and behavioural signals into actionable health information. This article reviews the principal smart technologies used for animal health monitoring, including accelerometer-based wearables, infrared thermography, in-line milk analysers, acoustic sensors, and machine-vision systems, and examines how they are applied to detect conditions such as mastitis, lameness, foot-and-mouth disease, lumpy skin disease, ketosis, and reproductive disorders. Evidence from recent scientometric and systematic reviews indicates that inertial sensors and image-based systems dominate current research, with machine learning increasingly replacing simple threshold-based classification. The article further discusses the benefits of PLF for early disease detection, reduced antimicrobial use, and improved productivity, alongside persistent challenges of cost, connectivity, data standardisation, and farmer training, particularly for smallholder systems typical of Indian livestock farming. The review concludes with recommendations for wider, more affordable adoption of PLF technologies within national livestock development programmes.

Keywords: Precision Livestock Farming, Animal Health Monitoring, Wearable Sensors, Internet of Things, Artificial Intelligence, Smart Dairy Technology, Disease Detection

1. Introduction

Livestock production underpins the food security and rural economy of much of the developing world, and India in particular holds the largest livestock population globally, supporting the livelihoods of millions of smallholder farmers. Traditional animal health management has relied heavily on visual inspection, periodic veterinary visits, and the experience of the herdsman, an approach that is increasingly difficult to sustain as herd sizes grow, labour becomes scarcer, and diseases spread faster under intensified production systems. Sub-clinical conditions such as early-stage mastitis, lameness, or metabolic disorders frequently go unnoticed until they cause significant production losses, since early behavioural and physiological changes are subtle and easily missed by the human eye.

Precision Livestock Farming (PLF) offers a solution to this challenge. PLF has been defined as the management of individual animals through continuous, automated, real-time monitoring of health, welfare, production and reproduction, and of the environmental impact of livestock systems. Rather than managing the herd as a single unit, PLF enables management at the level of the individual animal, using sensors and data-driven algorithms that function as a continuous digital extension of the farmer's own eyes, ears, and experience. The concept was first articulated in the early 2000s and has since expanded rapidly with the falling cost of sensors, wireless connectivity, cloud computing, and machine learning.

The health monitoring dimension of PLF is of particular importance because early detection of disease not only reduces production and economic losses but also has direct implications for animal welfare, judicious use of antimicrobials, and the containment of transboundary diseases such as foot-and-mouth disease and lumpy skin

disease, both of which remain of major concern to Indian livestock health authorities. This article reviews the current state of smart technologies used for animal health monitoring under PLF, describes their working principles and applications, and discusses the opportunities and constraints relevant to their wider adoption, with particular attention to the context of smallholder and semi-intensive livestock systems.

2. Concept and Evolution of Precision Livestock Farming

PLF extends the principles of precision agriculture matching input and management decisions to the specific needs of a defined unit to the domain of animal production, where the unit of interest is the individual animal rather than a plot of land. The foundational premise is that animals continuously emit biological signals (body temperature, heart rate, vocalisation, posture, activity pattern) that reflect their underlying physiological and health status, and that these signals can be captured non-invasively, processed automatically, and translated into early warnings well before a trained observer would notice a visible change.

The evolution of PLF has broadly progressed through three overlapping phases. The first phase, beginning in the 1990s and 2000s, focused on basic automation, such as electronic identification and automatic milking systems, primarily aimed at improving farm efficiency. The second phase introduced dedicated health- and behaviour-monitoring sensors, including pedometers, rumination collars, and in-line milk analysers, allowing continuous tracking of activity and production parameters. The third and current phase integrates the Internet of Things, cloud-based data platforms, computer vision, and artificial intelligence, enabling multi-sensor data fusion, predictive analytics, and automated decision support that can flag a sick animal to the farmer or veterinarian before clinical signs are visible.

A recent global scientometric review of PLF research found that studies in this field have grown steadily since the early 2010s, with dairy cattle attracting the largest share of research attention, followed by swine and poultry, and with mastitis detection, lameness, and general behaviour monitoring emerging as dominant research themes. Countries such as China, the United States, Australia, Japan, and India have been among the most active contributors to this literature, reflecting a broad international interest in translating PLF research into field-deployable technology.

3. Sensor and Smart Technologies for Health Monitoring

Health monitoring under PLF relies on a diverse array of sensing technologies, each suited to capturing particular physiological or behavioural indicators. Broadly, these fall into wearable devices attached directly to the animal, fixed or remote sensors that observe the animal from a distance, and in-line sensors integrated into farm infrastructure such as milking parlours. Table 1 summarises the principal sensor types currently used for animal health monitoring, their placement, and the health parameters they capture, while Figure 2 illustrates typical on-animal sensor placement points in dairy cattle.

Wearable accelerometer-based collars and leg bands are among the most widely deployed devices, as they can simultaneously capture activity level, rumination time, and lying behaviour, all of which change measurably in the days preceding clinical illness. Implantable reticulo-rumen boluses provide continuous core body temperature and rumen pH readings, offering an internal physiological signal that is less affected by ambient conditions than skin-surface measurements. Infrared thermography, whether handheld or fixed at parlour entrances, allows non-contact detection of localised temperature elevations associated with udder inflammation or systemic febrile illness, and has been highlighted in recent literature as a rapidly emerging, non-invasive diagnostic tool for early mastitis detection.

Machine-vision systems, using standard or depth cameras mounted above walkways or in loafing areas, are increasingly used for automated body condition scoring and lameness gait analysis, removing the need to physically restrain or handle animals for routine welfare assessment. Acoustic sensors, which detect and classify vocalisations or coughing sounds, are particularly valuable in poultry and swine housing, where visual inspection of large numbers of animals is impractical, and have shown promise for early detection of respiratory disease outbreaks. In-line milk analysers integrated into milking systems provide near-continuous measurement of milk electrical conductivity, somatic cell count, and yield, parameters that are directly diagnostic for subclinical and clinical mastitis.

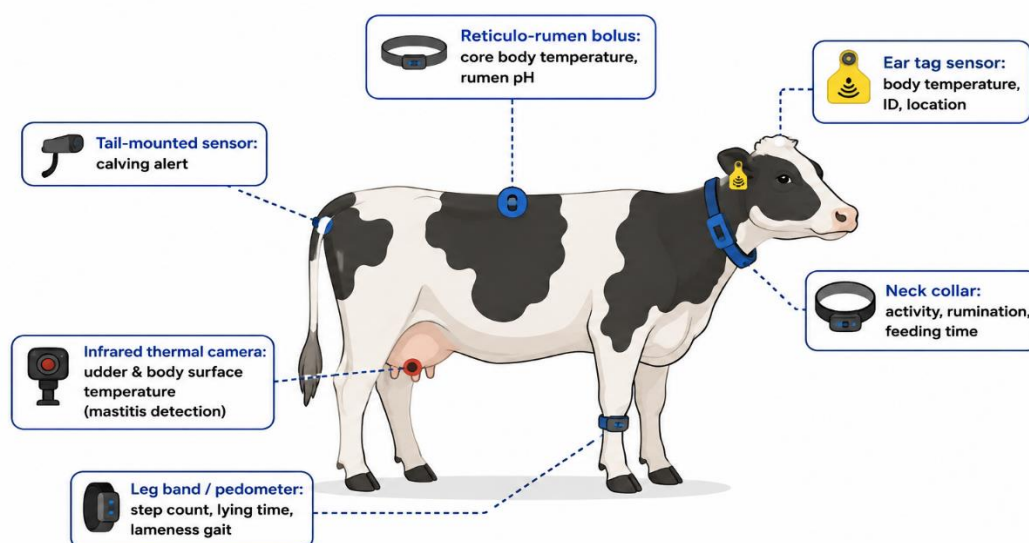


Figure 1. Common on-animal sensor placement points and the health parameters they monitor in dairy cattle

Table 1. Principal Sensor Technologies used for Livestock Health Monitoring

Sensor / Device	Placement	Health Parameter Monitored	Species / Application
Accelerometer/pedometer collar	Neck or leg	Activity level, rumination time, lying/standing bouts, gait irregularity	Dairy cattle, buffalo
Ear-tag / implantable bolus thermometer	Ear, reticulo-rumen	Core body temperature, rumen pH, animal ID	Cattle, sheep, goats
Infrared thermal camera	Fixed / handheld, remote	Udder and body-surface temperature (mastitis, febrile illness)	Dairy cattle
Acoustic microphone sensors	Pen / barn ceiling	Coughing frequency, respiratory distress sounds	Poultry, swine, calves
Machine-vision / RGB-depth camera	Overhead / side-view	Body condition score, lameness gait scoring, feeding behaviour	Cattle, swine, poultry flocks
In-line milk analysers	Milking parlour / robot	Milk electrical conductivity, somatic cell count, yield	Dairy cattle
Tail-mounted or vaginal sensor	Tail base / vagina	Imminent calving alert, activity change	Dairy and beef cattle

4. Connectivity, Data Analytics and Artificial Intelligence in PLF

Raw sensor signals alone are of limited value without a system to transmit, process, and interpret them in a timely manner. A typical PLF health-monitoring system, illustrated in Figure 1, consists of four interlinked layers. The sensing layer comprises the wearable, fixed, or in-line devices described above. The connectivity layer transmits sensor data using short-range protocols such as Bluetooth or Wi-Fi, or longer-range, low-power technologies such as LoRaWAN, which is particularly suited to large or remote grazing areas with limited network infrastructure. The data processing and analytics layer, hosted on cloud servers or increasingly on edge devices located on the farm itself, applies statistical thresholds or machine-learning models to distinguish normal physiological variation from patterns indicative of disease or distress. Finally, the decision-support layer presents processed information to the farmer or veterinarian through a dashboard, mobile application, or automated alert, closing the loop with a management action such as isolation, veterinary examination, or treatment.

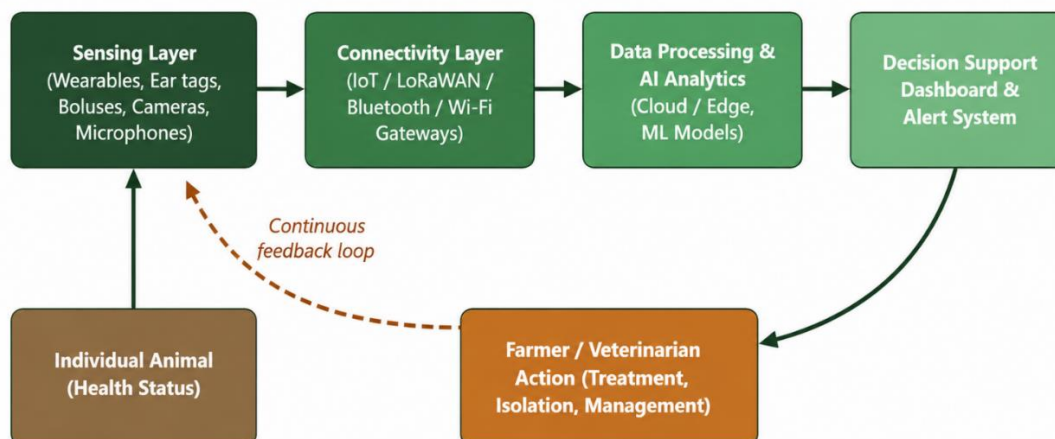


Figure 2. Conceptual architecture of a Precision Livestock Farming health monitoring system, from on-animal sensing to farmer or veterinary decision and action

A scoping review of 413 published studies on precision cattle-monitoring technologies found that inertial sensors and image- or video-based systems were the two most common technology types, together accounting for well over half of the reviewed literature, while nearly half of the studies still relied on relatively simple, threshold-based classification methods rather than machine learning to interpret sensor data, indicating substantial scope for further analytical sophistication (Figure 3). More recent work has increasingly applied machine-learning and deep-learning classifiers, including random forest, support vector machine, and neural network architectures, to fuse data from multiple sensor streams and generate individualised, herd-level disease-risk scores, in some cases achieving reported classification accuracies above ninety percent for specific conditions such as lumpy skin disease.

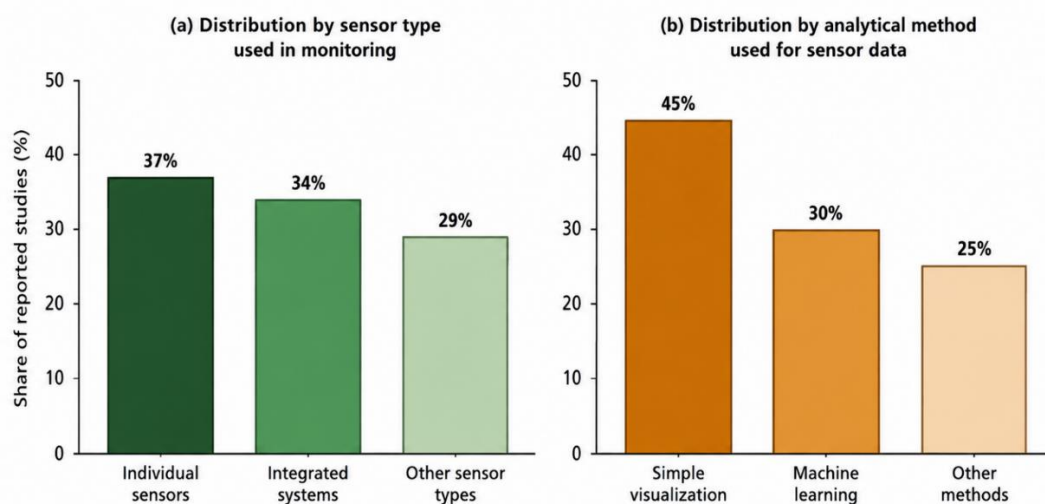


Figure 3. Distribution of sensor technology types and analytical methods reported across 413 precision cattle-monitoring studies (data adapted from a published scoping review)

5. Applications in Disease and Health-Event Detection

The practical value of PLF technologies is best illustrated through their application to specific diseases and health events of economic and welfare importance, summarised in Table 2. Mastitis, the most costly disease of dairy cattle worldwide, has received the greatest research attention, with systems combining milk electrical conductivity, udder-surface thermography, and activity-based sensors to flag inflammation before visible clinical

signs appear. For transboundary viral diseases of major concern in India, including foot-and-mouth disease and lumpy skin disease, IoT-based monitoring systems that track body temperature and activity, coupled with machine-learning classifiers, have demonstrated the ability to identify affected animals early enough to allow isolation and reduce within-herd spread; one recent system reported a classification accuracy of approximately ninety-two percent for lumpy skin disease detection using such an approach.

Lameness, a major welfare and productivity concern in intensive dairy systems, is now routinely monitored through accelerometer-based leg sensors that detect changes in step count, walking speed, and weight-bearing symmetry, supplemented in more advanced installations by camera-based gait-scoring systems. Metabolic disorders such as ketosis and reproductive conditions such as metritis have been addressed through cloud-based machine-learning models that combine milk yield, rumination time, activity level, and milk conductivity data drawn from routinely collected herd sensor streams, with one recent study training such a model on a dataset of over one hundred thirty affected and healthy cows to reliably distinguish disease status. Reproductive monitoring, particularly the detection of estrus, has similarly benefited from non-contact thermal infrared imaging, which identifies characteristic localised temperature changes associated with the onset of estrus without requiring physical restraint of the animal.

Table 2. Disease-Specific Applications of Precision Livestock Farming Technologies

Disease / Condition	PLF Technology Used	Sensed Indicator(s)	Illustrative Source
Mastitis	IoT wearables + infrared thermography + ML	Milk electrical conductivity, udder temperature, activity drop	Vyas et al., 2019
Foot-and-mouth disease	IoT sensor network + neural network classifier	Body temperature rise, reduced feeding activity	Vyas et al., 2019
Lameness	Accelerometer-based wearable gait sensors	Step count, walking speed, weight-bearing asymmetry	Multimodal Technol. Interact., 2018
Lumpy skin disease	IoT-based monitoring with machine-learning classifier	Skin temperature, activity, lesion-linked behaviour change	ScienceDirect, 2024 (92% accuracy)
Ketosis and metritis	Cloud-based ML model on multi-sensor herd data	Milk yield, rumination, activity, milk conductivity	Discover AI, Springer, 2025
Estrus / reproductive status	Non-contact thermal infrared imaging	Localised surface temperature change	Wang et al., Agriculture, 2023

6. Benefits and Impact on Animal Health and Productivity

The principal benefit of PLF-based health monitoring is the shift from reactive to proactive herd management. By flagging deviations from an individual animal's own behavioural and physiological baseline, PLF systems allow farmers and veterinarians to intervene during the sub-clinical phase of disease, when treatment is typically less costly and more effective, and production losses can be minimised. Continuous monitoring also reduces reliance on labour-intensive, time-consuming manual observation, freeing farm labour for other tasks, a particularly valuable benefit given the shrinking availability of skilled farm labour in many regions.

Early and targeted disease detection additionally supports more judicious use of antimicrobials, since treatment can be directed specifically to affected animals rather than applied prophylactically across the herd, contributing to broader efforts to contain antimicrobial resistance in livestock production. For transboundary diseases of major regulatory concern, rapid identification of the first affected animals through automated monitoring can meaningfully reduce the scale of outbreaks and the associated economic disruption to trade and rural livelihoods. Collectively, these benefits translate into improved milk yield, reproductive performance, and animal welfare outcomes, alongside more efficient use of veterinary and farm labour resources.

7. Challenges and Limitations in Adoption

Despite its demonstrated potential, the widespread adoption of PLF health-monitoring technology faces several practical constraints, particularly in smallholder and semi-intensive production systems that characterise much of Indian and other developing-country livestock farming. The upfront capital cost of sensors, gateways, and software subscriptions remains a significant barrier for farmers managing small herds, where the per-animal cost of instrumentation can be difficult to justify against expected returns. Reliable connectivity, whether cellular, Wi-

Fi, or dedicated IoT networks, is often lacking in rural and remote grazing areas, constraining the real-time data transmission on which many systems depend.

Technical challenges also persist at the level of data quality and interpretation. Sensor readings can be affected by environmental noise, device malfunction, or incorrect attachment, and many published detection algorithms are validated only within the specific population and management conditions in which they were developed, raising concerns about their external validity when transferred to different breeds, climates, or husbandry systems. A systematic review of PLF technologies for pig welfare assessment found that only a minority of commercially available systems had been subjected to rigorous external validation, underscoring the gap between research prototypes and field-ready, dependable products. Furthermore, the effective use of PLF systems requires a degree of digital literacy and training that may not be readily available to all farmers, and the lack of standardised data formats across different manufacturers' platforms can hinder integration of multiple sensor streams into a single coherent decision-support system.

Data ownership, privacy, and the long-term availability of manufacturer support and cloud services are additional considerations that farmers and policymakers must weigh when investing in PLF infrastructure, particularly where systems rely on proprietary, subscription-based platforms rather than open standards.

8. Conclusion

Precision Livestock Farming represents a significant advance in the way animal health can be monitored and managed, replacing periodic, subjective visual inspection with continuous, objective, sensor-derived information. The technologies reviewed here, spanning wearable accelerometers, implantable thermometers, infrared thermography, acoustic sensors, machine vision, and in-line milk analysis, combined with increasingly sophisticated data analytics and machine learning, have demonstrated clear value in the early detection of mastitis, lameness, metabolic disorders, reproductive events, and major transboundary diseases. Realising the full benefit of these technologies at scale, however, will require continued attention to cost reduction, connectivity infrastructure, algorithm validation across diverse production systems, and farmer training, alongside supportive institutional and policy frameworks. With sustained investment and adaptation to smallholder contexts, PLF-based health monitoring has the potential to meaningfully improve animal welfare, productivity, and disease control across both intensive and smallholder livestock systems, including the vast and diverse livestock sector of India.

References

- Chen, C., Zhu, W., & Norton, T. (2023). Precision Livestock Farming Research: A Global Scientometric Review. *Animals*, 13(13), 2096. <https://www.mdpi.com/2076-2615/13/13/2096>
- Riaboff, L., et al. (2024). Scoping review of precision technologies for cattle monitoring. *Smart Agricultural Technology*. <https://www.sciencedirect.com/science/article/pii/S2772375524002016>
- Berckmans, D. (2017). General introduction to precision livestock farming. *Animal Frontiers*, 7(1), 6-11.
- Berckmans, D. (2014). Precision livestock farming technologies for welfare management in intensive livestock systems. *Revue Scientifique et Technique (OIE)*, 33(1), 189-196.
- Matthews, S. G., Miller, A. L., Clapp, J., Plotz, T., & Kyriazakis, I. (2016). Early detection of health and welfare compromises through automated detection of behavioural changes in pigs. *Veterinary Journal*; reviewed in: *Precision Livestock Farming in Swine Welfare: A Review for Swine Practitioners*. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6523486/>
- Larsen, J. L. S., et al. (2021). A Systematic Review on Validated Precision Livestock Farming Technologies for Pig Production and Its Potential to Assess Animal Welfare. *Frontiers in Veterinary Science*. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8160240/>
- Wild, A., et al. (2024). Systematic Literature Review of Vision-Based Approaches to Outdoor Livestock Monitoring with Lessons from Wildlife Studies. *arXiv:2410.05041*. <https://arxiv.org/pdf/2410.05041>
- Vyas, S., Shukla, V., & Doshi, N. (2019). FMD and mastitis disease detection in cows using Internet of Things (IoT). *Procedia Computer Science*, 160, 728-733.
- Design and implementation of an IoT-based monitoring system for early detection of lumpy skin disease in cattle. *Smart Agricultural Technology*. <https://www.sciencedirect.com/science/article/pii/S2772375524002144>

An IoT-Driven hybrid AI model for health monitoring of cows. Discover Artificial Intelligence (Springer Nature). <https://link.springer.com/article/10.1007/s44163-025-00610-4>

Smart neck collar: IoT-based disease detection and health monitoring for dairy cows. Discover Internet of Things (Springer Nature). <https://link.springer.com/article/10.1007/s43926-025-00109-5>

Eckelkamp, E. A. (2019). Invited review: Current state of wearable precision dairy technologies in disease detection. Applied Animal Science, 35(2), 209-220.

Intelligent wearable devices and biosensors for monitoring cattle health conditions: A review and classification. Smart Health, 27, 100369. <https://doi.org/10.1016/j.smhl.2022.100369>

Wang, Z., Wang, S., Wang, C., Zhang, Y., Zong, Z., & Wang, H. (2023). A Non-Contact Cow Estrus Monitoring Method Based on the Thermal Infrared Images of Cows. Agriculture, 13(2), 385.

Awasthi, A., Awasthi, A., Riordan, D., & Walsh, J. (2016). Non-invasive sensor technology for the development of a dairy cattle health monitoring system. Computers, 5(4), 23.



Precision Agronomy: Bridging Technology and Crop Productivity



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Abstract

Global food systems are facing unprecedented challenges arising from rapid population growth, declining per capita arable land, water scarcity, climate change, and increasing climatic variability. Meeting the growing demand for food while conserving natural resources requires innovative and data driven approaches to crop management. Precision agronomy, which integrates geospatial positioning systems, remote sensing, the Internet of Things (IoT), variable rate technology (VRT), unmanned aerial vehicles (UAVs), artificial intelligence, and advanced data analytics, has emerged as a transformative approach for improving agricultural productivity, resource use efficiency, and environmental sustainability. This article reviews the fundamental technological components of precision agronomy, evaluates their agronomic, economic, and environmental benefits, and examines the key challenges limiting their large scale adoption, particularly among smallholder farming systems. Evidence from recent studies indicates that variable rate fertilizer application can improve nutrient use efficiency by 20 to 40 per cent while reducing fertilizer consumption by up to 40 per cent, whereas IoT based smart irrigation systems have demonstrated water savings of 30 to 47 per cent together with yield improvements exceeding 40 per cent under suitable conditions. Similarly, satellite imagery and UAV based remote sensing enable timely monitoring of crop health, nutrient deficiencies, water stress, and pest outbreaks, supporting more precise and informed management decisions. Despite these advantages, high initial investment, technical complexity, limited digital infrastructure, and inadequate farmer awareness continue to constrain widespread adoption. The article concludes that the future success of precision agronomy will depend not only on technological innovation but also on affordable solutions, interoperable digital platforms, effective extension services, and farmer centric implementation strategies that make precision agriculture accessible, practical, and economically viable for diverse farming systems.

Keywords: Artificial intelligence, Internet of Things, Precision agriculture, Remote sensing, Site specific crop management, Variable rate technology.

1. Introduction

Agriculture has always involved managing variability in soil, water, climate, and biological processes across both space and time. Traditionally, however, farmers have addressed this variability using uniform management practices, applying the same seed rate, fertilizer dose, irrigation schedule, and crop protection measures across an entire field, regardless of differences in soil fertility, moisture availability, or crop performance within individual locations. Such blanket management often results in inefficient resource use, increased production costs, and uneven crop growth. Precision agronomy, also known as precision agriculture or precision farming, has emerged as a scientific approach to overcome these limitations by enabling site specific crop management. The International Society of Precision Agriculture defines precision agriculture as a management strategy that collects, processes, and analyses spatial, temporal, and individual field data, integrating them with other sources of information to support informed management decisions that improve resource use efficiency, productivity, quality, profitability, and environmental sustainability.

The need for precision agronomy is driven not only by technological advancement but also by increasing demographic and environmental pressures. Rapid population growth, declining per capita availability of arable land, water scarcity, rising input costs, and the growing impacts of climate change have intensified the demand for more efficient and sustainable agricultural production systems. At the same time, conventional uniform application of fertilizers, irrigation water, and crop protection inputs has contributed to nutrient imbalances, declining soil health, reduced input use efficiency, and environmental pollution through nutrient losses and runoff.

Precision agronomy addresses these challenges by treating agricultural fields as a collection of distinct management zones, allowing inputs to be applied according to the specific requirements of each location rather than following a uniform approach.

The rapid development of **Global Navigation Satellite Systems (GNSS)**, remote sensing, unmanned aerial vehicles (UAVs), the **Internet of Things (IoT)**, wireless soil and weather sensor networks, artificial intelligence, machine learning, cloud computing, and advanced data analytics has transformed precision agronomy from a promising concept into a practical reality. These technologies enable continuous monitoring of crop growth, soil conditions, nutrient status, water availability, and pest or disease incidence, allowing farmers to make timely, data driven management decisions. This article reviews the major technological components of precision agronomy, evaluates their impact on crop productivity, resource use efficiency, and farm profitability, and discusses the economic, technical, and infrastructural challenges that continue to influence their adoption, particularly in smallholder farming systems.

2. Core Technologies Underpinning Precision Agronomy

Precision agronomy is best understood not as a single technology but as a stack of complementary tools, each addressing a different stage of the sense-analyse-act cycle described in Figure 1. Table 1 summarises the principal technologies and their agronomic function.

Table 1. Core precision agronomy technologies and their agronomic function

Technology	Primary Agronomic Function	Representative Data / Output
GNSS/GPS-guided machinery	Sub-metre accurate steering, planting, and input placement; eliminates overlap and skips	Auto-steer tracks, as-applied logs
UAV / satellite remote sensing	Field-scale crop health, water stress, and pest/disease detection via spectral indices	NDVI, GNDVI, SAVI maps; multispectral and thermal imagery
Variable rate technology (VRT)	Site-specific seeding, fertilisation, and spraying matched to zone-level need	Prescription maps; as-applied rate files
IoT soil and weather sensors	Continuous monitoring of soil moisture, temperature, EC, and micro-climate for irrigation and nutrient timing	Time-series sensor streams on cloud dashboards
GIS and data analytics / AI	Spatial integration of layered data to delineate management zones and predict yield	Management zone maps; yield forecasts
Yield monitors and mapping	Georeferenced measurement of harvested yield to close the feedback loop	Yield maps used to refine next season's prescriptions

2.1 GNSS-Guided Machinery

Global Navigation Satellite System (GNSS) receivers, corrected to sub-metre or even centimetre accuracy through real-time kinematic (RTK) signals, allow tractors, planters, and sprayers to follow pre-planned paths automatically. This auto-steering capability eliminates the overlap and skips that occur under manual driving, directly reducing seed, fuel, and chemical waste while also enabling machinery to operate for longer hours, including at night, without loss of accuracy.

2.2 Remote Sensing: Satellites and Unmanned Aerial Vehicles

Remote sensing platforms — ranging from freely available satellite imagery to purpose-built unmanned aerial vehicles (UAVs) equipped with multispectral, hyperspectral, or thermal sensors — provide the spatial crop-health data that underpins most precision decisions. Vegetation indices such as the Normalised Difference Vegetation Index (NDVI) and the Green NDVI are widely used to estimate canopy vigour, leaf area index, and nitrogen status well before visible symptoms of stress appear. Reviews of UAV-based multispectral sensing report mature, field-tested applications across four domains in particular: general crop growth monitoring, pest and disease

identification, nutrient status assessment, and yield prediction. UAVs are especially valued for covering large or fragmented plots quickly, which is difficult to achieve through ground-based scouting alone, and for enabling timely intervention during sensitive growth stages such as tillering or flowering.

2.3 Variable Rate Technology (VRT)

Variable rate technology allows seed, fertiliser, and crop-protection products to be applied at rates that vary across a field rather than uniformly. Two broad implementations exist: map-based systems, which apply a prescription generated in advance from soil sampling or historical yield data, and sensor-based systems, which measure crop or soil condition on-the-go and adjust application in real time. Table 2 compares these two approaches.

Table 2. Comparison of map-based and sensor-based variable rate technology (VRT) for fertiliser application

Attribute	Map-Based Variable Rate Technology	Sensor-Based Variable Rate Technology
Data source	Pre-generated prescription maps from grid soil sampling, yield maps, or satellite imagery	Real-time, on-the-go sensors (optical, electrical conductivity, spectral) mounted on the applicator
Positioning requirement	GPS/GNSS receiver required to georeference the field position against the map	GPS optional; some systems can operate using continuous sensor feedback alone
Responsiveness	Fixed to conditions at the time of mapping; cannot react to short-term change	Responds instantly to the crop or soil condition detected at that instant
Typical use case	Large, well-characterised fields with stable, known spatial fertility patterns	Fields with high temporal variability, or where soil sampling is impractical
Key limitation	Dependent on sampling density and map accuracy; costly re-sampling over time	Higher equipment and calibration cost; sensitive to sensor noise and calibration drift

2.4 The Internet of Things and Soil-Weather Sensing

Networks of low-cost, wirelessly connected sensors now allow continuous, real-time monitoring of soil moisture, soil temperature, electrical conductivity, and micro-climate variables. These IoT networks feed directly into automated or farmer-controlled irrigation scheduling, replacing calendar-based watering with demand-based watering, and are frequently combined with cloud dashboards and mobile alerts so that a farmer can monitor and adjust conditions remotely.

2.5 Geographic Information Systems and Data Analytics

Geographic Information Systems (GIS) integrate the spatial layers produced by the technologies above — yield maps, soil test results, elevation, and vegetation indices — into a single georeferenced dataset from which management zones can be delineated. Increasingly, this integration is being handed to machine learning models, which can identify non-linear relationships between multiple input layers and final yield, supporting both diagnostic analysis (why did yield vary here?) and predictive analysis (what yield can be expected under a given management plan?).

3. Impacts on Crop Productivity and Resource-Use Efficiency

The agronomic case for precision technology rests on a simple logic: if inputs are matched more closely to actual crop and soil need, less is wasted and more is converted into harvestable yield. The empirical literature broadly supports this logic, though the magnitude of benefit varies considerably with crop, region, and the specific technology deployed.

A systematic review of variable rate fertilisation technologies found that VRT can increase nutrient use efficiency by 20-40% relative to uniform application, while also reducing nitrogen losses and delivering fertiliser cost savings of up to 40% in some cropping systems. Separate industry analyses of variable rate seeding and fertilisation report yield increases in the range of 8-12% attributable to matching seeding density and nutrient rate to zone-level productivity potential. On the water-management side, Internet-of-Things-enabled smart irrigation systems have been shown in controlled trials to reduce water consumption by 30-47% compared with conventional irrigation while simultaneously increasing yield in one lettuce trial, by as much as 43% — by maintaining soil moisture closer to the crop's physiological optimum and reducing disease pressure associated with over-watering. Figure 2 summarises these reported ranges.

Reported Resource-Use and Yield Gains from Precision Agronomy Technologies

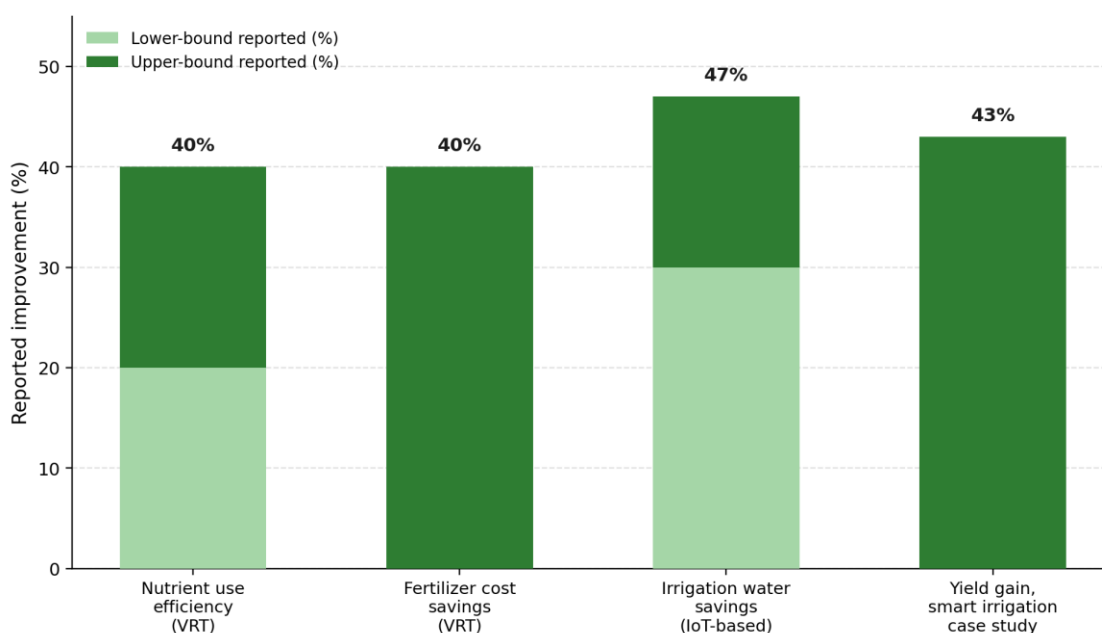


Figure 1. Reported resource-use and yield gains associated with variable rate technology and IoT-based irrigation, compiled from published field trials and review studies.

Remote sensing contributes a complementary benefit that is harder to express as a single percentage: earlier detection. Because spectral stress signatures in a crop canopy typically precede visually apparent symptoms, UAV and satellite monitoring shorten the interval between the onset of a nutrient deficiency, water stress event, or pest infestation and the corrective management response, which in turn limits the yield penalty associated with delayed intervention. Reviews of UAV-based nutrient and water status monitoring similarly note that fine spatial and temporal resolution allows problems to be caught and addressed at the management-zone level rather than only after they have affected the whole field.

Beyond the plot-level effects, precision agronomy also carries measurable environmental co-benefits. By curbing over-application of nitrogen and other nutrients, site-specific management reduces the risk of nutrient runoff into waterways and lowers the greenhouse-gas footprint per unit of production, an outcome increasingly relevant as agricultural policy and buyers place greater weight on the environmental performance of farm inputs, not only their yield outcome.

4. The Precision Agronomy Workflow

Although individual technologies are often discussed in isolation, their agronomic value is realised only when they are linked into a continuous management cycle. Figure 1 depicts this cycle as six linked stages: sensing (data capture from soil, crop, and weather sources), collection (aggregation of georeferenced data through IoT networks), analysis (processing through GIS and machine learning to identify patterns and management zones),

decision (translation of analysis into a prescription map), action (execution through variable rate machinery and guided equipment), and evaluation (yield mapping that closes the loop and refines the following season's plan).

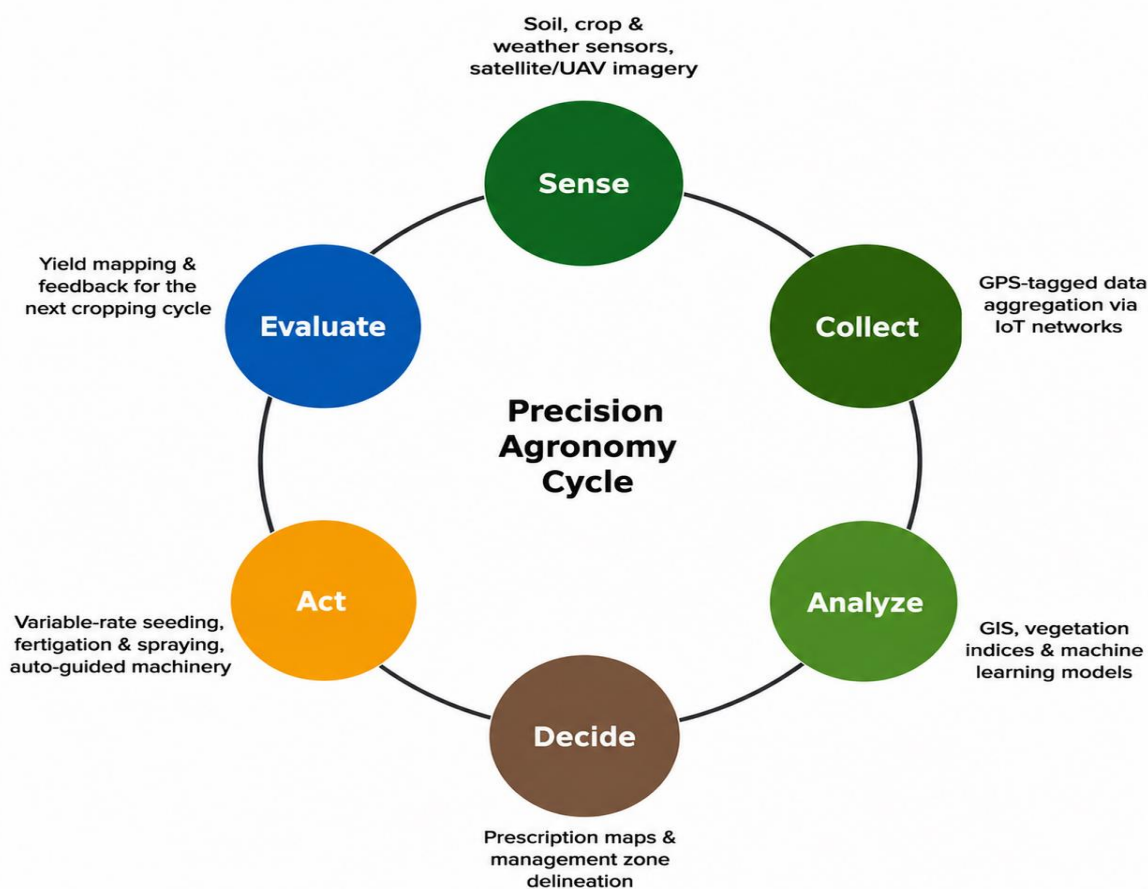


Figure 2. The precision agronomy management cycle, linking field sensing through to season-end evaluation and feedback.

5. Representative Field Applications

5.1 Site-Specific Nutrient Management

Nitrogen, phosphorus, and potassium requirements often vary substantially within a single field due to differences in soil texture, organic matter, and drainage. Site-specific nutrient management uses either grid-sampled soil test data or on-the-go optical sensors to generate prescription maps that direct more fertiliser to nutrient-poor zones and less to nutrient-rich zones, reducing both the risk of yield-limiting deficiency and the risk of costly, environmentally damaging over-application.

5.2 Precision Irrigation

In water-scarce or semi-arid regions, IoT soil-moisture networks combined with UAV-based thermal imagery allow irrigation to be scheduled according to actual crop water status rather than a fixed calendar, a practice shown to materially improve both water productivity and irrigation efficiency under semi-arid conditions.

5.3 Pest, Disease and Weed Detection

Multispectral and hyperspectral imagery, increasingly interpreted through machine learning classifiers, can flag anomalous canopy signatures associated with pest infestation, fungal disease, or weed pressure well before an agronomist could identify the same problem from the ground, enabling targeted rather than blanket pesticide application.

5.4 Yield Monitoring and Mapping

Combine-mounted yield monitors record georeferenced grain flow at harvest, producing yield maps that are among the most information-dense layers available to a grower — they reveal, retrospectively, exactly where the

season's management succeeded or fell short, and form the empirical backbone against which every other data layer is validated.

6. Adoption Challenges and Barriers

Despite the demonstrated agronomic and economic benefits, uptake of precision agronomy technologies remains uneven, both between large commercial farms and smallholder operations, and between high-income and developing agricultural economies. A U.S. Government Accountability Office assessment identified high up-front acquisition cost as a primary constraint limiting broader adoption and use, a finding echoed across multiple farmer surveys. A study of small-scale farmers in Kentucky similarly found that farm size and years of farming experience were positively associated with adoption, while complexity, uncertain profitability, privacy concerns, and lack of confidence in the technology were each cited by a meaningful share of respondents as reasons for non-adoption. Figure 3 summarises these self-reported barriers.

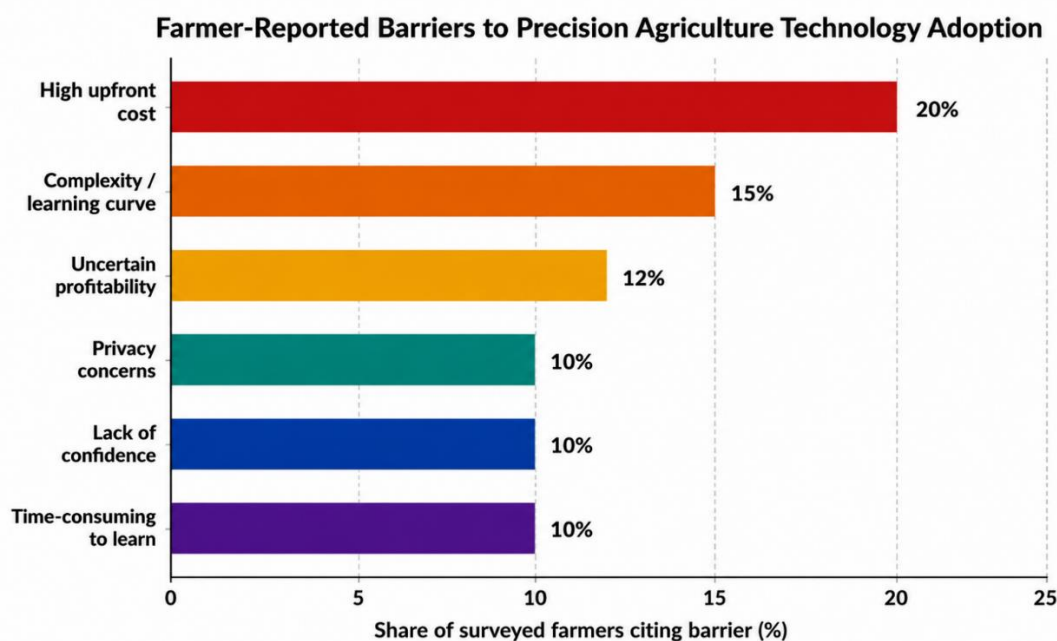


Figure 3. Farmer-reported barriers to precision agriculture technology adoption, compiled from U.S. smallholder survey data.

A systematic review of small-scale precision farming worldwide identified five recurring constraints: small land size (which limits the economies of scale needed to justify equipment cost), high cost of adoption, technology-related difficulties, lack of professional or technical support, and the absence of supportive policy frameworks. In lower-income regions, a Nigeria-focused agricultural report similarly attributed low precision agriculture adoption chiefly to the unaffordable cost of the technology relative to smallholder incomes, calling explicitly for more affordable, locally tailored solutions to accelerate uptake across the African continent.

These findings point to an important nuance: the constraint on wider adoption is often not a lack of belief in the technology's benefit, but a mismatch between the scale, cost, and complexity of currently available tools and the operating reality of small and medium-sized farms. Addressing this mismatch through shared-service models, subsidised access, simplified interfaces, and low-cost sensor hardware is treated in the literature as being as important to closing the productivity gap as any further advance in sensor or algorithm sophistication.

7. Future Directions

Several trends are likely to shape the next phase of precision agronomy. Edge computing and lightweight ('TinyML') machine learning models are beginning to allow data processing to happen directly on low-power field devices, reducing the cost and connectivity requirements that currently limit deployment in remote or resource-constrained settings. Integration across data sources combining satellite, UAV, ground sensor, and machine data within a single analytical platform is expected to improve the accuracy of management-zone

delineation beyond what any single data layer can achieve alone. Finally, growing attention to data privacy, interoperability standards, and financing mechanisms suggests that the next stage of adoption growth will depend as much on institutional and market design as on further technical innovation.

8. Conclusion

Precision agronomy represents a substantive, evidence-backed shift in how crop production can be managed: from uniform, field-level decisions to site-specific, data-informed ones. The reviewed literature indicates consistent gains in nutrient use efficiency, water productivity, and yield when GNSS guidance, remote sensing, variable rate technology, and IoT sensing are deployed as part of an integrated sense-analyse-act-evaluate cycle. At the same time, the persistence of cost, complexity, and support-related barriers — particularly for smallholder and resource-constrained farmers — means that the productivity gains documented in research trials have not yet been realised uniformly across global agriculture. Bridging that remaining gap will require continued attention not only to sensor and algorithm development, but to the affordability, usability, and support infrastructure that determine whether a given farmer can put those tools to work in their own field.

References

- Monteiro, A., Santos, S., & Goncalves, P. (2021). Precision agriculture for crop and livestock farming—Brief review. *Animals*, 11(8), 2345. <https://pmc.ncbi.nlm.nih.gov/articles/PMC8388655/>
- Getahun, S., et al. (2024). Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. *The Scientific World Journal*, 2024, Article 2126734. <https://doi.org/10.1155/2024/2126734>
- Saha, S., Kucher, O. D., Utkina, A. O., & Rebouh, N. Y. (2025). Precision agriculture for improving crop yield predictions: A literature review. *Frontiers in Agronomy*, 7, Article 1566201. <https://doi.org/10.3389/fagro.2025.1566201>
- Pawase, P. P., Nalawade, S. M., Bhanage, G. B., Walunj, A. A., Kadam, P. B., Durgude, A. G., & Patil, M. R. (2023). Variable rate fertilizer application technology for nutrient management: A review. *International Journal of Agricultural and Biological Engineering*, 16(4), 11–19. <https://ijabe.org/index.php/ijabe/article/view/7671>
- A review on variable rate technologies for fertilizer application in precision agriculture. (2025). *Agronomy Journals*. <https://www.agronomyjournals.com/archives/2025/vol8issue10S/PartC/S-8-10-35-631.pdf>
- Variable rate technology in agriculture: Top 5 trends shaping the future. (2026). *Farmonaut*. <https://farmonaut.com/precision-farming/variable-rate-technology-agriculture-2025-top-5-trends>
- A review of the application of UAV multispectral remote sensing technology in precision agriculture. (2025). *ScienceDirect*. <https://www.sciencedirect.com/science/article/pii/S2772375525006379>
- Integrating UAVs, satellite remote sensing, and machine learning in precision agriculture: Pathways to sustainable food production, resource efficiency, and scalable innovation. (2025). *Frontiers in Agronomy*. <https://www.frontiersin.org/journals/agronomy/articles/10.3389/fagro.2025.1670380/full>
- Advances in UAV remote sensing for monitoring crop water and nutrient status: Modeling methods, influencing factors, and challenges. (2025). *PMC*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC12389011/>
- Drone-based multispectral imaging for precision monitoring of crop growth variables. (2025). *Drones*, 41(1), 10. <https://www.mdpi.com/2673-9976/41/1/10>
- IoT-driven smart irrigation system to improve water use efficiency. (2026). *Scientific Reports*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC12820134/>
- Smart agriculture using IoT for automated irrigation, water and energy efficiency. (2025). *ScienceDirect*. <https://www.sciencedirect.com/science/article/pii/S2772375525003144>
- Integration of smart sensors and IoT in precision agriculture: Trends, challenges and future perspectives. (2025). *Frontiers in Plant Science*. <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2025.1587869/full>

Soil Biological Indicators for Monitoring Agricultural Sustainability



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Abstract

Soil health is the foundation of sustainable agriculture, supporting crop productivity, nutrient cycling, environmental quality, and ecosystem resilience. Among the various indicators used to assess soil health, biological indicators are considered the most sensitive because they respond rapidly to changes in land management and environmental conditions. Unlike physical and chemical properties, which often change slowly, biological indicators provide early evidence of improvements or degradation in soil quality. Important biological indicators include microbial biomass, soil enzyme activities, soil respiration, earthworm populations, microbial diversity, and labile carbon and nitrogen pools. These indicators reflect the biological functioning of soil and its ability to sustain nutrient cycling, organic matter decomposition, and healthy plant growth. Their status is strongly influenced by agricultural practices such as conservation agriculture, crop rotation, residue retention, integrated nutrient management, organic amendments, and tillage intensity. Monitoring biological indicators helps evaluate the effectiveness of these management practices and supports informed decisions for improving soil fertility and long-term agricultural sustainability. Although several biological assessment frameworks have been developed, their routine use is still limited by the lack of standardized methodologies, seasonal variability, and the cost and complexity of biological analyses. This article reviews the major biological indicators of soil health, their significance in sustainable land management, their response to different agricultural practices, and the challenges associated with their wider adoption. Integrating biological indicators with conventional physical and chemical assessments provides a more comprehensive and reliable evaluation of soil health for sustainable agricultural production.

Keywords: Earthworms, Microbial biomass, Soil enzyme activity, Soil health, Sustainable agriculture.

1. Introduction

Soil is far more than an inert medium for anchoring plant roots; it is a living, dynamic system that hosts an enormous diversity of microorganisms, fauna and biochemical processes essential to nutrient cycling, organic matter decomposition and the maintenance of soil structure. As global agriculture faces mounting pressure from population growth, climate variability and land degradation, the concept of soil health has moved to the centre of strategies for sustainable land management. Soil health is generally defined, following Doran and Zeiss (2000), as the capacity of soil to function as a vital living system that sustains plant and animal productivity while maintaining environmental quality. Soil quality assessment traditionally relied heavily on physical properties, such as bulk density and aggregate stability, and chemical properties, such as pH, organic carbon content and nutrient status. However, soil biological properties, including microbial diversity, microbial biomass, enzyme quantities and activities, and soil respiration, have been shown to respond far more rapidly to changes in agricultural management or environmental stress than physical or chemical indicators (Bhaduri et al., 2022).

This heightened sensitivity makes biological indicators particularly valuable for monitoring agricultural sustainability, because they can reveal early signs of soil degradation or improvement long before these changes become apparent in yield data or in slower-changing chemical properties. This article examines the principal categories of soil biological indicators used in sustainability monitoring, discusses how they respond to different agricultural management practices, reviews established biological monitoring frameworks, and considers the practical challenges and future directions for incorporating biological indicators into routine soil health assessment.

2. The Concept of Soil Health and the Role of Biological Indicators

Soil quality and soil health are often used interchangeably to describe the fitness of a soil to support its intended functions, whether producing food and fibre, regulating water and nutrient flows, or supporting biodiversity. A

defining feature of the soil health concept, as articulated by Doran and Zeiss (2000), is its explicit inclusion of the biotic component of soil quality alongside physical and chemical properties. Soil biological indicators are attributes of the living component of soil, ranging from the total biomass of microorganisms to the activity of specific enzymes and the abundance of soil fauna such as earthworms and nematodes, that can be measured to infer the functional status of the soil ecosystem.

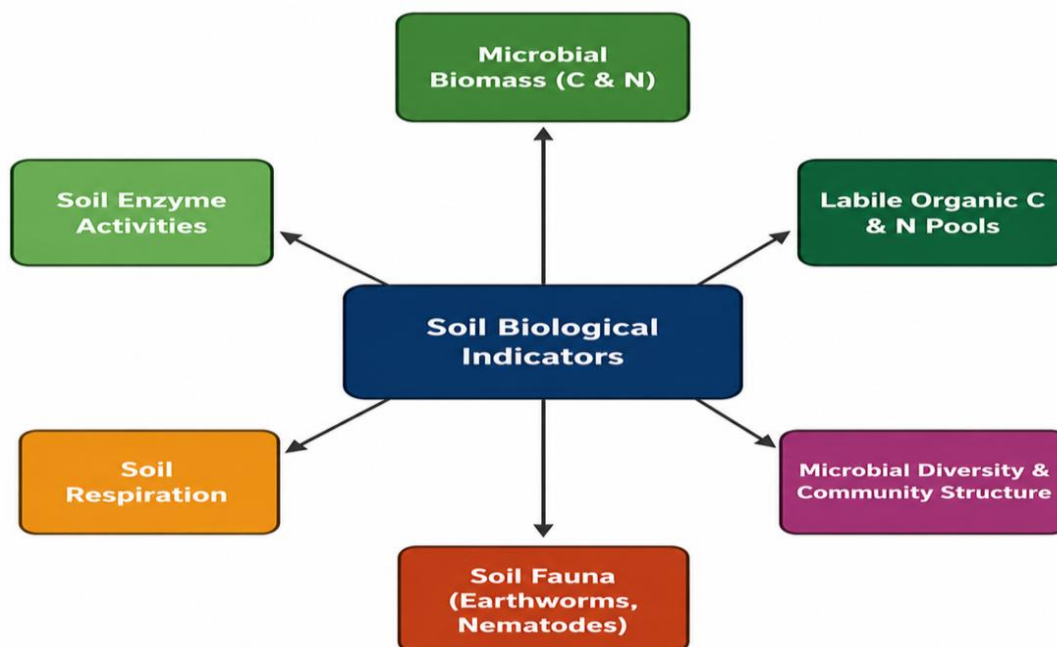


Figure 1: Major categories of soil biological indicators used in sustainability monitoring

As illustrated in Figure 1, soil biological indicators span several interconnected categories: microbial biomass carbon and nitrogen, soil enzyme activities, soil respiration, soil fauna such as earthworms and nematodes, microbial community diversity and structure, and labile or readily mineralisable organic carbon and nitrogen pools. While chemical and physical indicators provide a general assessment of overall soil condition, microbiological indicators offer direct insight into the processes that actually drive nutrient cycling, organic matter transformation and the maintenance of favourable soil structure (Sharma et al., 2024).

3. Major Categories of Soil Biological Indicators

3.1 Microbial Biomass

Microbial biomass carbon (MBC) represents the living component of soil organic matter and is widely regarded as one of the most useful early indicators of management-induced change, since soil management practices alter it well before total organic carbon shows a measurable response. Because microbial biomass is at the base of nutrient cycling in soil, it is highly sensitive to inputs of organic residues, tillage intensity and cropping system diversity (Bhaduri et al., 2022).

3.2 Soil Enzyme Activities

Soil enzymes such as dehydrogenase, β -glucosidase, urease and phosphatase catalyse the biochemical reactions that drive carbon, nitrogen, phosphorus and sulphur cycling, and their activities are widely used as sensitive indicators of soil biological health. Dehydrogenase activity, for example, is not usually suppressed by heavy metals at low concentrations and can indicate the extent of recovery of degraded soils, while β -glucosidase, the key enzyme in cellulose breakdown, has been shown to decline significantly in arable soils compared with undisturbed forest or meadow soils, reflecting the impact of cultivation on the carbon cycle (Bhaduri et al., 2022).

3.3 Soil Respiration

Soil respiration, measured as the rate of carbon dioxide evolution from soil, reflects the combined metabolic activity of the whole soil biological community and is closely linked to microbial biomass and enzyme activity.

Because soil temperature, microbial biomass and enzyme activity jointly regulate the rate of carbon dioxide release, respiration measurements are considered sensitive and reliable indicators of change in the broader physicochemical and biological status of soil.

3.4 Soil Fauna: Earthworms and Nematodes

Earthworms are among the most widely used bioindicators of soil quality and sustainability in agriculture, owing to their sensitivity to soil disturbance, contamination and management change, and their central role in organic matter decomposition, nutrient cycling and soil structure formation (Earthworm: a keystone species of soil quality, ScienceDirect, 2025). Earthworms can indicate soil quality through the abundance and species composition of the local earthworm fauna, and their absence often signals adverse conditions such as contamination, severe acidification or extreme drought, whereas an abundant, diverse earthworm community typically denotes healthy soil. A meta-analysis further found that the presence of earthworms increased crop yields by an average of 25 percent, with the largest gains observed in nitrogen-deficient soils or soils that had previously been disturbed and had lost structural integrity (Environmental DNA study, bioRxiv, 2023). Nematode communities are similarly used to construct trophic-structure-based soil quality indices that integrate both functional diversity and disturbance response.

3.5 Microbial Community Diversity and Structure

Beyond simple biomass measurements, the composition and functional diversity of the soil microbial community, assessed through phospholipid fatty acid (PLFA) profiling or molecular sequencing of bacterial and fungal marker genes, provides insight into how management practices reshape the functional capacity of the soil biota. Active soil organic matter fractions and microbiological indicators such as microbial biomass carbon, PLFA profiles and enzyme activities have been shown to be more sensitive to agricultural management practices than traditional indicators such as total soil organic carbon or total nitrogen.

3.6 Labile Organic Carbon and Nitrogen Pools

Labile, or readily decomposable, fractions of soil organic matter, such as permanganate-oxidisable carbon and mineralisable nitrogen, respond more quickly to changes in management than total organic carbon or total nitrogen, making them useful complementary indicators when integrated with microbial and enzymatic measurements.

4. Synthesis of Biological Indicators and Assessment Methods

Table 1 summarises the major categories of soil biological indicators discussed above, along with what each indicator measures and the assessment methods most commonly used in soil health monitoring programmes.

Table 1: Major Soil Biological Indicators, What They Measure and How They Are Assessed

Indicator	What It Measures	Typical Assessment Method
Microbial Biomass C & N	Total mass of living microorganisms; an active, labile pool of soil organic matter	Chloroform fumigation-extraction; substrate-induced respiration
Dehydrogenase Activity	Overall intracellular oxidative/microbial activity in soil	Triphenyltetrazolium chloride (TTC) reduction assay
β-Glucosidase Activity	Carbon-cycle enzyme activity linked to cellulose/organic matter breakdown	p-Nitrophenyl-β-D-glucopyranoside (PNG) colorimetric assay
Urease & Phosphatase Activity	Nitrogen and phosphorus mineralisation potential	Colorimetric assay of released ammonium or p-nitrophenol
Soil Respiration (CO ₂ flux)	Overall microbial metabolic activity and organic matter turnover	Basal or substrate-induced respiration (CO ₂ evolution)
Earthworm Abundance & Diversity	Macrofaunal activity, bioturbation and organic matter incorporation	Hand-sorting, formalin/mustard extraction, QBS-e index
Nematode Community Structure	Trophic structure and disturbance/stress response of soil fauna	Nematode extraction and maturity/enrichment indices
Microbial Community Structure/Diversity	Composition and functional diversity of the microbial community	PLFA profiling; 16S/18S rDNA sequencing
Labile (Active) Organic C & N Pools	Readily decomposable organic matter fractions sensitive to management	Permanganate-oxidisable carbon (POXC); mineralisable N assays

5. Linking Biological Indicators to Agricultural Sustainability

The practical value of soil biological indicators lies in their ability to link day-to-day management decisions to longer-term sustainability outcomes. Figure 2 presents a simplified conceptual pathway: agricultural management

practices, such as tillage intensity, crop rotation, residue retention and organic or chemical input use, directly alter soil biological indicators; these indicators, in turn, govern key soil functions including nutrient cycling, organic matter transformation and the maintenance of soil structure; and these functions ultimately determine broader agricultural sustainability outcomes such as yield stability, resource-use efficiency and long-term resilience to environmental stress.

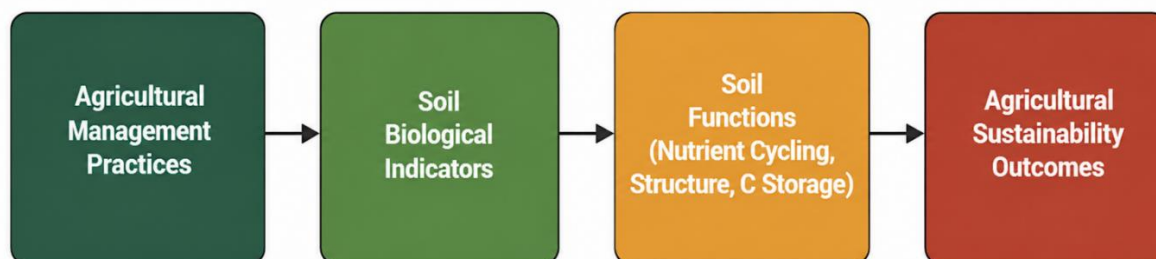


Figure 2: Conceptual pathway linking management practices, soil biological indicators, soil functions and sustainability outcomes.

This pathway framework underlines why soil biological parameters, although still underrepresented in routine soil quality monitoring compared with chemical and physical measurements, are considered valuable indicators of sustainable soil management strategies.

6. Response of Biological Indicators to Farming Management Systems

A substantial body of research has compared how soil biological indicators respond to different farming management systems, most commonly organic, low-input and conventional systems. A comparative study of microbial biomass and enzyme activities in a vegetable field growing celery under these three management systems found that soil microbial biomass in the organic farming system was significantly higher than in either the conventional or low-input systems, and concluded that long-term application of organic fertilisers plays a major role in maintaining higher microbial and enzymatic activity and, consequently, improved soil quality.

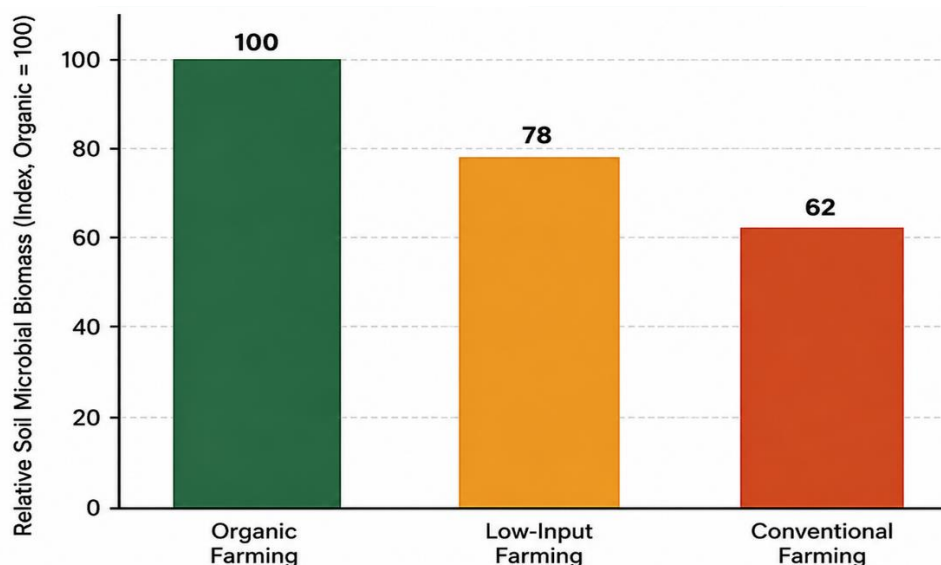


Figure 3: Illustrative pattern of relative soil microbial biomass under organic, low-input and conventional farming management, based on comparative trends reported in the literature

Table 2 summarises the general direction of response of several key biological indicators across these three broad management categories, drawing on the pattern reported in comparative farming-system studies.

Table 2: General Response of Key Biological Indicators Across Farming Management Systems

Biological Indicator	Organic Farming	Low-Input Farming	Conventional Farming
Microbial Biomass C	Highest	Intermediate	Lowest
β -Glucosidase Activity	Highest	Intermediate	Lowest
Earthworm Abundance	High (favoured by residue return, no/low pesticide use)	Moderate	Low (reduced by tillage and agrochemical inputs)
Soil Respiration	High (greater substrate availability)	Moderate	Lower to variable
Microbial Diversity (PLFA/DNA-based)	Generally higher	Intermediate	Generally lower, more disturbance-sensitive taxa lost

7. Monitoring Frameworks and Applications

Several structured frameworks have been developed to translate biological indicators into practical monitoring tools. The Soil Biological Quality Index based on earthworms (QBS-e) was developed specifically to provide a standardised way of using earthworm communities as bioindicators in agroecosystems, reflecting the long-standing recognition of earthworms as one of the most frequently used indicators of soil fertility and sustainable soil use (Soil Biological Quality Index based on earthworms, ScienceDirect, 2018). At a national scale, earthworm population monitoring programmes have been established in several European countries, with assessment networks covering around 800 sites in Germany and 300 sites in the Netherlands, illustrating how a single faunal indicator group can be scaled up into a routine, large-area sustainability monitoring system (Earthworms as Bioindicators of Soil Quality, Academia, citing Joschko et al., 2006 and Krück et al., 2006). More broadly, meta-analyses of soil microbial indicators recommend integrating measures of active soil organic matter, microbial biomass, PLFA profiles and enzyme activities into routine laboratory testing to better support the transition toward sustainable management of arable farming systems (Which soil microbial indicators, ScienceDirect, 2024).

8. Challenges in Using Soil Biological Indicators

Despite their sensitivity and diagnostic value, several practical challenges constrain the wider adoption of soil biological indicators in routine agricultural sustainability monitoring.

- I. High spatial and temporal variability of biological properties, driven by season, soil moisture and temperature, which complicates the interpretation of single-point measurements.
- II. Lack of standardised protocols and universally accepted threshold or reference values for many biological indicators, unlike well-established chemical benchmarks.
- III. Limited taxonomic and technical expertise, particularly for faunal indicators such as earthworms and nematodes, restricting their routine use as soil health indicators (Environmental DNA study, bioRxiv, 2023).
- IV. Relatively high cost and turnaround time for molecular and biochemical assays compared with conventional soil chemical tests, limiting uptake among smallholder farmers and extension systems.
- V. Biological indicators are still underrepresented in routine soil quality monitoring relative to chemical and physical measurements, despite their demonstrated sensitivity (Soil microbial biomass and enzyme kinetics, ScienceDirect, 2021).

9. Way Forward

Strengthening the use of soil biological indicators in sustainability monitoring requires a combination of technical and institutional measures. Developing simplified, low-cost field kits for key indicators such as dehydrogenase activity, basal respiration and earthworm counts would make biological monitoring more accessible to farmers and extension agencies. Establishing regional reference or baseline values for key indicators, stratified by soil type and climate, would help convert raw measurements into meaningful sustainability assessments. Encouraging the use of a minimum data set that combines a small number of the most sensitive and cost-effective biological indicators, alongside conventional physical and chemical measurements, would allow biological information to be incorporated into routine soil testing without excessive additional cost. Finally, expanding national and

regional monitoring networks modelled on established earthworm-monitoring programmes, and integrating emerging molecular tools such as environmental DNA analysis, can help scale biological indicators from research plots to operational, farm-level sustainability assessment.

10. Conclusion

Soil biological indicators, including microbial biomass, enzyme activities, respiration, soil fauna and microbial community diversity, provide a sensitive and functionally meaningful window into the health of agricultural soils that physical and chemical measurements alone cannot capture. Because these indicators respond rapidly to changes in tillage, crop rotation, residue management and input use, they offer an early warning system for degradation and a means of tracking real progress toward more sustainable farming systems. Evidence from comparative farming-system studies consistently shows that organic and reduced-input management tends to support higher microbial biomass, enzyme activity and earthworm abundance than intensive conventional management, reinforcing the practical relevance of these indicators for guiding management decisions. Realising the full potential of soil biological indicators for monitoring agricultural sustainability will require continued investment in standardised methods, reference values, and accessible monitoring tools, so that the living component of soil is given the same weight as its physical and chemical properties in assessing and safeguarding long-term agricultural productivity.

References

- Bhaduri, D., et al. (2022). A Review on Effective Soil Health Bio-Indicators for Ecosystem Restoration and Sustainability. *Frontiers*, PubMed Central (PMC9428492).
- Doran, J. W., & Zeiss, M. R. (2000). Soil Health and Sustainability: Managing the Biotic Component of Soil Quality. *Applied Soil Ecology*, 15, 3–11.
- Earthworm: A Keystone Species of Soil Quality, Health and Functions. (2025). ScienceDirect.
- Earthworm Contributions to Agricultural Sustainability. (2024). In *Biology and Ecology of Earthworms*, SpringerLink.
- Earthworms as Bioindicators of Soil Quality. Fründ, H. C., Graefe, U., & Tischer, S. In *Biology of Earthworms, Soil Biology*, Vol. 24. Springer; and ResearchGate/Academia versions.
- Environmental DNA Is More Effective Than Hand Sorting in Evaluating Earthworm Biodiversity Recovery Under Regenerative Agriculture. (2023). bioRxiv preprint.
- Role of Soil Microbiota Enzymes in Soil Health and Activity Changes Depending on Climate Change and the Type of Soil Ecosystem. PubMed Central (PMC10886310).
- Sainju, U. M., et al. (2022). Enzyme Activities as Soil Health Indicators in Relation to Soil Characteristics and Crop Production. *Agroecosystems, Geosciences & Environment*, Wiley Online Library.
- Soil Biological Quality Index Based on Earthworms (QBS-e): A New Way to Use Earthworms as Bioindicators in Agroecosystems. (2018). ScienceDirect.
- Soil Microbial Biomass and Enzyme Kinetics for the Assessment of Temporal Diversification in Agroecosystems. (2021). ScienceDirect.
- Soil Temperature, Microbial Biomass and Enzyme Activity Are the Critical Factors Affecting Soil Respiration in Different Soil Layers in Ziuling Mountains, China. PubMed Central (PMC9978110).
- Effect of Different Agricultural Farming Practices on Microbial Biomass and Enzyme Activities of Celery Growing Field Soil. PubMed Central (PMC8657710).
- Soil Quality Indicators: Soil Enzymes. USDA Natural Resources Conservation Service (NRCS).
- Which Soil Microbial Indicators Should Be Included in Routine Laboratory Tests to Support the Transition to Sustainable Management of Arable Farming Systems? A Meta-Analysis. (2024). ScienceDirect.

Soil Carbon Restoration as a Tool for Climate-Smart Agriculture



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Abstract

Soil organic carbon is one of the most reliable indicators of soil health and plays a central role in sustaining agricultural productivity, environmental quality, and climate resilience. However, decades of intensive cultivation, excessive tillage, crop residue removal, and inadequate application of organic inputs have substantially depleted soil organic carbon in cultivated lands. In India, the organic carbon content of agricultural soils is commonly below 5 g kg⁻¹, compared with 15 to 20 g kg⁻¹ under natural vegetation. Although Indian soils store an estimated 21 petagrams of organic carbon within the upper 30 cm soil layer, a significant proportion has been lost through long term agricultural intensification. Restoring this depleted carbon is not only essential for improving soil fertility but also represents an effective strategy for climate change mitigation. Conservation practices such as reduced tillage, crop residue retention, cover cropping, organic amendments, and agroforestry have demonstrated considerable potential to enhance soil carbon sequestration while improving water retention, nutrient cycling, soil biological activity, and crop productivity. This article reviews the status of soil carbon depletion, the major agronomic approaches for restoring soil organic carbon, their effectiveness under different production systems, and the policy initiatives supporting soil carbon sequestration as a key component of climate smart and sustainable agriculture.

Keywords: Carbon sequestration, Climate resilient agriculture, Conservation agriculture, Soil health, Soil organic carbon, Sustainable land management.

1. Introduction

Soil holds more carbon than the atmosphere and global vegetation combined, making it, after the oceans, the largest active carbon reservoir on the planet's surface. This carbon, present mainly as organic matter derived from decomposed plant and microbial residues, is not a passive store. It is the substrate that feeds soil microbial life, the glue that binds soil particles into a structure resistant to erosion, and the sponge that allows soil to hold water and nutrients for crop use. When land is converted to continuous cultivation without adequate replenishment, this carbon pool declines steadily, often losing 30 to 50 per cent of its original stock within a few decades of cultivation.

This decline is not merely a historical curiosity; it defines the scale of the opportunity now in front of agriculture. Because so much carbon has already been lost from cultivated soils worldwide, those same soils retain a substantial capacity to reabsorb carbon if management is changed, a capacity that positions soil carbon restoration as one of the few climate strategies that pays for itself through improved productivity even before its climate benefit is counted. This paper examines why soil carbon restoration matters, how large the deficit is globally and in India specifically, which agronomic practices are best supported by evidence, and how soil carbon fits into the broader policy architecture of climate-smart agriculture.

2. The Global and Indian Soil Carbon Deficit

Globally, soils store an estimated 615 gigatonnes of organic carbon in the top 20 centimetres and about 2,344 gigatonnes to a depth of three metres, more than the combined carbon held in the atmosphere and in living biomass, making soil organic carbon management directly relevant to the global carbon budget. In India, the picture is similarly large in scale but sharply uneven in distribution. The country's soil organic carbon pool has been estimated at approximately 21 petagrams to a depth of 30 centimetres and 63 petagrams to 150 centimetres, alongside a soil inorganic carbon pool of about 196 petagrams to one metre depth, concentrated particularly in the calcareous soils of the semi arid and arid regions (Table 1, Figure 3). Despite this large aggregate stock, the concentration of organic carbon actually found in most cultivated Indian soils tells a more troubling story: commonly less than 5 grams per kilogram, compared with 15 to 20 grams per kilogram in adjoining uncultivated land, a gap attributable to decades of ploughing, residue removal and insufficient return of organic material to the soil (Figure 1).

Table 1. Global and Indian soil carbon pools

Indicator	Value
Global soil organic carbon, 0 to 20 cm depth	About 615 gigatonnes
Global soil organic carbon, 0 to 3 m depth	About 2,344 gigatonnes
India soil organic carbon pool, 0 to 30 cm depth	About 21 petagrams (billion tonnes)
India soil organic carbon pool, 0 to 150 cm depth	About 63 petagrams
India soil inorganic carbon pool, 0 to 100 cm depth	About 196 petagrams
Organic carbon in cultivated Indian soils	Commonly less than 5 g per kg
Organic carbon in uncultivated Indian soils	Typically 15 to 20 g per kg

Source: Batjes, 1996; Lal, 2004b; and Indian Journal of Agroforestry, ICAR.

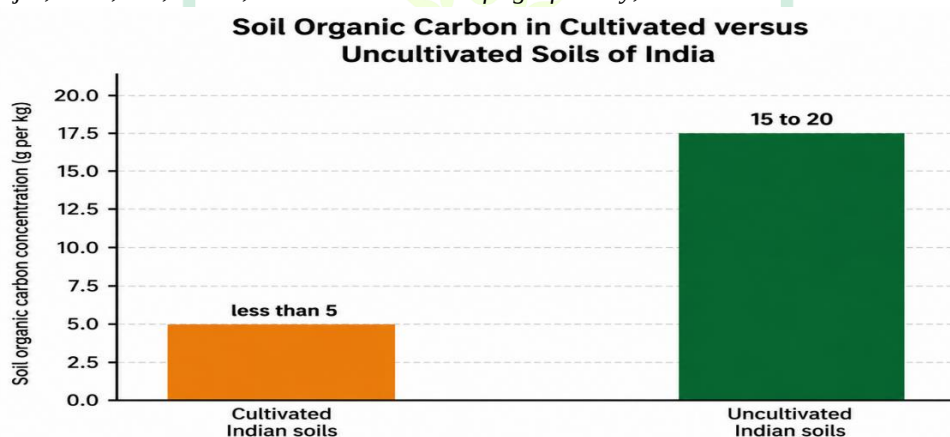


Fig. 1. Soil organic carbon in cultivated versus uncultivated soils of India

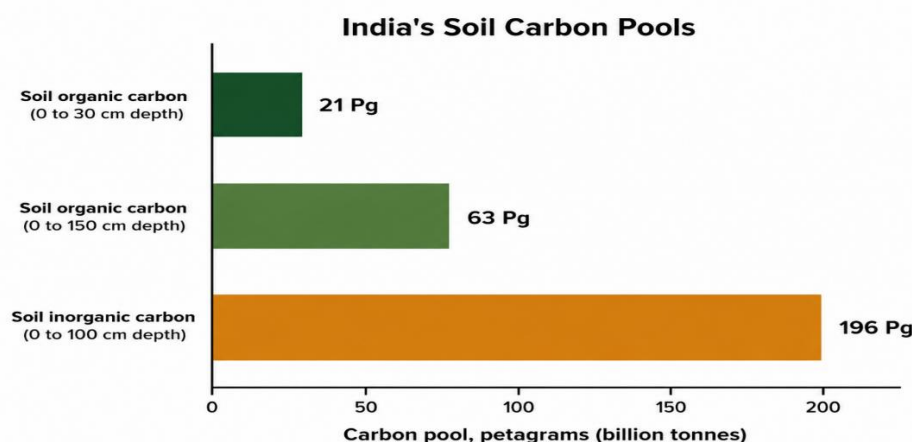


Fig. 2. India's soil organic and inorganic carbon pools by depth

3. Why Soil Carbon Matters for Climate-Smart Agriculture

The case for soil carbon restoration rests on a rare alignment of agronomic and climate interests. Agronomically, soil organic carbon underpins water holding capacity, nutrient supply and microbial activity, and its depletion is directly linked to declining yield stability, particularly under the erratic rainfall that climate change is making more common. Field assessments indicate that each additional tonne of carbon restored to the root zone of a degraded cropland soil can raise wheat yield by 20 to 40 kilograms per hectare, maize yield by 10 to 20 kilograms per hectare, and cowpea yield by 0.5 to 1 kilogram per hectare, a productivity dividend that arrives independently of any climate benefit. From a climate perspective, because agricultural and degraded soils worldwide have already lost an estimated 42 to 78 gigatonnes of carbon through historical cultivation, they retain the biophysical capacity to reabsorb 50 to 66 per cent of that loss, a sink large enough to offset an estimated 0.4 to 1.2 gigatonnes of carbon annually, or 5 to 15 per cent of global fossil fuel emissions, if restorative management were adopted widely. This dual return, higher and more stable yields alongside a genuine climate mitigation contribution, is what places soil carbon restoration at the centre of climate-smart agriculture rather than treating it as a co-benefit.

4. Practices for Restoring Soil Carbon

A relatively small set of agronomic practices, applied consistently over multiple seasons, accounts for most of the documented gains in soil organic carbon (Table 2, Figure 4). Reduced or no tillage limits the physical disturbance that exposes previously protected organic matter to microbial decomposition, slowing carbon loss even where it does not immediately raise total carbon content. Cover cropping and green manuring add fresh, readily decomposable organic material to the soil between main crop cycles, feeding the microbial biomass that ultimately stabilizes carbon into longer lived soil organic matter fractions. Retaining crop residue rather than removing or burning it returns a substantial share of the carbon a crop has already fixed back to the soil surface, where it slows erosion as well as feeding decomposition. Organic amendments, including farmyard manure, compost and biochar, directly add stabilized carbon and simultaneously improve the nutrient and microbial environment that supports further carbon accumulation. Agroforestry and the integration of trees into cropping systems add a woody biomass and deep rooting component that captures carbon at depths and over timescales that annual cropping systems cannot match on their own.

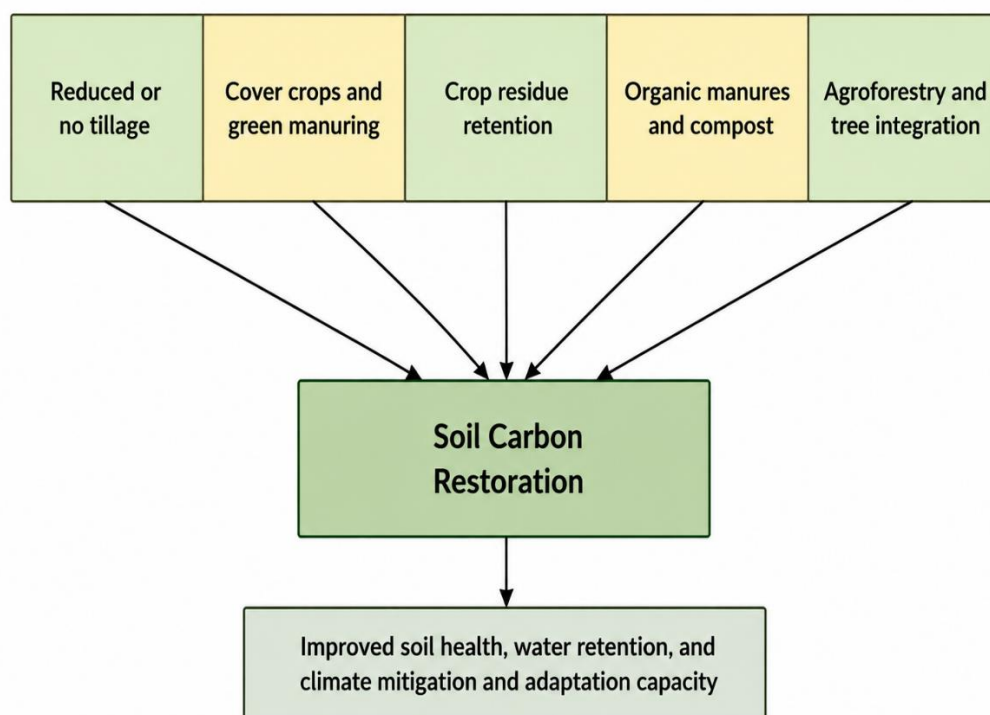


Fig. 3. Practices for restoring soil organic carbon

Table 2. Agronomic practices for soil carbon restoration

Practice	Primary mechanism	Additional benefit
Reduced or no tillage	Limits physical disturbance and exposure of protected organic matter	Reduces erosion and fuel and labour costs
Cover crops and green manuring	Adds fresh organic material and continuous root activity	Suppresses weeds; can supply biologically fixed nitrogen
Crop residue retention	Returns carbon already fixed by the crop to the soil surface	Reduces erosion and moisture loss
Organic manures, compost and biochar	Directly adds stabilized carbon and feeds microbial activity	Improves nutrient supply and soil structure
Agroforestry and tree integration	Adds deep rooted, woody biomass carbon input	Diversifies farm income and improves microclimate

Source: Compiled from Lal, 2004a; Paustian et al., 2016; and Indian Journal of Agroforestry, ICAR.

5. Field and Global Evidence of Soil Carbon Restoration

The evidence base for soil carbon restoration spans both global synthesis and India specific research. Long term experiments compiled from across cropping systems show that shifting from conventional tillage with residue removal to reduced tillage with residue retention and improved rotation consistently raises measured soil organic carbon over periods of 10 to 20 years, though the rate of gain depends strongly on climate, soil texture and the specific combination of practices adopted. In India, assessments coordinated through the National Bureau of Soil Survey and Land Use Planning and allied ICAR institutes estimate the country's overall soil carbon sequestration potential, achieved by converting degraded agricultural land to restorative management, at approximately 39 to 49 teragrams of carbon per year, a figure that reflects both the scale of past soil carbon loss and the extent of land still available for improved management. These India specific findings sit within a global framework formalized by the 4 per mille Soils for Food Security and Climate initiative, launched at the twenty first Conference of the Parties in Paris in 2015, which set out an aspiration to increase global soil carbon stocks by 0.4 per cent annually as a partial offset to anthropogenic greenhouse gas emissions, framing soil carbon restoration explicitly as a shared climate commitment rather than a purely local agronomic choice.

6. Climate-Smart Agriculture: Linking Soil Carbon to Mitigation and Adaptation

Agriculture and associated land use change contribute close to a quarter of global anthropogenic greenhouse gas emissions, with direct agricultural production, mainly through soil and livestock emissions, accounting for 10 to 14 per cent of the total, and soils specifically responsible for a substantial share of this, chiefly as nitrous oxide and methane. Improved soil carbon management addresses this problem from two directions simultaneously. As a mitigation measure, it draws atmospheric carbon dioxide into stable soil organic matter, functioning as a genuine, verifiable sink when implemented and monitored consistently. As an adaptation measure, the same restored organic matter improves the water holding capacity and structural resilience of soil, buffering crops against the more erratic and extreme rainfall patterns that climate change is bringing to many agricultural regions. This combination of mitigation and adaptation benefit, delivered through the same set of practices, is precisely what distinguishes climate-smart agriculture from conventional productivity focused farming, and soil carbon sits at the centre of that combination rather than at its periphery (Figure 5).

7. Policy Frameworks and Institutional Support

Soil carbon restoration is increasingly embedded in formal policy architecture rather than left to individual farm decisions alone. The 4 per mille initiative, though framed more as an aspirational concept than a rigid national target, has drawn nearly 150 signatories, including countries, regions, research institutions and private sector bodies, and has helped position soil carbon within international climate negotiations. In India, coordinated research programmes under the Indian Council of Agricultural Research, including long term experiments maintained by the National Bureau of Soil Survey and Land Use Planning and the Indian Institute of Soil Science, continue to generate the region specific data on soil carbon change that national planning and, increasingly, voluntary carbon market frameworks in the agriculture sector depend on. The 2017 Global Symposium on Soil Organic Carbon, convened by the Food and Agriculture Organization in Rome, further consolidated the technical case for treating soil organic carbon monitoring and restoration as core components of both food security and

climate strategy, recommendations that continue to shape how national soil programmes, India's included, prioritize their research and extension effort.

Soil Carbon as the Hub of Climate-Smart Agriculture

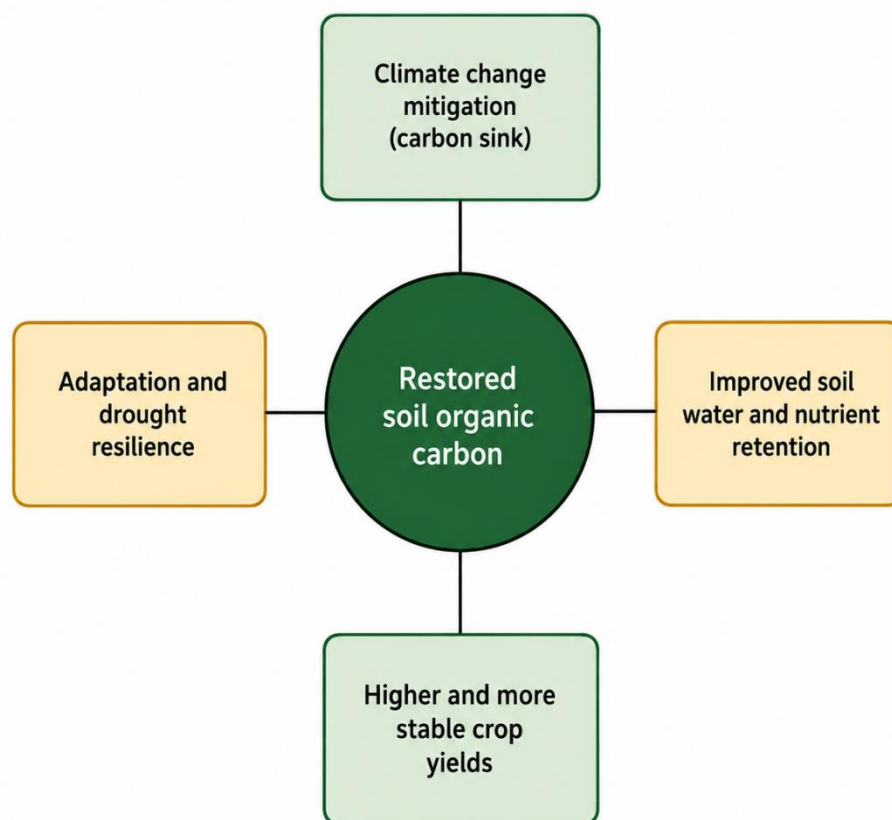


Fig. 4. Soil carbon as the hub of climate-smart agriculture outcomes

8. Practical Recommendations

Farmers and extension programmes seeking to rebuild soil carbon should treat it as a multi season commitment rather than a single input decision. Reducing tillage intensity and retaining crop residue wherever feasible are the lowest cost starting points and can be adopted without major investment. Where residue is needed for fodder or other uses, substituting a portion with farmyard manure, compost or a green manure crop preserves much of the same carbon benefit. Cover cropping in the gap between main cropping seasons, even for a short duration, adds carbon input at a time when the soil would otherwise lie bare and exposed to erosion. Where land use planning allows, integrating trees into field boundaries or as part of an agroforestry system adds a carbon accumulation pathway that annual cropping alone cannot achieve. Above all, soil testing for organic carbon should become as routine a practice as testing for nitrogen, phosphorus and potassium, since a farm cannot manage what it does not measure, and repeated testing over several years is the only reliable way to confirm that a given combination of practices is actually rebuilding carbon rather than merely slowing its loss.

9. Conclusion

Soil carbon restoration occupies an unusually favourable position among climate strategies: it is grounded in agronomic practices that farmers already understand, it delivers a productivity benefit that justifies adoption even without reference to climate policy, and it draws down atmospheric carbon dioxide as a genuine side effect of better farming rather than as a separate, costly intervention. The scale of the opportunity, in India and globally, is large precisely because the scale of past loss has been large, and the practices needed to reverse that loss, reduced tillage, cover cropping, residue retention, organic amendment and agroforestry, are neither exotic nor unproven.

What remains is the harder task of consistent, multi season adoption at scale, supported by routine soil carbon monitoring and by policy frameworks, from the 4 per mille initiative to India's own research and extension programmes, that keep soil carbon restoration positioned where it belongs, as a foundation of climate-smart agriculture rather than an afterthought to it.

References

- Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, 47(2), 151-163.
- Bhattacharyya, T., Chandran, P., Ray, S.K. et al. 2014. Carbon sequestration in Indian soils: present status and the potential. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*.
- Bhattacharyya, T., Chandran, P., Ray, S.K. et al. 2014. Processes determining the sequestration and maintenance of carbon in soils, a synthesis of research from tropical India. *Soil Horizons*.
- Food and Agriculture Organization of the United Nations. 2017. *Soil Organic Carbon: The Hidden Potential*. FAO, Rome.
- Indian Journal of Agroforestry. Carbon sequestration in agricultural soils, issues and strategies. ICAR, New Delhi.
- Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623-1627.
- Lal, R. 2004. Soil carbon sequestration in India. *Climatic Change*, 65, 277-296.
- Minasny, B., Malone, B.P., McBratney, A.B. et al. 2017. Soil carbon 4 per mille. *Geoderma*, 292, 59-86.
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P. and Smith, P. 2016. Climate-smart soils. *Nature*, 532(7597), 49-57.
- Velayutham, M., Pal, D.K. and Bhattacharyya, T. 2000. Organic carbon stock in soils of India. In Lal, R., Kimble, J.M. and Stewart, B.A. (eds), *Global Climate Change and Tropical Ecosystems*. CRC/Lewis Publishers, Boca Raton, pp. 71-97.
- West, T.O. and Post, W.M. 2002. Soil organic carbon sequestration rates by tillage and crop rotation. *Soil Science Society of America Journal*, 66(6), 1930-1946.
- Minasny, B., Arrouays, D., McBratney, A.B. et al. 2018. Rejoinder to comments on Minasny et al., 2017, soil carbon 4 per mille. *Geoderma*, 309, 124-129.

Value Addition and Processing of Fruits and Vegetables for Better Income



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Abstract

Fruits and vegetables constitute one of the most valuable sectors of Indian agriculture, playing a vital role in improving nutrition, ensuring food and nutritional security, and enhancing farmers' income. However, their highly perishable nature leads to considerable post-harvest losses, reducing both economic returns and food availability. Value addition and processing offer effective solutions to minimize these losses by extending shelf life, improving product quality, diversifying market opportunities, and generating higher returns for farmers, processors, and rural entrepreneurs. Activities such as grading, sorting, packaging, drying, canning, juicing, fermentation, freezing, and by product utilization not only reduce wastage but also increase the commercial value of horticultural produce. This article discusses the concept, importance, and scope of value addition and processing in fruits and vegetables, highlights major processing technologies and government initiatives, and examines the key challenges and opportunities for developing a competitive, sustainable, and market oriented horticultural processing sector that supports rural employment and income generation.

Keywords: Food processing, Horticultural crops, Post harvest management, Rural entrepreneurship, Shelf-life extension, Value addition.

1. Introduction

Horticulture, comprising fruits and vegetables, occupies a central place in agricultural economies worldwide. Fruit and vegetable production is central to the livelihoods of a very large number of small-scale farmers, and processed forms of these commodities are important for farmers' livelihoods, income, trade, food security and nutrition (FAO, 2021a). Globally, more than half of all fruit and vegetables are grown on farms smaller than 20 hectares, and in developing countries such farms account for the vast majority of horticultural output, making the sector especially significant for smallholder income (FAO, 2021b). India, for instance, is the second largest producer of fruits and vegetables in the world, yet the country converts only a small fraction of this produce into processed goods, in sharp contrast to high-income countries where nearly all agricultural produce undergoes industrial processing (Value Addition and Processing, n.d.).

Because fruits and vegetables are biologically perishable, they begin to deteriorate soon after harvest due to respiration, moisture loss, microbial attack and mechanical injury. Where cold storage, transport and processing infrastructure are inadequate, large volumes of produce are lost before they reach the consumer, and the income that farmers might otherwise have earned is lost with them. Value addition and processing address this problem directly: by converting fresh, perishable produce into more stable, higher-value products, farmers and small entrepreneurs can capture a larger share of the final consumer price, smooth out seasonal price fluctuations, and open access to new domestic and export markets. This article discusses the importance of value addition, the extent of post-harvest losses that make it necessary, the principal methods of processing, the resulting economic benefits, relevant government support programmes, and the challenges that must be overcome for the sector to realise its full potential.

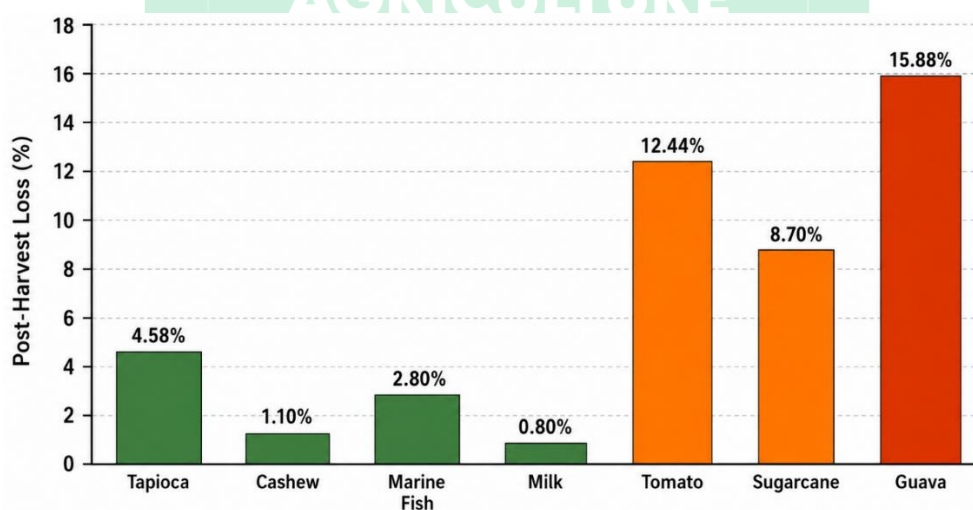
2. Importance of Fruits and Vegetables in the Rural Economy

Fruit and vegetable cultivation is far more labour- and income-intensive per unit of land than most cereal crops, which makes it an important driver of rural employment and household income. Family farmers, who are often small-scale producers, account for roughly 80 percent of the world's food in value terms and a large share of global fruit and vegetable output (FAO, 2021b). In several countries, horticultural crops have become the second most important income-earning commodity group after staple grains, and in specific value chains such as avocado in Mexico or banana in Guatemala, small-scale farmers dominate production and derive a substantial share of household income from these crops (FAO, 2021b). This underlines why any strategy to raise farm income must pay close attention to how fruits and vegetables are handled, marketed and processed after harvest.

Value addition in this context is not limited to full industrial processing. It also includes basic activities such as sorting, grading, cleaning, packaging, cooling and transport, all of which are performed by a wide range of actors from micro-enterprises to large companies, and all of which raise the price a farmer or trader can command for the same physical quantity of produce (Markets and Value Chains, FAO). Even relatively simple, low-cost interventions at the farm or village level can therefore translate into a meaningful improvement in net income for producers.

3. Post-Harvest Losses: The Scale of the Problem

The urgency of value addition becomes clear when the scale of post-harvest losses is examined. A study by the Central Institute of Post-Harvest Engineering and Technology (ICAR-CIPHET), commissioned by India's Ministry of Food Processing Industries and published in 2015, assessed losses across 45 major crops and estimated the annual economic value of these losses at about Rs 92,651 crore, of which fruits accounted for roughly Rs 16,644 crore and vegetables for about Rs 14,842 crore (Post Harvest Food Loss, PIB; India: Post Harvest Loss of Fruits and Vegetables). The same study found that losses in vegetables ranged from about 4.6 percent in tapioca to over 12 percent in tomato, while losses in fruits ranged even higher, reaching close to 16 percent in commodities such as guava, with harvesting, sorting and grading, transportation and storage at the wholesale and retail level identified as the principal points of loss (Jha et al., 2015; Storage woes, farmers grapple with post-harvest loss, The Tribune, 2024).



Source: Jha et al., 2015 (ICAR-CIPHET); Post Harvest Food Loss, PIB

Figure 1: Post-Harvest Losses Across Select Commodities in India

A more recent nationwide survey conducted by NABARD Consultancy Services (NABCONS) in 2022 estimated total food loss in India at over 7,400 million metric tonnes with an economic value of roughly Rs 1,527,871 million, with horticultural produce—fruits, vegetables, plantation crops and spices—alone accounting for close to 50 million metric tonnes of loss annually, driven largely by inadequate cold-chain infrastructure (National Economic Forum, 2025). Globally, the picture is similarly stark: in developing regions, post-harvest losses can reduce incomes by at least 15 percent for an estimated 470 million smallholder farmers and other value-

chain participants, and in parts of Sub-Saharan Africa nearly 45 percent of fruits and vegetables are discarded before reaching the consumer (Study protocol, PMC, 2025). These figures demonstrate that the absence of adequate processing and value-addition capacity is not a marginal inefficiency but a major economic and nutritional loss that directly depresses farm income.

4. Concept and Scope of Value Addition

Value addition refers to any process that increases the economic worth, utility, shelf life or market appeal of a raw agricultural commodity. For fruits and vegetables, this spans a continuum from minimal processing—cleaning, sorting, grading, trimming and packaging fresh produce—to full processing, which includes juicing, canning, dehydration, freezing, fermentation and pickling (Fruit and Vegetables: Essential for Healthy Lives, FAO). Minimal processing retains most of the inherent freshness and nutritional properties of the produce while improving its presentation and marketability, whereas full processing converts the produce into an entirely different, shelf-stable product form.

Value-added processing can occur at different points in the supply chain and by different types of actors: individual farmers processing their own surplus produce into pickles or jams for local sale; farmer producer organisations (FPOs) or self-help groups (SHGs) running shared processing units; and larger food companies operating industrial-scale canning or juice plants. Regardless of scale, the underlying economic logic is the same processing allows the same physical unit of raw produce to be sold at a higher price, for a longer period, and often to a wider market, than would be possible in its raw, perishable state.



Figure 2: The Value Chain of Fruits and Vegetables

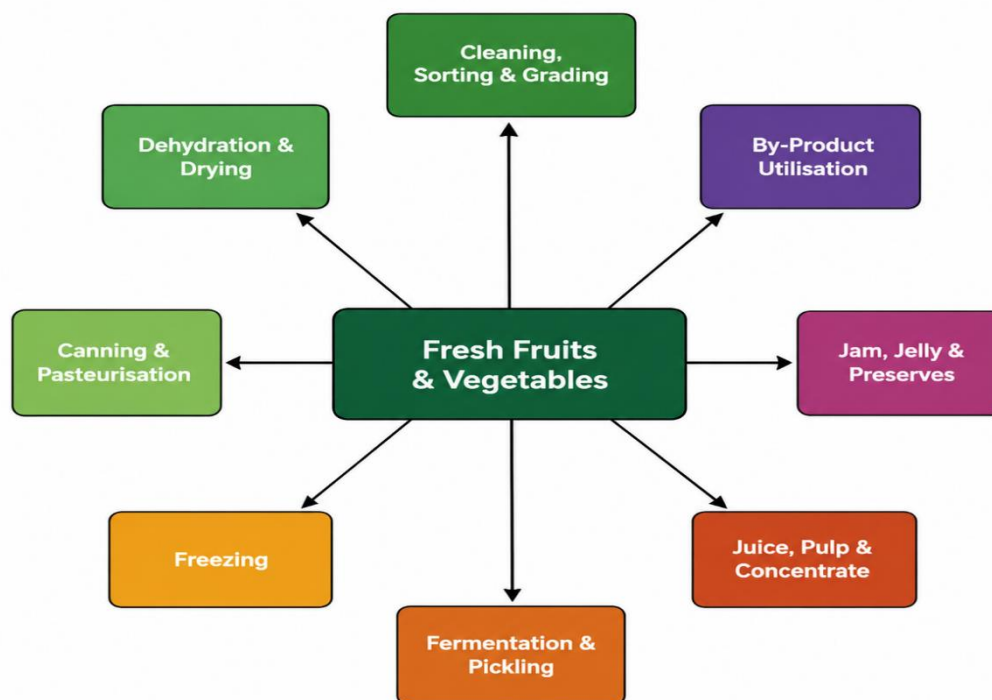


Figure 3: Principles Methods of Value Addition and Processing

5. Key Methods and Technologies of Processing

5.1 Cleaning, Sorting, Grading and Packaging

The most basic and least capital-intensive form of value addition involves cleaning, sorting by size or quality, grading and appropriate packaging. Even without any chemical or thermal treatment, these steps can substantially raise the price realised by a farmer, because uniform, well-presented produce commands a premium in organised retail and export markets.

5.2 Dehydration and Drying

Drying is one of the oldest and most widely used preservation methods. Removing moisture inhibits microbial growth and enzymatic spoilage, allowing dried fruits, vegetable flakes and powders to be stored for extended periods without refrigeration. The FAO notes that mechanical and solar dryers help bring harvested produce to safe moisture levels, and dried products such as sun-dried fruits and dehydrated vegetable powders last significantly longer than their fresh counterparts, while also being lightweight and easy to transport.

5.3 Thermal Processing: Canning and Pasteurisation

Thermal processing techniques such as canning, bottling and pasteurisation use controlled heat treatment with hermetic packaging to destroy spoilage organisms and extend shelf life to a year or more. Canned or bottled products such as canned tomatoes, mango pulp or mixed vegetable preserves allow glut-season produce to be sold gradually, smoothing out the sharp seasonal price swings that otherwise erode farmer income.

5.4 Freezing

Freezing preserves nutritional quality, colour and texture better than most other methods and is widely used for peas, corn, mixed vegetables and berries. Its main constraint is the need for continuous cold-chain infrastructure from the processing unit to the retail point, which remains inadequate in many developing regions.

5.5 Fermentation and Pickling

Fermentation and pickling use salt, acid, sugar or beneficial microorganisms to preserve produce while creating distinctive flavours. Traditional pickles, sauerkraut-type ferments and fruit-based chutneys are especially suited to small-scale, low-investment production and have strong domestic demand, making them attractive entry points for micro and household-level enterprises.

5.6 Juice, Pulp and Concentrate Production

Juicing and pulping convert fruit into beverages, concentrates and purees that can be sold fresh, chilled, frozen or shelf-stable, and are often blended into other food products. Full processing of this kind, including juicing and canning in brine, juice or syrup, is recognised as an important route to increasing the shelf life, year-round availability and overall value of fruit and vegetable produce.

5.7 Jam, Jelly and Preserves

Cooking fruit with sugar and, where required, pectin and acid produces jams, jellies, marmalades and fruit preserves. These products are popular, have long shelf lives at ambient temperature, and require relatively modest equipment, making them one of the most common first products for small food-processing entrepreneurs and self-help groups.

5.8 By-Product and Residue Utilisation

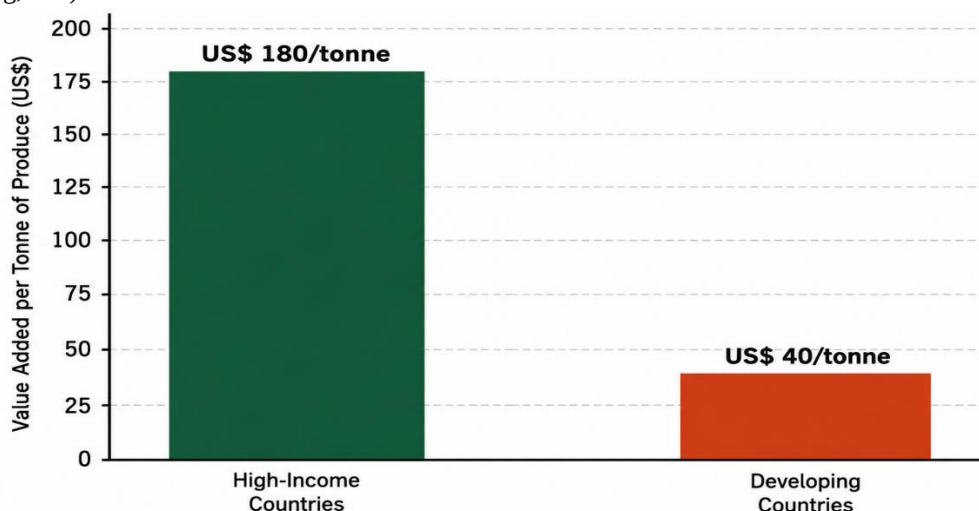
Processing generates substantial peels, seeds and pomace that are often discarded, representing both an economic loss and environmental burden; under-utilised residues and by-products lead to a loss of income and sustainability concerns (Value Addition and Processing, n.d.). Extracting pectin from citrus peel, producing animal feed or compost, and recovering natural colourants from fruit residues are examples of how by-product utilisation can generate extra revenue and reduce waste.

6. Economic Benefits and Income Generation

The income-generating potential of value addition is well documented. Analyses of value-added agricultural enterprises in the United States show that when a farmer processes raw produce for example, turning vegetables into salsa rather than selling it wholesale, labour income for the entrepreneur can roughly double, and the wider economic benefit to the surrounding community can triple, because processing retains more of the value chain, and its associated wages and profits, within the local economy (Dudensing, Texas A&M AgriLife). The same analysis notes that while value-added processing is not equally suited to every farm, it presents a promising

opportunity particularly for smaller producers seeking to differentiate their products and capture a larger share of the retail price.

At the macro level, the contrast between processing rates in high-income and developing countries illustrates the scale of the missed opportunity: high-income countries add roughly US\$180 of value to every tonne of agricultural produce and process nearly all of it industrially, whereas developing countries process only about 30 percent of their output and add an average of only about US\$40 of value per tonne (Value Addition and Processing, n.d.).



Source: Value Addition and Processing of Agri-Products (presentation data)

Figure 4: Value Added per Tonne of Agriculture Produce

Beyond direct income to primary producers, processing creates employment along the value chain in harvesting and sorting, in processing units, in packaging and quality control, and in transport, marketing and retail much of which is generated in rural and semi-urban areas where alternative employment opportunities are limited. It also allows farmers and farmer collectives to move away from complete dependence on volatile fresh-produce prices, since processed products can be stored and sold when prices are most favourable, reducing distress sales that typically occur during harvest gluts.

7. Government Policy and Institutional Support in India

Recognising the income potential of food processing, the Government of India has introduced targeted policy support. The Pradhan Mantri Formalisation of Micro Food Processing Enterprises (PMFME) Scheme, launched on 29 June 2020 as part of the Atmanirbhar Bharat Abhiyan, is a centrally sponsored scheme with an outlay of about Rs 10,000 crore aimed at supporting roughly two lakh unorganised micro food-processing enterprises across the country, with a particular emphasis on the One District One Product (ODOP) approach that prioritises perishable produce such as fruits, vegetables and spices (PIB, 2025; Make in India, PMFME). Under the scheme, financial, technical and business support is extended to individual entrepreneurs, farmer producer organisations, self-help groups and producer cooperatives for upgrading equipment, improving packaging and branding, and strengthening common infrastructure such as sorting, grading and cold storage facilities.

Documented case studies illustrate the real-world impact of such support: a micro food-processing unit in Ernakulam, Kerala, that began with a single traditional snack product received a loan of over Rs 3 lakh under the PMFME Scheme in 2021, which enabled the purchase of new machinery, doubled production, and increased daily profits from about Rs 12,000 to nearly Rs 20,000, with annual turnover crossing Rs 32 lakh in 2021–22 (PIB, 2025). More broadly, the Ministry of Food Processing Industries has also commissioned periodic national assessments of post-harvest losses—through ICAR-CIPHET in 2015 and NABCONS in 2022—specifically to guide investment in processing infrastructure and reduce the wastage that erodes farmer income (Post Harvest Food Loss, PIB).

8. Challenges Facing Value Addition and Processing

Despite this potential, several structural challenges constrain growth in this sector:

- i. Inadequate cold-chain and storage infrastructure, which limits the ability to hold perishable produce long enough for processing or for prices to improve, and contributes directly to high storage-stage losses (National Economic Forum, 2025).
- ii. Fragmented and unorganised supply chains that leave a large gap between farm-gate prices and final consumer prices, with limited price transmission back to primary producers (Value Addition and Processing, n.d.).
- iii. Limited access to affordable credit, appropriate processing technology and quality-testing facilities, particularly for micro and small enterprises and individual farmers.
- iv. Low awareness and technical skill among farmers and rural entrepreneurs regarding food-safety standards, hygienic processing practices and packaging requirements needed to access organised retail and export markets.
- v. Heavy reliance on road transport with around 97 percent of fruits and vegetables in India moved by road which is less efficient and more loss-prone than rail-based cold-chain logistics (Post Harvest Loss in India, pmfias.com, 2024).
- vi. Seasonal and locational mismatches between where produce is grown and where processing capacity exists, increasing transport costs and spoilage risk.

9. Conclusion

Fruits and vegetables represent one of the most economically significant yet most vulnerable segments of agriculture, given their high perishability and the substantial post-harvest losses documented across both Indian and global studies. Value addition and processing—ranging from simple grading and packaging to drying, canning, freezing, fermentation, juicing and by-product recovery—offer a practical and proven means of converting this vulnerability into opportunity. By extending shelf life, smoothing seasonal price volatility, opening new markets and retaining a larger share of value within farming communities, processing can meaningfully raise the income of farmers, farmer collectives and rural entrepreneurs. Realising this potential at scale, however, requires sustained investment in cold-chain and processing infrastructure, wider access to credit and technology, stronger skill development, and continued policy support of the kind offered through schemes such as PMFME. With these elements in place, the fruit and vegetable processing sector can become a durable engine of rural income growth, employment generation and food-loss reduction.

References

- Dudensing, R. Value-Added Ag and Food Products. Southern Ag Today / Texas A&M AgriLife Extension. Retrieved from <https://sat-wp.afpc.tamu.edu/>
- Food and Agriculture Organization of the United Nations (FAO). (2021a). Fruit and Vegetables: Essential for Healthy Lives. International Year of Fruits and Vegetables 2021 Background Paper. Rome: FAO.
- Food and Agriculture Organization of the United Nations (FAO). (2021b). Growing Green: Sustainable Production. International Year of Fruits and Vegetables 2021 Background Paper. Rome: FAO.
- Food and Agriculture Organization of the United Nations (FAO). Markets and Value Chains. International Year of Fruits and Vegetables 2021 Background Paper. Rome: FAO.
- Food and Agriculture Organization of the United Nations (FAO) & World Health Organization (WHO). (2021). Promoting Sustainable and Inclusive Value Chains for Fruits and Vegetables – Policy Review. Background paper for the FAO/WHO International Workshop on Fruits and Vegetables 2020. Rome: FAO.
- Jha, S. N., et al. (2015). Assessment of Quantitative Harvest and Post-Harvest Losses of Major Crops/Commodities in India. ICAR-Central Institute of Post-Harvest Engineering and Technology (CIPHET), Ludhiana.
- Make in India / Invest India. PM Formalization of Micro Food Processing Enterprises (PMFME) Scheme. Retrieved from <https://www.makeinindia.com/>
- National Economic Forum. (2025). Addressing Post-Harvest Losses in India: A Silent Crisis in Agriculture. Press Information Bureau (PIB), Government of India. Post Harvest Food Loss.

Press Information Bureau (PIB), Government of India. (2025). PM Formalisation of Micro Food Processing Enterprises (PMFME) Scheme launched under the Atmanirbhar Bharat Abhiyan with an outlay of Rs 10,000 crore, supporting 2 lakh micro food processing enterprises following the One District One Product (ODOP) approach.

Study Protocol: Post-Harvest Losses of Fruits and Vegetables and their Relationship with the Nutritional Status of Women and Children. (2025). PubMed Central (PMC), National Institutes of Health.

Sharma, R. R., et al. (2024). A Review of the Economic Impact of Value Addition and Food Processing on Farmers' Income: An Extension Perspective. ResearchGate.

The Tribune. (2024). Storage Woes, Farmers Grapple with Post-Harvest Loss.

Value Addition in Post-Harvest Management: Enhancing Shelf Life and Marketability. Agriculture Notes, Agriculture.Institute.

World Resources Institute (WRI) India. (2021). Food Loss and Waste in India.



Weather Abnormalities in Rajasthan: Challenges, Impacts, and Climate Resilient Agricultural Practices



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Highlight of the Article

Rajasthan, which encompasses nearly two thirds of India's hot arid region, is witnessing a rapid shift in its climatic patterns. Weather events that were once considered exceptional are becoming increasingly frequent and unpredictable. The 2025 monsoon was the sixth wettest in 125 years across western Rajasthan, while pre-monsoon rainfall in June 2026 exceeded the long-term average by more than 150 per cent. In contrast, the state also recorded its highest ever temperature of 50.5 °C at Churu in 2024 and experienced repeated hailstorms during early 2026 that caused extensive damage to standing rabi crops. These contrasting extremes highlight the growing vulnerability of Rajasthan's agriculture to climate variability. This article examines recent changes in rainfall and temperature patterns, their implications for soil health, crop productivity, and farmer livelihoods, and discusses climate resilient technologies, rainwater harvesting interventions, drought and heat tolerant crop varieties, and agroforestry systems promoted by ICAR, particularly the ICAR Central Arid Zone Research Institute, Jodhpur, to strengthen the adaptive capacity of farming systems in the state's arid and semi-arid regions.

Keywords: Agroforestry, Climate resilience, Desertification, Extreme weather events, Heat waves, Rainwater harvesting.

Introduction

Rajasthan has always been a land of climatic extremes, its farmers accustomed to scanty and undependable rainfall, scorching summers and cold, dry winters. What has changed in recent years is not the presence of extremes but their unpredictability and severity. A location that recorded barely seven and a half millimetres of rain as its normal for early June received more than nineteen millimetres in the same period in 2026, a departure of over 150 per cent even before the formal onset of the southwest monsoon. In the two preceding years, farmers in Bikaner and neighbouring districts watched hailstones the size of lemons flatten standing wheat and mustard just days before harvest, while in 2024 the thermometer at Churu touched 50.5 degrees Celsius, among the highest temperatures ever recorded in the country. These are not isolated events but part of a broader pattern in which a historically dry state is swinging between prolonged dry spells and sudden, intense wet periods, a whiplash proving far more damaging to standing crops and soil than either extreme on its own. This article traces the recent record of weather abnormalities in Rajasthan, examines what they mean for the state's agriculture and land resources, and outlines the climate resilient practices that research institutions, led by ICAR CAZRI at Jodhpur, have developed to help farmers manage this uncertainty.

A Desert State Turning Wetter and More Erratic

Historically, Rajasthan's agriculture has been built around scarcity, with average annual rainfall ranging from under 250 millimetres in the western districts bordering the Thar Desert to around 600 to 700 millimetres in the more humid south east. That pattern has become far less predictable over the past two monsoon seasons. The 2025 monsoon delivered rainfall well above the long term average in every one of its four months, with June recording 133 per cent of normal, July 78 per cent, August 118 per cent and September as much as 182 per cent (Table 1, Figure 1). Western Rajasthan, including large tracts of the Thar Desert, received 69 per cent excess rainfall for the season overall, making it the sixth wettest monsoon in 125 years of record, and by early June 2026

the state was already running 154 per cent above normal for the season, with eastern districts at 207 per cent, even before the monsoon had formally arrived.

For a state whose entire cropping calendar, from sowing dates to variety selection, has been calibrated around dependable scarcity, such a swing toward abundance is not necessarily good news. Sudden, concentrated rainfall on soils that are naturally low in organic matter and poorly structured leads to waterlogging in low lying fields, lodging of standing crops, and a sharp rise in fungal disease pressure, problems the region's traditional cropping systems were never designed to handle.

Table 1. Recent extreme rainfall events recorded in Rajasthan

Period	Rainfall departure from normal	Remark
June 2025	133 per cent of long term average	Second wettest June in Rajasthan since 1901
July 2025	78 per cent of long term average	Third wettest July on record for the state
August 2025	118 per cent of long term average	Continued above normal monsoon activity
September 2025	182 per cent of long term average	Sharp late season surge in rainfall
1 to 10 June 2026	154 per cent, state average; 207 per cent, eastern Rajasthan	Excess pre monsoon rainfall driven by western disturbances

Source: India Meteorological Department data, cited in *Down To Earth*, 2026.

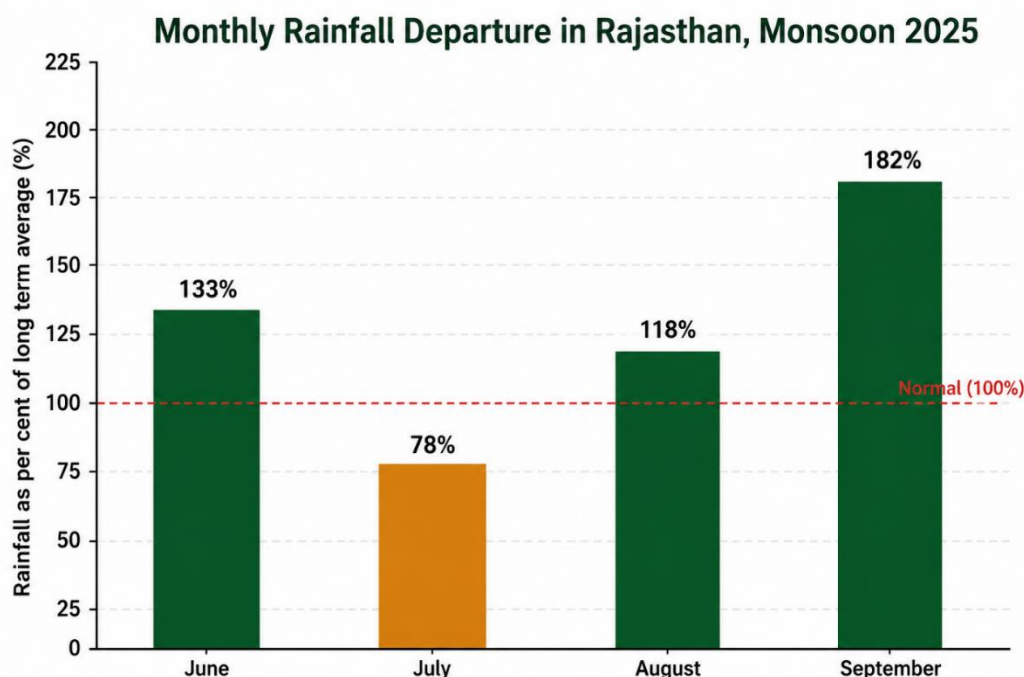


Fig. 1. Monthly rainfall departure in Rajasthan during the 2025 monsoon

Rising Temperature Extremes

Alongside the shift in rainfall, Rajasthan has also recorded some of the country's most severe heat extremes in recent summers. During the prolonged heat wave that struck India between April and June 2024, Churu in Rajasthan registered 50.5 degrees Celsius, the peak temperature recorded anywhere in the country that year, part of a spell that contributed to more than 219 heat related deaths and upward of 40,000 hospitalizations nationally. Unlike a hailstorm or a flood, heat stress rarely announces itself as a single dramatic event; it accumulates quietly in the field, causing flower and pod drop, reduced grain filling, poor nutrient uptake and lower produce quality, effects that are easy to underestimate until the harvest weighs in well below expectation.

Hailstorms and Unseasonal Rain at Harvest Time

Perhaps the most visible damage in recent seasons has come not from drought or heat but from unseasonal rain and hail arriving precisely when the rabi crop is at its most vulnerable. In early April 2026, repeated spells of rain and hailstones as large as lemons struck Bikaner district's Arjunsar region over three days, destroying standing

wheat, mustard and chana across some twenty villages, with several farmers reporting complete, hundred per cent loss on fields they had nursed through an already difficult season of unseasonable heat. For a crop only days from harvest there is no recovery possible, only the paperwork of a damage assessment and the long wait that has too often followed for insurance claims under the Pradhan Mantri Fasal Bima Yojana (Table 2).

Table 2. Recent weather extremes in Rajasthan and their agricultural impact

Event	Period	Impact on agriculture
Severe heat wave	April to June 2024	Peak temperature of 50.5 degrees Celsius at Churu, cumulative heat stress on standing rabi crops and livestock
Extreme monsoon rainfall	June to September 2025	Sixth wettest season in 125 years in western Rajasthan; waterlogging and lodging in several districts
Hailstorm and heavy rain	2 to 4 April 2026	Complete loss of standing wheat, mustard and chana in about twenty villages of Bikaner district
Excess pre monsoon rainfall	1 to 10 June 2026	State rainfall 154 per cent above normal before formal monsoon onset, eastern districts at 207 per cent

Source: Compiled from Down To Earth, 2026, and India Meteorological Department seasonal reports.

Desertification and the Slow Loss of Productive Land

Running beneath these episodic shocks is a slower, more persistent form of degradation. According to the Desertification and Land Degradation Atlas prepared by the Space Applications Centre of ISRO, roughly two thirds of Rajasthan's geographical area, an estimate that has ranged between about 63 and 68 per cent across successive assessments, is undergoing some form of desertification or land degradation, the highest share recorded for any Indian state. Wind erosion is by far the dominant process, accounting for about 44.2 per cent of the degraded area, followed by water erosion at 11.2 per cent, vegetal degradation at 6.25 per cent and salinization at 1.07 per cent, with the remaining share attributed to other and combined processes (Table 3, Figure 2). Left unaddressed, the combination of an eroding, wind blown soil surface and increasingly erratic rainfall compounds the damage each does on its own, since bare, degraded soil sheds water rather than absorbing it, worsening both the dry spells and the flash flooding that now follow one another within a single season.

Table 3. Leading processes driving land degradation in Rajasthan

Degradation process	Share of degraded area
Wind erosion	44.2 per cent
Water erosion	11.2 per cent
Vegetal degradation	6.25 per cent
Salinization	1.07 per cent

Source: Desertification and Land Degradation Atlas of India, Space Applications Centre, ISRO, 2021. Figures represent the largest individually identified processes; the remaining degraded area reflects other and combined factors.

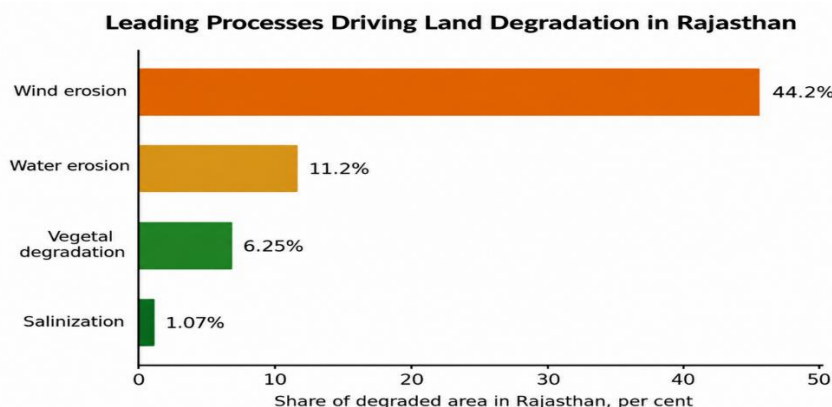


Fig. 2. Leading processes driving land degradation in Rajasthan (ISRO, 2021)

What This Means for Farmers and Agriculture

Taken together, these abnormalities are reshaping the risk that a Rajasthan farmer carries into every cropping season. A wetter monsoon is welcome for groundwater recharge, but it can equally mean a mustard crop lost to lodging, a moth bean crop rotting in waterlogged sandy loam, or a delayed sowing window that pushes the crop into the path of an early winter cold wave. A hotter summer shortens the safe window for kharif sowing and raises livestock heat stress in a state where livestock rearing is as central to rural livelihoods as cropping itself. And a slow, wind driven loss of topsoil steadily narrows the productive base on which any of these adaptations must work. The Pradhan Mantri Fasal Bima Yojana and the Restructured Weather Based Crop Insurance Scheme exist precisely to cushion these shocks, yet as the Bikaner hailstorm episode illustrates, delayed claim settlement continues to blunt the protection these schemes are meant to provide, an implementation gap that deserves as much attention as the underlying weather risk.

Climate Resilient Agricultural Practices

The ICAR Central Arid Zone Research Institute at Jodhpur, together with its regional stations and the state's network of Krishi Vigyan Kendras, has spent more than six decades developing technologies specifically suited to this volatile arid environment, and these now form the backbone of climate resilient farming advice for the state (Figure 3, Table 4).

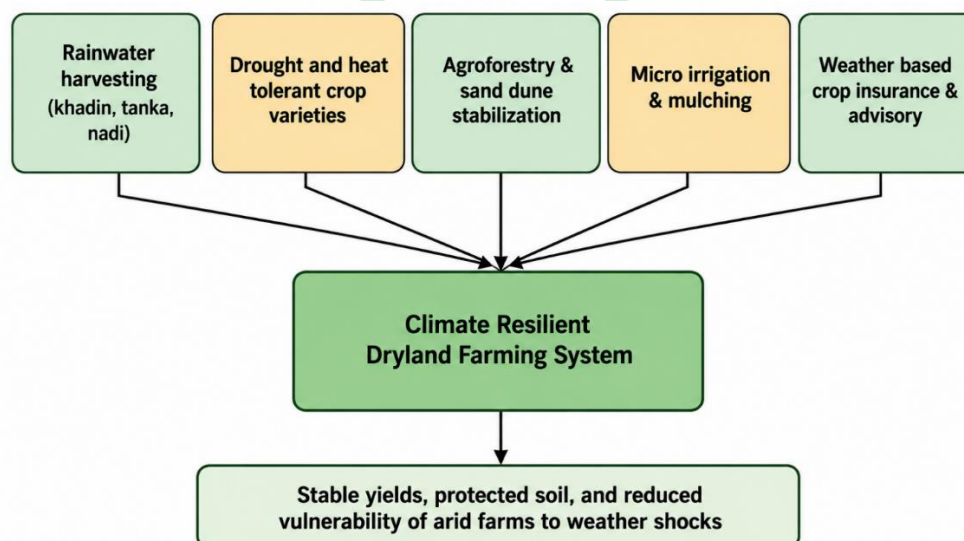


Fig. 3. Building blocks of climate resilient agriculture in Rajasthan

Rainwater harvesting

Traditional structures such as the khadin, tanka and nadi, refined with modern lining and catchment design, continue to be the most reliable way of capturing the region's scarce and increasingly episodic rainfall for both drinking water and supplemental irrigation, and their revival has become a priority wherever concentrated downpours are now more common than steady seasonal rain.

Sand dune stabilization and agroforestry

Since the 1960s, CAZRI has promoted afforestation of active sand dunes using hardy species such as Khejri (*Prosopis cineraria*), which anchors soil, moderates local temperature and continues to provide fodder and fuelwood even in drought years. Tree based cropping systems built around Khejri, ber and rohida, integrated with pearl millet, moth bean or cluster bean in the alleys between trees, buffer the crop beneath from wind erosion and extreme heat while adding a second, more stable income stream.

Drought and heat tolerant varieties

Breeding programmes at CAZRI and allied ICAR institutes have released pearl millet hybrids and moth bean and cluster bean varieties bred specifically for the erratic rainfall and high temperatures of the arid zone, offering farmers a form of genetic insurance where agronomic management alone cannot fully offset a difficult season.

Micro irrigation and mulching

Drip and sprinkler systems, combined with organic or plastic mulching, reduce the evaporative loss that is otherwise severe in the region's sandy soils and high temperatures, allowing the same volume of harvested water to cover more area and support crops through short dry spells within an otherwise wet season.

Weather based advisories and insurance

The Restructured Weather Based Crop Insurance Scheme, which triggers payouts once rainfall, temperature or humidity readings from automatic weather stations cross defined thresholds, is being extended in Rajasthan under the Weather Information Network Data System, expanding the density of the weather station network and, in principle, making both advisories and claim settlement faster and less dependent on manual crop cutting experiments.

Institutional and Policy Support

Rajasthan's response to a more erratic climate draws on a set of complementary national programmes (Table 4). The National Action Plan to Combat Desertification, launched alongside the Aravalli Green Wall Project, targets the restoration of degraded land through forestry interventions across the state's most affected districts. The Pradhan Mantri Fasal Bima Yojana and its weather indexed counterpart provide the financial safety net, however imperfect in practice, that allows a farmer to absorb a single bad season without abandoning the next one. And Krishi Vigyan Kendras, working with CAZRI's regional research stations at Jodhpur, Pali, Bikaner and Jaisalmer, remain the channel through which laboratory bred varieties and engineered water harvesting designs reach an actual farmer's field.

Table 4. Institutional programmes supporting climate resilient agriculture in Rajasthan

Programme	Focus area	Implementing agency
ICAR CAZRI research and extension	Drought tolerant varieties, agroforestry, water harvesting	ICAR Central Arid Zone Research Institute, Jodhpur, and its regional stations
Pradhan Mantri Fasal Bima Yojana	Yield based crop insurance against natural calamities	Ministry of Agriculture and Farmers Welfare, State governments
Restructured Weather Based Crop Insurance Scheme	Index based payouts linked to automatic weather stations	Ministry of Agriculture and Farmers Welfare, insurance companies
National Action Plan to Combat Desertification	Restoration of degraded land through forestry	Ministry of Environment, Forest and Climate Change, State Forest Department
Krishi Vigyan Kendras	Last mile transfer of technology and farmer training	ICAR, State agriculture universities

Source: Compiled from CAZRI, Jodhpur, and PMFBY and RWBCIS operational guidelines, Government of India.

Way Forward

Rajasthan's weather is not simply becoming hotter or wetter in any single direction; it is becoming less predictable in both directions at once, and it is this unpredictability, more than any single extreme, that agriculture in the state must now be built to absorb. The technologies to do so, water harvesting, agroforestry, drought and heat tolerant varieties, and weather indexed insurance, already exist and have been tested over decades of CAZRI research. What remains uneven is their reach: too many farmers still learn about a khadin or a weather based insurance claim only after a season has already been lost. Closing that gap, through faster claim settlement, denser weather monitoring and sustained extension contact, is now as important to Rajasthan's agricultural future as any single new variety or structure.

Summary

Rajasthan's climate is shifting from dependable scarcity toward volatile extremes, with the 2025 monsoon ranking as the sixth wettest in 125 years in the western districts, June 2026 rainfall already 154 per cent above normal before the monsoon's formal onset, a record temperature of 50.5 degrees Celsius recorded at Churu in 2024, and

hailstorms that destroyed entire rabi fields in Bikaner in early 2026. Beneath these episodic shocks, roughly two thirds of the state's land continues to degrade, chiefly through wind erosion. Climate resilient practices developed by ICAR CAZRI, including rainwater harvesting structures, agroforestry built around Khejri and ber, drought and heat tolerant varieties, micro irrigation and weather based crop insurance, offer a proven pathway forward, but their benefit reaches farmers only where extension outreach and timely insurance settlement keep pace with the technology itself. For Rajasthan's farmers, resilience now depends as much on institutional responsiveness as on the science already available.

References

- Business Standard. 2026. How extreme heat is exposing gaps in India's crop insurance system. Business Standard, Mumbai.
- Central Arid Zone Research Institute. 2026. CAZRI, Jodhpur. Indian Council of Agricultural Research, Jodhpur.
- Down To Earth. 2026. Rajasthan's rains are rewriting desert records with 154 per cent excess rainfall by June 10. Down To Earth, New Delhi.
- Down To Earth. 2026. Caught off guard, unseasonal hailstorms and rain wipe out entire fields in Rajasthan, Punjab days before harvest. Down To Earth, New Delhi.
- GKToday. 2025. Desertification in India. GKToday, New Delhi.
- India Meteorological Department. 2024. Seasonal heat wave summary, April to June 2024. IMD, New Delhi.
- Space Applications Centre, ISRO. 2021. Desertification and Land Degradation Atlas of India. ISRO, Ahmedabad.
- Tewari, J.C. 2018. Agroforestry for climate resilient agriculture and livelihood in arid regions of India. Indian Journal of Agroforestry.
- Department of Agriculture and Farmers Welfare. 2026. Restructured Weather Based Crop Insurance Scheme, operational guidelines. Government of India, New Delhi.



Integrated Nutrient Management in Pulses: Improving Soil Health and Nutrient Use Efficiency



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Abstract

Pulses occupy a unique position in Indian agriculture as the country's principal source of dietary protein for a predominantly vegetarian population and as leguminous crops capable of enriching soil through biological nitrogen fixation. Despite their nutritional and ecological importance, the national average productivity remains low, at around 900 kg ha⁻¹, and India continues to import more than seven million tonnes of pulses annually to meet domestic demand. A major reason for this productivity gap is the widespread cultivation of pulses with minimal nutrient inputs, based on the misconception that biological nitrogen fixation alone can meet their nutrient requirements. In reality, efficient nodulation and nitrogen fixation depend on an adequate supply of phosphorus, sulphur, and essential micronutrients, together with the presence of effective Rhizobium strains in the soil, conditions that are often lacking in degraded or continuously cultivated fields. Integrated Nutrient Management, which combines soil test based fertilizer application with Rhizobium and phosphate solubilizing bacteria inoculation, organic manures, and micronutrient supplementation, has consistently improved nodulation, nutrient use efficiency, soil fertility, and grain yield in field studies on chickpea and pigeonpea compared with the use of either chemical fertilizers or biological inputs alone. This article reviews the nutrient management challenges in pulse-based production systems, outlines the key components of an effective Integrated Nutrient Management strategy, and highlights its role in improving productivity, sustaining soil health, and enhancing nutrient use efficiency.

Keywords: Biofertilizers, Integrated Nutrient Management, Nitrogen fixation, Pulse based cropping systems, Rhizobium, Soil health.

1. Introduction

Pulses have been part of Indian farming systems for millennia, valued as much for the protein they place on the plate as for the fertility they leave behind in the soil. Being legumes, chickpea, pigeonpea, black gram, green gram, lentil and their relatives form a partnership with Rhizobium bacteria in root nodules, drawing nitrogen directly from the atmosphere rather than depending entirely on nitrogen already present in the soil or applied as fertilizer. This biological nitrogen fixation has long been treated as reason enough to place pulses at the bottom of the input priority list, grown as a catch crop on residual fertility with little more than a token dose of fertilizer, if any at all.

That assumption has not served pulse productivity well. India's average pulse yield has crept up only slowly, from around 609 kilograms per hectare in the early 2000s to roughly 907 kilograms per hectare by 2024, a level still well below what balanced nutrient management can deliver on the same soils. The gap is not a shortcoming of the crop but of the way it is fed. Nodulation and nitrogen fixation are themselves nutrient demanding processes, requiring phosphorus for energy transfer, sulphur for the enzymes and amino acids involved, and molybdenum as a direct cofactor of the nitrogenase enzyme that fixes nitrogen. Where any of these is deficient, a pulse crop nodulates poorly, fixes little nitrogen, and ends up drawing down whatever nitrogen already exists in the soil rather than adding to it. Integrated Nutrient Management, or INM, addresses this by combining judicious chemical fertilizer, biofertilizers and organic sources in a single, soil test guided package, and this paper sets out why that combination matters and what the evidence shows about its impact.

2. Pulses in Indian Agriculture: Extent and the Productivity Gap

India is the world's largest producer, consumer and importer of pulses, cultivating the crop on close to 28 to 30 million hectares and producing around 244.93 lakh tonnes in 2023-24. Despite this scale, domestic production has not kept pace with demand, and the country imported a record 72.56 lakh tonnes of pulses in 2024-25, worth about 5.48 billion US dollars, exposing farmers and consumers alike to global price volatility (Table 1). In recognition of this gap, the Union Cabinet approved the Mission for Aatmanirbharta in Pulses in the 2025-26 budget, a six year, 11,440 crore rupee initiative targeting self reliance in tur, urad and masoor specifically.

Table 1. Area, production and trade indicators for pulses in India

Indicator	Value
Area under pulses	About 28 to 30 million hectares
Production, 2023-24	244.93 lakh tonnes
Productivity, 2024 (approx)	About 907 kg per hectare, up from 609 kg per hectare in 2001-03
Imports, 2024-25	72.56 lakh tonnes, valued at about USD 5.48 billion
Mission for Aatmanirbharta in Pulses	Rs 11,440 crore, 2025-26 to 2030-31, targeting tur, urad and masoor

Source: ClearIAS, Pulses Production in India, 2025, and Agriculture Institute, Production Statistics and Acreage of Pulses in India, 2026.

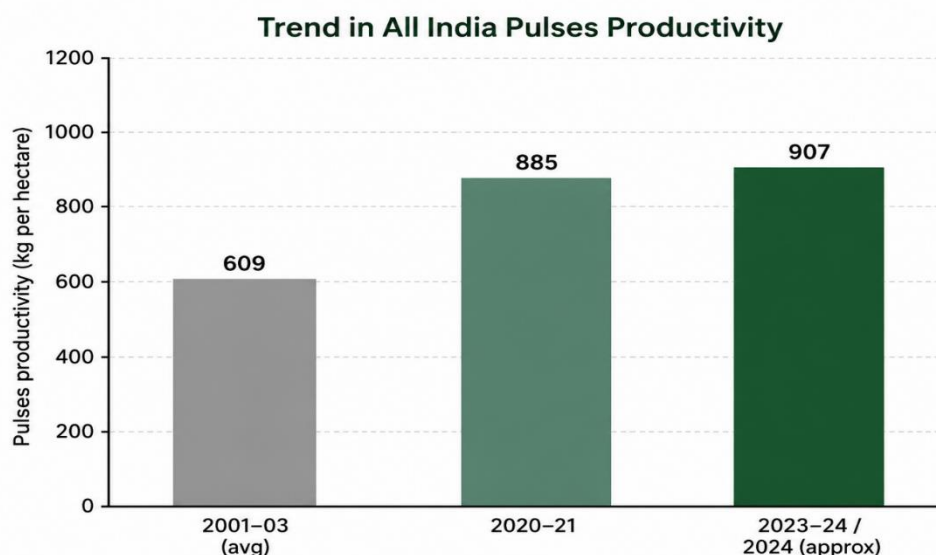


Fig. 1. Trend in all India pulses productivity

3. Why Pulses Need More Than Nitrogen Fixation Alone

A well nodulated pulse crop can add up to about 30 kilograms of nitrogen per hectare to the soil through biological fixation, a benefit that improves the fertility available to the crop that follows it in rotation. This process is, however, conditional rather than automatic. Nodule formation depends on the presence of compatible, effective Rhizobium strains in the soil, which may be absent, present at low populations, or displaced by ineffective native strains in fields where the crop has not been grown for years or where soil conditions are unfavourable. Even where compatible rhizobia are present, the energy intensive process of converting atmospheric nitrogen into a usable form draws heavily on phosphorus, since the reaction is powered by ATP, while sulphur is required for the amino acids and enzymes involved in nodule function and molybdenum acts as a direct cofactor of the nitrogenase enzyme itself. Zinc and boron, though not directly involved in fixation, influence flowering, pod set and grain filling, and their absence can limit yield even where nitrogen supply is adequate.

Where phosphorus, sulphur or these micronutrients are deficient, which is common in the light textured, often marginal soils on which pulses are frequently grown, nodulation is poor and the crop behaves less like a nitrogen contributor and more like any other nitrogen demanding crop, drawing down existing soil reserves. The

common practice of skipping fertilizer application entirely on the assumption that the crop will fix all the nitrogen it needs therefore tends to depress rather than protect yield, and it is precisely this gap that integrated nutrient management is designed to close.

Nutrients Required for Effective Nodulation in Pulses

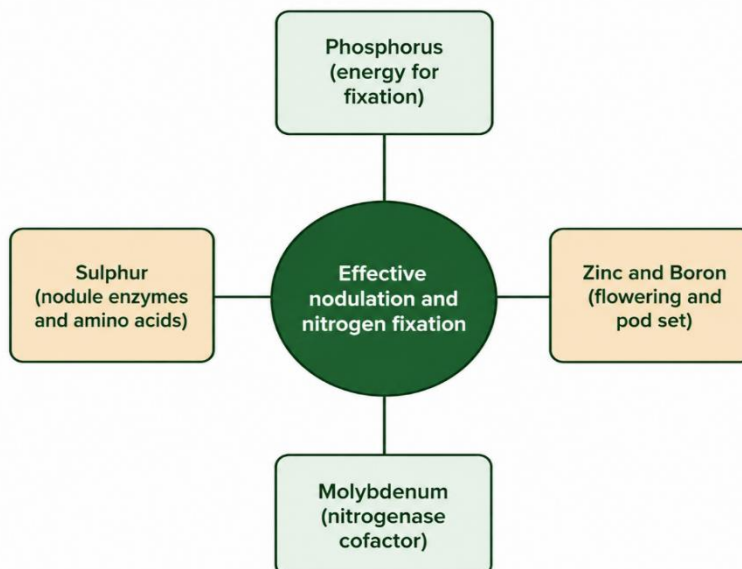


Fig. 2. Nutrients required for effective nodulation and nitrogen fixation in pulses

4. Components of Integrated Nutrient Management in Pulses

Components of Integrated Nutrient Management in Pulses

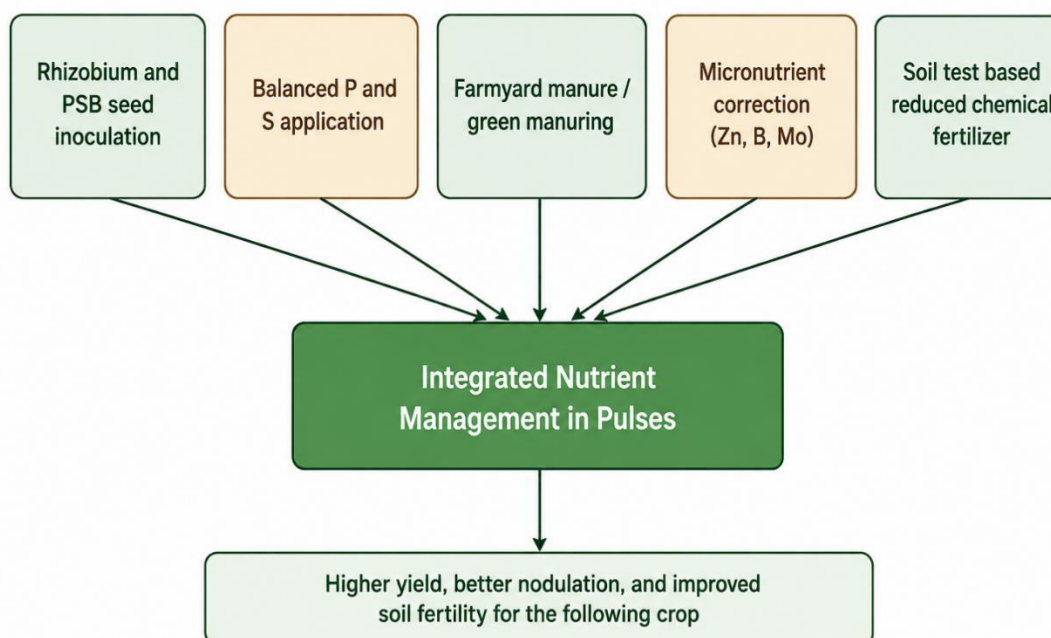


Fig. 3. Components of integrated nutrient management in pulses

4.1 Rhizobium and other biofertilizers

Seed treatment with a crop specific Rhizobium culture, ideally combined with phosphate solubilizing bacteria and, where available, potassium solubilizing bacteria, remains the single most cost effective input in pulse

cultivation. Even in fields where pulses have been grown before, inoculation with a fresh, high quality culture is worthwhile, since native rhizobial populations are frequently outnumbered by strains that nodulate the root but fix little or no nitrogen.

4.2 Balanced phosphorus and sulphur application

Because nodulation is phosphorus dependent, a starter dose of phosphorus, typically applied as a basal dressing at sowing, supports early nodule development even in a crop that will eventually meet most of its own nitrogen needs. Sulphur, often supplied through gypsum or single superphosphate, addresses a deficiency that is increasingly common in intensively cropped soils and directly supports both nodule function and oil and protein synthesis in the grain.

4.3 Organic manures and green manuring

Farmyard manure, vermicompost or a green manure crop worked into the soil ahead of sowing improves organic carbon, soil structure and the population of beneficial microorganisms, creating conditions in which both applied and native rhizobia establish and function more effectively. Replacing a modest share of the recommended fertilizer dose, commonly around 25 per cent, with an organic source has repeatedly been shown to sustain yield while improving residual soil fertility for the following crop.

4.4 Micronutrient correction

Zinc and boron deficiencies are widespread across pulse growing soils and are readily corrected through soil or seed applied zinc sulphate and borax, while molybdenum, required in only trace amounts but essential to nitrogenase function, is best supplied as a seed treatment, particularly in acidic soils where its availability is naturally low.

5. Field Evidence on Yield, Nutrient Uptake and Soil Health

Field trials across different pulse crops and agro climatic zones consistently point in the same direction: a combination of reduced chemical fertilizer, biofertilizer inoculation and an organic source outperforms either full chemical fertilization or biofertilizer use alone, both in yield and in the residual condition of the soil (Table 2). In chickpea trials conducted at Lovely Professional University, the treatment combining 75 per cent of the recommended fertilizer dose with farmyard manure and Rhizobium inoculation recorded the highest post harvest soil nitrogen, phosphorus and potassium levels among all treatments tested, indicating that the crop had left the soil measurably more fertile than it found it. In a separate multi season trial in Rajasthan, chickpea receiving 50 to 75 per cent of the recommended fertilizer dose along with Rhizobium and phosphate solubilizing bacteria returned the best economics of any treatment, with benefit cost ratios of 3.2 and 3.1 respectively. In pigeonpea trials conducted over three kharif seasons in Odisha, the combination of 75 per cent nitrogen, full phosphorus and potassium, Rhizobium, phosphate solubilizing bacteria and lime produced the highest productivity, grain quality and nutrient uptake among seven treatments compared, ahead of the full recommended fertilizer dose applied alone.

Table 2. Selected field trial findings on integrated nutrient management in pulses

Crop and location	Best performing treatment	Key outcome
Chickpea, Lovely Professional University, Punjab	75% RDF + farmyard manure + Rhizobium	Highest post harvest soil N, P and K among treatments tested
Chickpea, Vivekananda Global University, Rajasthan	50 to 75% RDF + Rhizobium + PSB	Best economics, benefit cost ratio of 3.2 and 3.1 respectively
Pigeonpea, Eastern Ghat High Land Zone, Odisha	75% N + 100% PK + Rhizobium + PSB + lime	Highest productivity, grain quality and nutrient uptake over 3 seasons
Chickpea, Vertisol, Central India	INM modules versus inorganic fertilizer alone	Higher soil organic carbon and improved soil physical and chemical properties

Source: Compiled from IJERT, 2026; ResearchGate field trial reports, 2017 and 2025; and PMC, Performance of chickpea in maize chickpea sequence, 2021.

6. Benefits for Soil Health and Nutrient Use Efficiency

Beyond individual field trials, broader comparisons between legume based and cereal monoculture systems reinforce the same pattern. Soils under legume crops have been found to show more than 11 per cent higher availability of nitrogen, phosphorus and potassium and 16 to 17 per cent greater carbon sequestration than soils under continuous cereal cultivation, alongside a requirement for around 25 per cent less irrigation water (Fig. 4). When these ecosystem benefits are valued in economic terms, they have been estimated at close to 15,000 rupees per hectare, a contribution that conventional yield and price calculations for pulses typically overlook entirely. Integrated nutrient management amplifies these benefits rather than working against them, since the organic and biological components of an INM package build the same soil organic carbon and microbial activity that make the crop's own nitrogen fixation more effective in the first place, creating a cycle of improvement rather than a one off gain.

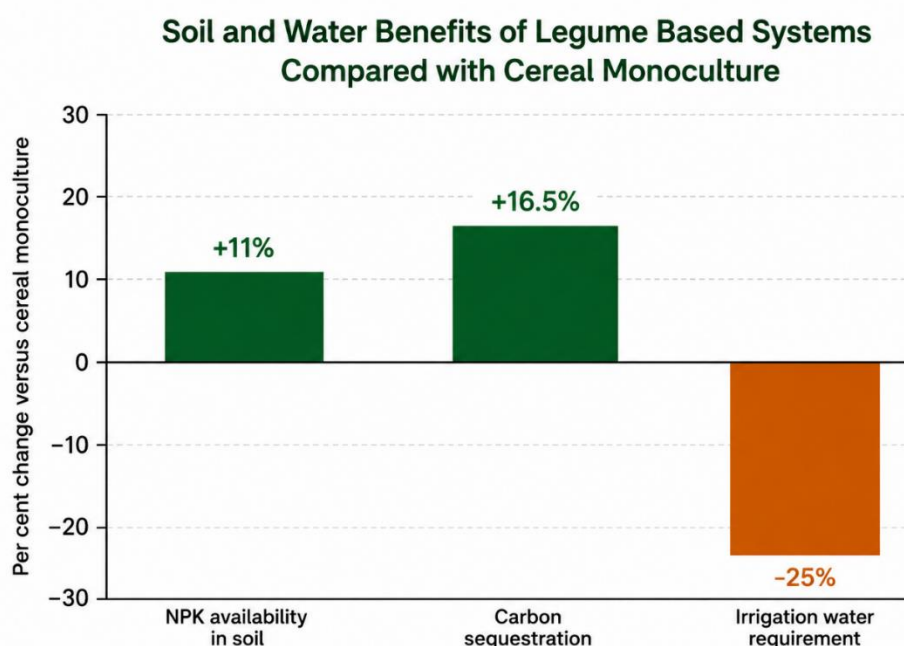


Fig. 4. Soil and water benefits of legume-based systems compared with cereal monoculture

7. Practical Recommendations for Farmers and Extension Workers

Treat every pulse crop with a fresh, crop specific Rhizobium and phosphate solubilizing bacteria culture at sowing, regardless of whether the crop has been grown in the field before. Apply the full recommended dose of phosphorus and potassium as per soil test, since these support nodulation rather than compete with it, while reducing nitrogen fertilizer to a small starter dose that helps the crop establish before nodules become active. Where soil tests indicate deficiency, apply gypsum or a sulphur containing fertilizer, and treat seed with molybdenum, particularly in acidic soils. Replace a portion of the chemical fertilizer dose, typically around a quarter, with farmyard manure, vermicompost or a green manure crop wherever feasible, and avoid the common practice of applying no fertilizer at all in the belief that the crop's nitrogen fixing ability makes this unnecessary, since the evidence consistently shows the opposite to be true.

8. Conclusion

Pulses carry a reputation as self-sufficient, soil building crops, and under the right conditions they genuinely are. That reputation, however, has too often been used to justify starving them of the very nutrients, phosphorus, sulphur and micronutrients in particular, that make effective nitrogen fixation possible in the first place. Integrated Nutrient Management restores the balance, combining biofertilizers, judicious chemical fertilizer and organic sources into a package that field trials across chickpea and pigeonpea have repeatedly shown to outperform any single input used alone, both in yield and in the fertility left behind for the next crop. As India works toward self-reliance in pulse production under missions such as Aatmanirbharta in Pulses, closing the gap between the

productivity pulses could achieve and what farmers actually harvest will depend less on new technology than on applying, consistently and at scale, the integrated nutrient management principles already validated by research.

References

ClearIAS. 2025. Pulses production in India. ClearIAS, Kochi.

Agriculture Institute. 2026. Production statistics and acreage of pulses in India. Agriculture Institute.

Down To Earth. 2026. Pulse power, how legumes can cut India's farm emissions and restore soil health. Down To Earth, New Delhi.

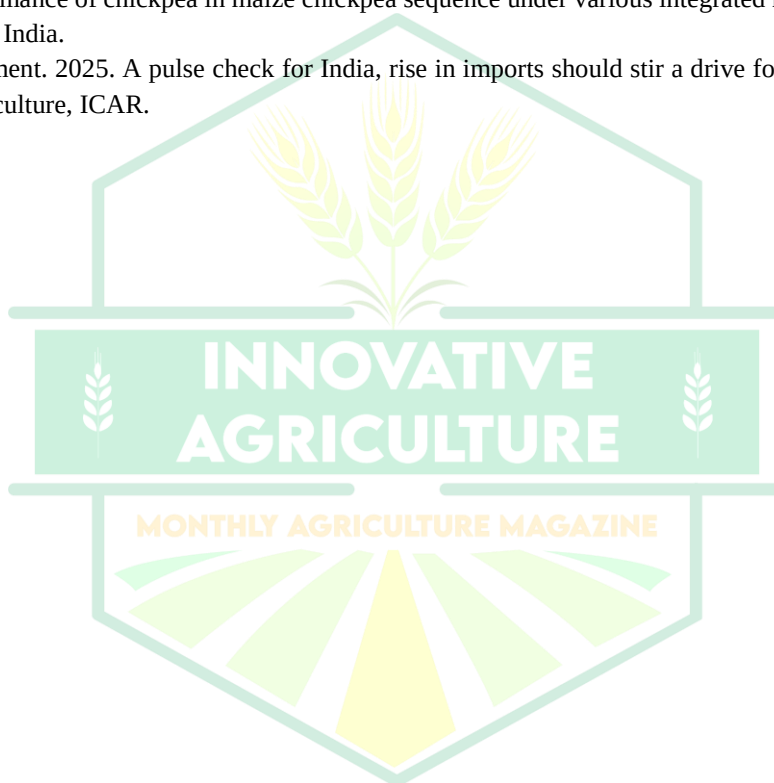
IJERT. 2026. Effect of liquid biofertilizers on growth and yield of chickpea. International Journal of Engineering Research and Technology.

ResearchGate. 2017. Integrated nutrition management in pigeonpea intercropping systems for enhancing production and productivity in a sustainable manner. A review.

ResearchGate. 2025. Effect of integrated nutrient management on growth, yield and quality of chickpea. Lovely Professional University.

PMC. 2021. Performance of chickpea in maize chickpea sequence under various integrated nutrient modules in a Vertisol of Central India.

Good Food Movement. 2025. A pulse check for India, rise in imports should stir a drive for self reliance, citing Handbook of Agriculture, ICAR.



Biological Control: A Sustainable Path to Healthy Crops

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Introduction

Agriculture faces an ever-growing challenge from plant diseases, insects and pests that reduce crop yield and quality. For decades, chemical pesticides have been the primary tool for managing these problems. While effective, their excessive use has led to pesticide resistance, environmental pollution, destruction of beneficial organisms, and concerns about food safety.

Biological control, commonly known as biocontrol, offers a sustainable and environmentally friendly alternative. It uses naturally occurring organisms or their products to suppress plant pathogens and pests, helping farmers produce healthier crops while reducing dependence on chemical pesticides.

What is Biological Control?

Biological control is the use of **beneficial microorganisms, insects or natural enemies** to manage plant diseases and pests. Instead of eliminating all microorganisms, biocontrol restores the natural balance in agricultural ecosystems by encouraging beneficial organisms that keep harmful pathogens under control.

How Does Biological Control Work?

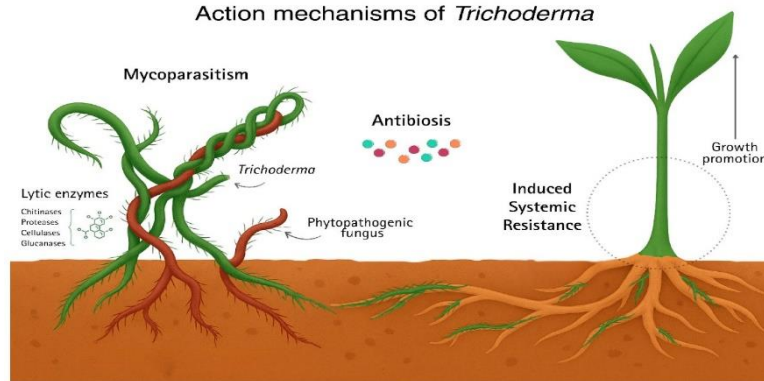
Beneficial organisms protect plants through several mechanisms:

- **Competition:** Beneficial microbes compete with pathogens for nutrients and space.
- **Antibiosis:** They produce natural antibiotics that inhibit pathogen growth.
- **Parasitism:** Some microorganisms directly attack and destroy plant pathogens.
- **Induced Resistance:** They stimulate the plant's own immune system, making it more resistant to diseases

Table 1: Major Biological Control Agents

Biological control agent	Target organism	Mode of action	Common application
<i>Trichoderma</i> spp.	Soil-borne fungi	Parasitism, antibiosis, induced resistance	Seed treatment, soil application
<i>Bacillus</i> spp.	Fungi and bacteria	Antibiotic production, competition	Seed treatment, foliar spray
<i>Pseudomonas fluorescens</i>	Multiple pathogens	Siderophore production, induced resistance	Seed treatment and soil application
<i>Beauveria bassiana</i>	Insect pests	Infects and kills insects	Foliar spray
Ladybird beetles	Aphids	Predation	Field release
<i>Metarhizium anisopliae</i>	Insect pests	Infects insect body	Soil and foliar application

Action mechanisms of *Trichoderma*



Why Biological Control Matters Today?

The world's population is increasing rapidly, creating a greater demand for food production. At the same time, climate change, emerging plant diseases, pesticide resistance and environmental degradation are threatening agricultural productivity. Biological control offers a practical and sustainable solution by reducing dependence on chemical pesticides while maintaining crop health and protecting natural ecosystems. It supports eco-friendly farming practices and contributes to long-term food security.

Benefits of Biological Control

Environmentally Safe

Biological control reduces dependence on chemical pesticides by using beneficial microorganisms and other natural enemies to suppress plant pathogens. This minimizes soil and water pollution, lowers environmental contamination and helps maintain ecological balance.

Healthier Crops

Beneficial microbes such as *Trichoderma*, *Bacillus* and *Pseudomonas* not only suppress disease-causing pathogens but also stimulate root growth, improve nutrient uptake, and activate the plant's natural defense mechanisms. As a result, crops become healthier more vigorous, and better able to withstand disease.

Protects Beneficial Organisms

Unlike many broad-spectrum pesticides, biological control agents are generally selective in their action. They help conserve pollinators such as bees and butterflies, beneficial insects, earthworms, and natural predators that play essential roles in pollination, soil fertility and pest regulation.

Supports Sustainable Agriculture

Biological control contributes to sustainable farming by improving soil microbial diversity, maintaining soil fertility, and reducing the development of pesticide-resistant pathogens. It is an important component of Integrated Disease Management (IDM) and promotes long-term agricultural productivity.

Produces Safer Food

Reduced use of chemical pesticides lowers pesticide residues on fruits, vegetables and other food products. This results in safer produce for consumers while also protecting the health of farmers and agricultural workers who are regularly exposed to pesticides.

Cost-Effective in the Long Run

Although some biological control products may require careful application and initial investment, they can reduce the need for repeated chemical sprays, improve crop health and lower production costs over time. When combined with good agricultural practices, biological control provides an economical and sustainable approach to disease management.

Success Stories:

- *Trichoderma* species effectively suppress diseases caused by *Fusarium*, *Rhizoctonia*, *Sclerotium*, and *Pythium*.
- *Pseudomonas fluorescens* protects several vegetable, cereal and pulse crops by enhancing natural plant immunity.
- *Bacillus subtilis* produces natural antimicrobial compounds that reduce fungal and bacterial diseases.
- Ladybird beetles naturally control aphid populations, reducing the need for insecticides.

Challenges

- Despite its many advantages, biological control also has limitations:
- Performance may vary with temperature, humidity and soil conditions.
- Beneficial organisms often act more slowly than chemical pesticides.
- Proper storage and handling are essential to maintain effectiveness.
- Farmers need awareness and training for successful adoption.

Did you know?

- Less than 1% of microorganisms present in the soil are harmful to plants; the vast majority are either beneficial or harmless.

- A single gram of healthy soil may contain billions of microorganisms, including bacteria, fungi and actinomycetes that help maintain soil fertility and suppress plant diseases.
- Some beneficial microbes not only control diseases but also promote plant growth by improving nutrient uptake and producing growth-promoting substances.

The Future of Biological Control

Advances in biotechnology, genomics, microbiome research and precision agriculture are making biological control more reliable and effective. Scientists are developing improved microbial formulations, microbial consortia and climate-resilient biocontrol agents. When combined with resistant crop varieties and good agricultural practices, biological control will play an increasingly important role in sustainable crop protection.

Table 2: Quick Comparison: Biological vs Chemical Control

Feature	Biological Control	Chemical Control
Source	Natural organisms	Synthetic chemicals
Environmental impact	Low	Often high
Target specificity	Usually specific	Often broad-spectrum
Risk of resistance	Lower	Higher
Residue in food	Minimal	May occur
Effect on beneficial organisms	Generally safe	May harm beneficial insects and microbes
Long-term sustainability	High	Moderate to low

Conclusion

Biological control is transforming modern agriculture by harnessing nature's own defense mechanisms to protect crops. Although it is not a complete replacement for chemical pesticides in every situation, it is a cornerstone of Integrated Pest Management (IPM). By promoting healthier soils, conserving biodiversity and reducing environmental pollution, biological control offers a sustainable path toward resilient agriculture, improved food security and healthier crops for future generations.

References

- Berendsen, R. L., Pieterse, C. M. J., & Bakker, P. A. H. M. (2012). The rhizosphere microbiome and plant health. *Trends in Plant Science*, 17(8), 478-486.
- Compant, S., Samad, A., Faist, H., & Sessitsch, A. (2019). A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. *Journal of Advanced Research*, 19, 29–37.
- Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). *Trichoderma* species-Opportunistic, avirulent plant symbionts. *Nature Reviews Microbiology*, 2(1), 43-56.
- Howell, C. R. (2003). Mechanisms employed by *Trichoderma* species in the biological control of plant diseases: The history and evolution of current concepts. *Plant Disease*, 87(1), 4–10.
- Jacobsen, B. J., Zidack, N. K., & Larson, B. J. (2004). The role of *Bacillus*-based biological control agents in integrated pest management systems: Plant diseases. *Phytopathology*, 94(11), 1272-1275.
- Pan, S., & Bhagat, S. (2020). Biological control of plant diseases. *Journal of Plant Protection Sciences*, 12(1), 1-10.
- Stenberg, J. A. (2017). A conceptual framework for integrated pest management. *Trends in Plant Science*, 22(9), 759-769.
- Yao, X., Guo, H., Zhang, K., Zhao, M., Ruan, J., & Chen, J. (2023). *Trichoderma* and its role in biological control of plant fungal and nematode disease. *Frontiers in Microbiology*, 14, 1160551.

Artificial Intelligence: A New Era in Plant Disease Diagnosis and Management



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Introduction

Plant diseases continue to pose a serious challenge to global agriculture by reducing crop yield, quality, and farmer income. Traditional plant disease diagnosis relies heavily on visual inspection by experts, laboratory testing and farmer experience. These methods are often time-consuming, costly and inaccessible to small and marginal farmers, especially in remote areas. Moreover, delayed or incorrect disease identification frequently leads to improper pesticide use, resulting in environmental pollution, pesticide resistance and increased production costs.

In recent years, **Artificial Intelligence (AI)** has emerged as a revolutionary technology with the potential to transform agriculture, particularly in the field of plant disease diagnosis and management. Artificial Intelligence refers to the simulation of human intelligence in machines that are programmed to think, learn and make decisions like humans. By combining computing power with data-driven learning, AI enables faster, more accurate and real-time disease detection and management, thereby supporting sustainable and precision agriculture.

Why is AI becoming essential in agriculture?

With increasing climate change, emergence of new plant diseases, shortage of skilled plant pathologists and rising production costs, farmers need rapid and accurate advisory services. Artificial Intelligence can analyze thousands of plant images within seconds and recommend suitable disease management practices. This helps farmers reduce crop losses, minimize unnecessary pesticide applications and increase profitability. AI thus serves as a digital assistant for farmers, making scientific crop protection accessible even in remote villages through smartphones.

Evolution of Artificial Intelligence in Agriculture

The concept of Artificial Intelligence was first introduced by John McCarthy in 1956. Its application in agriculture began in the mid-1980s when expert systems such as **GOSSYM**, a cotton crop simulation model, were developed to assist decision-making. Since then, advancements in computing, sensor technology, image processing and data analytics have significantly expanded the scope of AI in agriculture. Today, AI is being used not only for plant disease diagnosis but also for crop yield prediction, weather forecasting, soil health monitoring, intelligent spraying, robotic harvesting and market price analysis. These applications are helping farmers make informed decisions and reduce uncertainties associated with farming.

Key Domains of Artificial Intelligence used in Plant Pathology

1. Machine Learning

Machine Learning is basically the science of getting machines to interpret processes and analyze the data to solve real world problems. Machine learning supervised and unsupervised in enforcement learning.

2. Deep Learning:

Deep Learning is an advanced branch of Artificial Intelligence that uses artificial neural networks to learn from large volumes of complex data and identify hidden patterns. It enables computers to automatically recognize and classify images with high accuracy, making it particularly useful for plant disease diagnosis. In agriculture, deep learning models analyze images of infected plant leaves, stems or fruits to detect diseases at an early stage and recommend appropriate management practices. This technology is also widely used in facial recognition systems, self-driving cars, voice assistants such as Alexa and Siri and many other intelligent applications.

3. Robotics:

Robotics is a branch of artificial intelligence which focuses on different branches and applications of robots. AI robots are artificial environments to produce results by taking some accountable actions. Example: Sofia robo

4. Expert Systems:

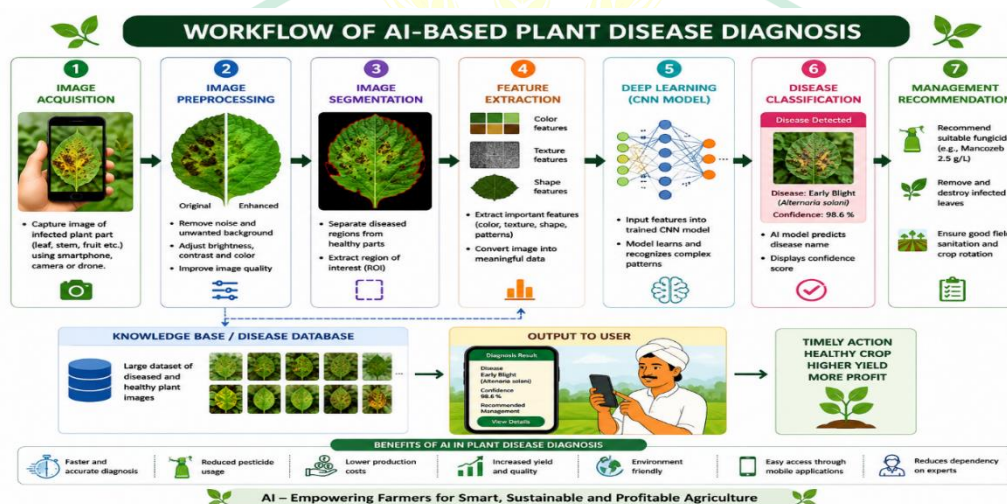
Expert systems are AI based computer systems that learn and reciprocate the decision-making ability of human experts. Expert systems use IF/Then logics mentioned in order to solve any complex problems. They do not relay conventional proceeding programming. Expert systems mainly used in information management seem to use virus detection, medical and hospital records and so on.

5. Internet of Things:

- IoTs describes the network of physical object “things” that are embedded with sensors, software and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet
- In agriculture, IoT uses the sensors, cameras and other devices to turn every element and action involved in farming into data.

Role of AI in Plant Disease Diagnosis

One of the most impactful applications of AI in agriculture is early and accurate plant disease detection. AI-based systems use digital images of infected plant parts captured through smartphones, cameras or drones. These images are processed through several steps, including image acquisition, preprocessing, segmentation, feature extraction and classification.



During preprocessing, unwanted noise, background elements and lighting variations are removed to improve image quality. Image segmentation divides the image into meaningful regions, allowing the system to focus on diseased areas. Features such as color, texture, shape and lesion patterns are then extracted and compared with large disease databases. Finally, AI models classify the disease and provide diagnostic results, often within seconds.

Table 1. Comparison between Conventional and AI-based Plant Disease Diagnosis

Parameter	Conventional Diagnosis	AI-based Diagnosis
Disease detection	Visual observation by experts	Automated image-based detection
Time required	Hours to days	Few seconds to minutes
Accuracy	Depends on expert experience	High (80–99% in many studies)
Cost	Higher due to laboratory testing	Lower after initial setup
Accessibility	Limited in remote areas	Available through smartphones and AI apps
Pesticide use	Often excessive due to delayed diagnosis	Precision recommendations reduce unnecessary spraying
Decision making	Manual	Real-time and data-driven

Deep Learning and Neural Networks in Disease Detection

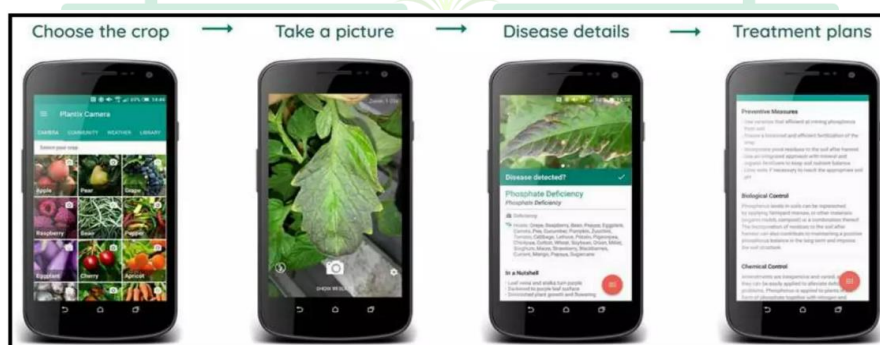
Deep learning has revolutionized plant disease diagnostics by enabling automated and highly accurate image-based analysis. Artificial Neural Networks (ANNs) process numerical data, while CNNs are widely used for image-based disease detection due to their ability to recognize complex visual patterns. Recurrent Neural Networks (RNNs) are useful for time-series data and disease forecasting. Studies have reported disease detection accuracies ranging from 80% to over 99% using deep learning models. These systems outperform traditional diagnostic methods and reduce dependency on plant pathology experts, especially in regions where expert access is limited.

AI-Based Robotics for Disease Management

AI-powered robots are transforming disease management by enabling real-time monitoring and targeted intervention. Agricultural robots equipped with cameras and sensors can detect early disease symptoms in the field and initiate localized spraying to prevent disease spread. Robots such as e-Agrobots use image processing and microcomputers like Raspberry Pi to identify infected plants and apply treatment only where needed. This approach reduces pesticide use, minimizes environmental impact and lowers production costs.

Mobile Applications and AI tools for Farmers

AI-driven mobile applications are bringing advanced plant disease diagnostics directly to farmers' hands. Applications like **Plantix** allow farmers to diagnose plant diseases by simply uploading photos of infected crops. The app covers dozens of crops, identifies hundreds of diseases and nutrient deficiencies and provides treatment recommendations in multiple languages. Another significant initiative is **AI-DISC**, developed by ICAR-IASRI in collaboration with several State Agricultural Universities. AI-DISC offers disease identification, expert consultation and reporting modules, strengthening digital plant health advisory services across India. These tools bridge the gap between research institutions and farmers, promoting timely and informed decision-making.



Popular AI-based Applications for Farmers

Application	Purpose
Plantix	Disease diagnosis and nutrient deficiency detection
AI-DISC	Disease identification and expert consultation
PlantVillage Nuru	Offline disease diagnosis
Google Lens (Experimental)	Preliminary plant identification
Krishi AI Apps	Crop advisory and disease management

Challenges in Adoption of AI in Agriculture

- Limited digital literacy among farmers, especially small and marginal farmers, restricting effective use of AI-based tools and applications.
- High initial investment cost for AI technologies, including sensors, cameras, drones, robots and computing infrastructure.
- Lack of quality and large datasets, as AI models require extensive, well-labeled data for accurate training and validation.
- Variability in field conditions such as crop varieties, soil types, climate and management practices, which affects model generalization.

- Poor internet connectivity and network infrastructure in rural and remote agricultural regions.
- Dependence on continuous power supply, which is often unreliable in many farming areas.
- Complexity of AI systems, making them difficult to understand, maintain and troubleshoot by end users.
- Insufficient technical support and extension services for training, maintenance and adoption of AI tools.
- Risk of unemployment or skill displacement, particularly in labor-intensive agricultural operations.

Advantages and Limitations of Artificial Intelligence

AI offers several advantages, including reduced human error, faster decision-making, 24×7 availability, multitasking capability and efficient handling of large and complex datasets. However, AI also has limitations such as high development costs, lack of emotional intelligence, potential job displacement and dependence on data quality. Therefore, AI should be viewed as a supportive tool rather than a replacement for human expertise.

Conclusion

Artificial Intelligence is rapidly transforming plant disease diagnosis and management by offering faster, accurate and cost-effective solutions. Through machine learning, deep learning, robotics, IoT and mobile applications, AI enables early disease detection, precision spraying and informed decision-making. Although challenges remain in terms of accessibility, cost and awareness, continued research, farmer training and institutional support can accelerate AI adoption in agriculture. In the future, AI-driven systems are expected to play a central role in sustainable crop protection, reducing chemical dependency, increasing productivity and ensuring food security. By integrating human knowledge with machine intelligence, AI represents a powerful tool for shaping the future of modern plant pathology.

Reference

- Abade, A. S., Ferreira, P. A., & Vidal, F. B. (2023). Artificial intelligence in plant disease diagnosis: Recent advances and future perspectives. *Frontiers in Plant Science*, 14.
- Bag, S., Kumar, S., & Tiwari, M. K. (2021). A review on artificial intelligence applications in plant disease detection and diagnosis. *Artificial Intelligence in Agriculture*, 5, 48–64.
- Barbedo, J. G. A. (2018). Impact of dataset size and variety on the effectiveness of deep learning and transfer learning for plant disease classification. *Computers and Electronics in Agriculture*, 153, 46–53.
- Boulent, J., Foucher, S., Théau, J., & St-Charles, P. L. (2019). Convolutional neural networks for the automatic identification of plant diseases. *Frontiers in Plant Science*, 10, 941.
- Fang, Y., & Ramasamy, R. P. (2015). Current and prospective methods for plant disease detection. *Biosensors*, 5(3), 537–561.
- Kamilaris, A., & Prenafeta-Boldu, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70–90.
- Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), 2674.
- Mahlein, A. K., Oerke, E. C., Steiner, U., & Dehne, H. W. (2012). Recent advances in sensing plant diseases for precision crop protection. *European Journal of Plant Pathology*, 133(1), 197–209.
- Mohanty, S. P., Hughes, D. P., & Salathe, M. (2016). Using deep learning for image-based plant disease detection. *Frontiers in Plant Science*, 7, 1419.
- Singh, A., Ganapathysubramanian, B., Singh, A. K., & Sarkar, S. (2016). Machine learning for high-throughput stress phenotyping in plants. *Trends in Plant Science*, 21(2), 110–124.

Digital Agriculture and Mobile-Based Farmer Advisory Services



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Abstract

Digital agriculture drives productivity, livelihoods, and resilience across various agricultural sectors for over 500 million farmers in the Global South. Attainable impacts through scalable, inclusive digital solutions amount to yield gains of 15–25% in Africa, Asia, and Latin America; improved access to routine information enhances resilience to costly variability. Effective mobile-based farmer advisory services yield timely, localized agronomic advice in text, audio, or video, adapting to farmers' specific contexts and knowledge gaps. Extrapolated to reach 95 million farmers, anticipated annual impacts include net income increases of \$1 billion; average additional income exceeds \$10 per farmer per month. Adoption relies on policy actions for trusted, open, equitable governance across the entire digital ecosystem covering data, platforms, and services. Private-sector partners across sectors digital, agricultural, financial play crucial roles in developing platforms, building economies of scale, and extending service coverage. Farmer organizations and community networks harness peer learning to increase uptake and enhance services. Prioritizing farmer empowerment through demand-driven technology stewardship, content sharing, and capacity strengthening fosters effective, trusted, and entrepreneurial systems open to all.

1. Introduction

Over the years, agricultural transformation has emerged as part of the broader development endeavor of many developing countries to eradicate poverty and hunger (Rajkhowa & Qaim, 2021). Given the pervasive presence of heterogeneous data from diverse spatial, temporal, and thematic domains, digital agriculture has begun to leverage the new opportunities offered by proliferating satellite systems, remote-sensing technologies, low-cost sensors, citizen and participatory science, social media, and big-data techniques. Evidence shows that small-farm agriculture can drive significant economic growth and poverty reduction under appropriate conditions by improving productivity and facilitating market participation (Wani et al., 2016). However, many smallholder farmers still face numerous challenges that lead to low productivity and scant second-level market participation. Digital extension services as one of the components of digital agriculture have thus emerged as a promising approach to enhance agricultural productivity and livelihoods. This guide focuses on one of the most promising types mobile-based farmer advisory services.

2. The Concept of Digital Agriculture

Digital agriculture encompasses the transformation of agricultural systems, practices, and support services through information and communication technology (ICT). It includes the use of advanced data collection technology and analytical solutions to address challenges across the agri-food value chain that remain unanswered through more traditional means. Digital agriculture includes models and technologies that allow agronomic, environmental, financial, and socio-economic challenges to be dynamically captured, informed, and addressed. The emergence of digital agriculture underscores the urgent need for farmers, agribusinesses, and other value chain actors to adopt and implement a new generation of data-driven advisory services as the global population soars toward ten billion (Wani et al., 2016). By empowering farmers and agribusinesses with timely access to contextualized, localized, and actionable guidance, it becomes possible to leapfrog productivity and propel national and regional economies toward upper-middle-income and high-income levels. The advancement of

digital agriculture is significantly improving the livelihoods and resilience of farmers and rural communities in an increasingly volatile economic and environmental landscape. Digital agriculture and mobile-based advisory services proffer an integrated model for the collection, analysis, dissemination, and application of data-driven insights across a wide array of agronomic, environmental, financial, and socio-economic challenges, thereby enhancing the productivity, resilience, and well-being of farm households. These challenges encompass climate variability and change; soil degradation, fertility, and water scarcity; pest pressure; market access; post-harvest losses; knowledge gaps; and the evolving agricultural practices of peers. Supporting transformation along these critical dimensions provides a pathway through which agricultural productivity may be raised sufficiently to offset the adverse effects of rapidly expanding land and water volumes consumed to produce food, feed, and fuels. (Caine et al., 2016)

3. Mobile-Based Farmer Advisory Services: An Overview

Mobile-based services providing timely and tailored advice to farmers hold great promise for enhancing productivity. Such services are particularly attractive in the context of climate change and rising demand for food. Agriculture faces intense pressure due to climate change. The effects of global warming are already observed, and the situation is expected to deteriorate further. The increasing frequency and intensity of climate-related shocks, such as extreme weather events threaten the lives and livelihoods of farming households, and the agricultural sector in general. Farmers worry increasingly about the impact of uncertainty regarding rainfall and temperature patterns. These increased risks manifest in less stable production and income flows, tending to drive climate-affected farmers toward abandoning agriculture and rural areas. Farmers and farming enterprises having access to reliable and timely information double their chances of increasing annual yields from plot crops during the cultivation period. However, agriculture is knowledge-intensive and information regarding weather and climate, soil and crop management, pest and disease occurrence, and other topics is still often not accessible to farmers. Finding and using this knowledge requires significant effort because extension services often lack the required quality and timeliness. Gaps still exist due to high staff turnover, insufficient operational budgets, and the inability to harness the latest information and knowledge efficiently to produce sustainable and targeted responses, even using existing information (Wani et al., 2016).

4. Core Components of Effective Advisory Systems

Advisory systems help farmers adapt practices, optimize resource allocation, and improve farming decisions. Using data on climate forecasts, pest and disease threats, soil nutrients, and water supply, advisory services determine appropriate management strategies suited to local conditions and communicate these recommendations to farmers with clear guidance and substantial relevance. For maximal adoption and impact, systems must have the five components listed below.

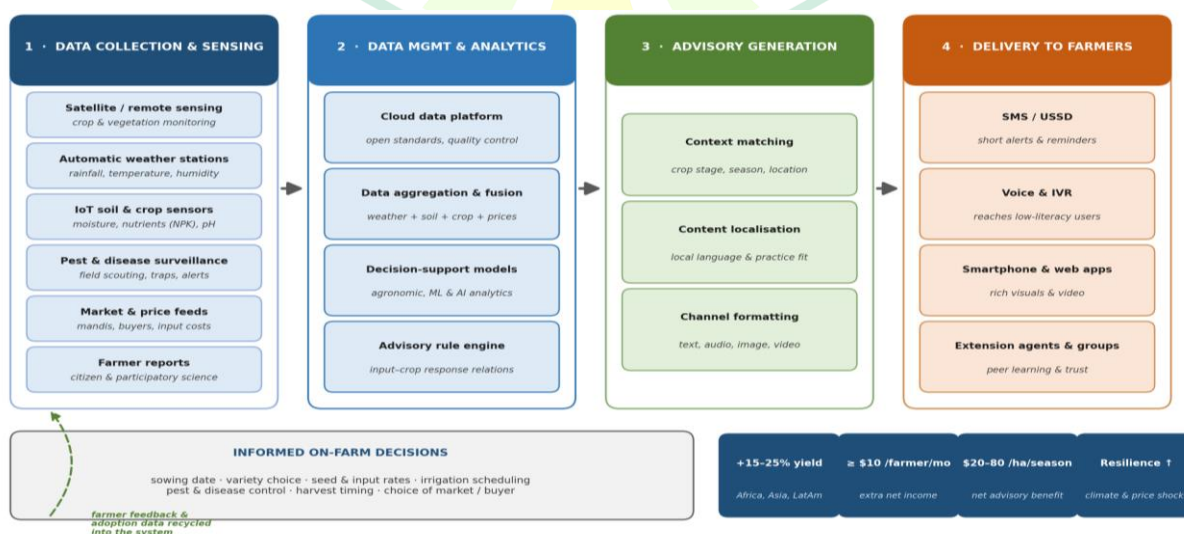


Figure 1. End-to-end architecture of a mobile-based farmer advisory system

4.1. Data Collection and Sensing Technologies

Farmers depend on high-quality data to make informed decisions. Digital agriculture relies on sensors, remote sensing, and IoT devices to collect weather, soil, crop, price, and pest data. Yet lack of data coverage, accuracy, and quality hampers the development and adoption of data-driven services. Most farmers in developing countries cannot access remotely sensed data (Bayih et al., 2022). To address these challenges, systems must combine indicators from diverse sources, ensuring both coverage and reliability. Flexible algorithms allow on-the-go data to complement missing sources, broadening the range of services feasible and improving their overall quality (Peets et al., 2012).

4.2. Decision Support Algorithms and AI

Digital agriculture solutions draw on diverse disciplines, including physical, biological, engineering, social sciences, and information technologies. Historically, crop and livestock management methods were mainly experiential and empirical, but these approaches may produce suboptimal results due to limited understanding of underlying mechanisms. Consequently, a number of agronomic and other models have been developed and continue to be refined. These frameworks describe physical and biological phenomena governing the growth, development, and yield of crops in relation to environmental conditions, factors affecting the quality of livestock products in connection with inputs, fertilization strategies and nutrient dynamics, agrochemical transport processes, soil erosion, climate change impacts, and many more aspects of agriculture (Thilakarathne et al., 2022)). Digital agriculture tools, including data analytics and artificial intelligence, enable farmers to use such models to simulate different management alternatives that maximize productivity while adhering to site-specific agronomic practices (Ibrahim et al., 2024). Through sensory technologies, large amounts of data are collected and transmitted on seasonal, spatial, and other dimensions. Specialized norms and procedures for measuring and monitoring agricultural, weather, and other phenomena have been established and refined to facilitate data capture. Aggregated data can then be analyzed and transformed into advice that benefits farmers. Thanks to easy access to information technology, computing power, and communications technology, model-driven agricultural services are being developed for crops, livestock, fish, and other agricultural domains over an extensive range of agricultural disciplines and technological levels around the world (Tsoumas et al., 2022).

Table 1. Core components of an effective mobile-based farmer advisory system

Component	Role in the system	Examples cited in the document
1. Data collection & sensing	Captures raw field-level data	Satellite / remote sensing, weather stations, IoT soil-crop sensors, pest, price & farmer-reported data
2. Data management & analytics	Turns raw data into decisions	Cloud platforms, data-quality standards, agronomic & machine-learning decision-support models
3. Content adaptation & localisation	Makes advice locally usable	Local languages & formats, season and crop-stage fit, postal-code-level specificity
4. Delivery channels & interfaces	Reaches every farmer type	SMS / USSD, voice & IVR for low-literacy users, smartphone / web apps, extension agents

(Wani, 2016)

4.3. Content Adaptation and Localization

Mobile-based farmer advisory systems must offer content in languages and formats accessible to users. Letters and semantics should resonate with local culture, customs, and practices. Recommendations must be applicable in relevant seasons and growth cycles (Caine et al., 2016). Farmers prefer information suited to local soil and moisture rather than county- or region-wide patterns. Becoming more specific about precise locations say, by postal code instead of a larger region enhances resonance (Shepherd, 2018). Bharat Agri's insights on customising advisory systems for farmers underscore a broader observation: projects should engage users from inception, integrating their preferences on tone, medium, timing, and complexity throughout the advisory offer's design and roll-out.

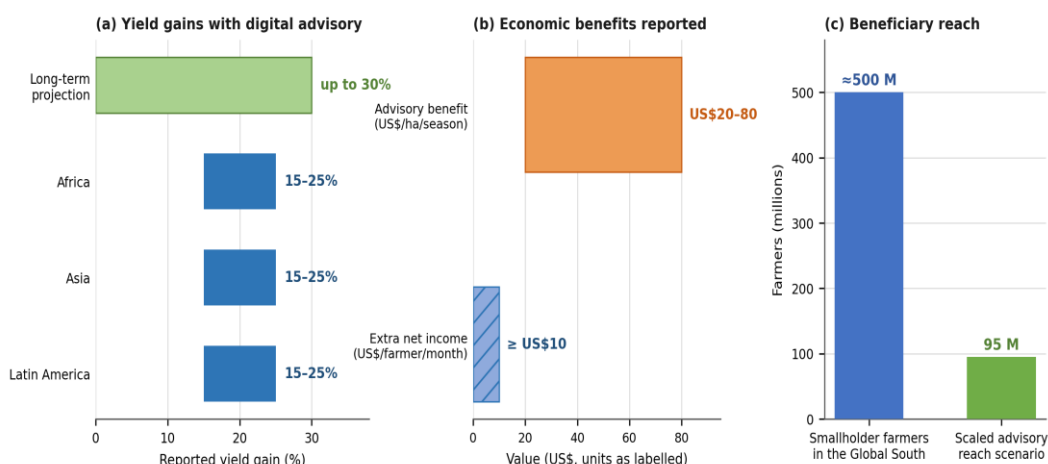


Figure 2. Documented impact magnitudes of digital

4.4. Delivery Channels and User Interfaces

Rural advisors as the main motivators to improve field productivity and livelihoods influence farmers' livelihoods positively. According to (Rajkhowa & Qaim, 2021), several studies show that providing farmers with market and weather information via mobile phones or Internet can promote productivity and market efficiency. Recent studies analyze Internet and smartphone use in rural developing areas, finding positive effects on household welfare. (Caine et al., 2016) emphasize the capacity of advisory services via mobile-based technology. Mobile channels offer advantages over other information providers, but the quality of each information strand may not be sufficient to ensure credibility. SMS is popular but excludes illiterate farmers and women, and messages can be too brief for complex topics. Voice services include native voice, IVR, and outbound messaging, while text-based methods include SMS, USSD, and Text-to-Speech. With decreasing costs of smartphones, some projects have developed mobile and web apps, offering visual and video content for complex messages and illiterate audiences.

5. Benefits for Farmers and Rural Economies

Mobile-based farmer advisory services, encompassing real-time, location-specific information and tailored recommendations, represent one of the most promising digital agriculture applications. Their overarching objective is to enhance productivity, livelihoods, and resilience, thereby facilitating sustainable development. The productivity of crop and livestock operations depends heavily on decisions made throughout the production process. Countries experience significant yield gaps when comparing actual and potential productivity, often exceeding 50%. These gaps divert substantial investments, undermine food security, constrain farm income, and increase the exposure of rural households to climate risks. Poor decision-making contributes to these considerable yield gaps, as farmers frequently lack access to timely, context-specific information regarding inputs, practices, and problems throughout the growing season (Rajkhowa & Qaim, 2021). Policymakers consistently emphasize, and farmers explicitly request, improved access to useful information as a means of addressing this challenge. Conventionally, public and private agricultural advisory services have operated through face-to-face consultations with trained experts, thereby limiting coverage and accessibility. Tawanchai & Patthasil (2020) demonstrate that 25% of farmers many in remote areas are indeed disconnected from traditional information channels. Mobile-based advisory services harness telecommunication infrastructure to close this gap, supporting access to up-to-date, personalized guidance through one or more complementary delivery mechanisms tailored to the specific circumstances of farmers.

5.1. Yield Optimization and Resource Efficiency

Intensified competition for limited water and land resources enforces the need for crop input efficiency, prompt and appropriate pest and disease control, proper harvest timing, crop diversification, changed planting dates as well as other measures able to either relax the constraints imposed by natural resources or compensate for any losses caused by a changing climate. Optimization of the employment of crop inputs allows to decrease costs, constrain excessive fertilization under high and uncertain prices and raise prices benefits underlined by the

availability of agricultural extension. Efficiency of crop production indispensable in times of climate variability and unstable prices (Rajkhowa & Qaim, 2021) enables farmers to maintain economic viability and at the same-time stabilizes production, thereby enabling even small holders to cumulate banks deposits, pre harvest sales contracts and capital for future investment, the basis pillar of household resilience (Gallardo et al., 2021) stimulating not only investments to enhance productivity but also stimulating adaptation practices with moderate specificity to enable farmers to escape from high fertility soils already pre paqueté to in periods under climate variability.

5.2. Risk Management and Resilience

In the face of climate variability and uncertainty, digital advisory supports risk management and resilience in three key ways: early warning systems for climate-related hazards, promotion of diversification strategies, and provision of adaptive practices (Maru & Tafuna'I, 2018). Timely alerts about extreme weather such as droughts or flooding allow farmers to take preventive action, such as adjusting planting dates or changing crop varieties (Caine et al., 2016). Advisory services that suggest options for diversifying production across crops, livestock, or value-added activities enhance both value chain and income diversification, increasing overall resilience to climatic shifts (Ali et al., 2018). In a similar vein, advice on practicing climate-smart agriculture, soil conservation, or water-efficient techniques helps farmers adapt to changing conditions while protecting the productivity of their land.

5.3. Market Linkages and Income Stability

Digital technologies can dramatically lower communication and transaction costs, heightening market efficiency alongside the corresponding capacity to spur economic growth and alleviate poverty (Rajkhowa & Qaim, 2021). In turn, mobile phones enhance market access, boost farm productivity and income, and improve nutrition, gender equality, off-farm employment, and migration. The emergence of new ICTs particularly internet platforms and smartphones continues to broaden the horizons for smallholder farmers. Pre-sale market information strengthens household revenue and income stream stability through more informed post-harvest decisions (Caine et al., 2016). Market-linking services mitigate price risk and guarantee the sale of crops via forward contracts with pre-arranged customer partnerships, contributing to more reliable revenues. The capacity for efficient price discovery particularly critical for high-volatility crops advances household financial management practices, again enhancing revenue stability through the establishment of clear contracts along the value chain, notably for dairy, horticultural, and high-value crops.

6. Case Studies: Success Stories from Diverse Contexts

Farmer advisory services delivered via mobile platforms provide actionable insights to increase crop productivity, enhance resource efficiency, and build resilience against climate shocks. In sub-Saharan Africa, such services for smallholdings have driven widely documented productivity gains; for instance, farm demonstrations in the Malawi Fertilizer and Maize Revolutions yielded 1.5–5.7 times higher than average revenue per hectare (Caine et al., 2016). In South Asia, models focused on findable, affordable, and accessible digital learning are accelerating widespread adoption. Adapting existing agricultural practices to off-the-shelf products improved profitability of horticultural crops by 25% for several thousand firms across Latin America.

6.1. Smallholder Farms in Sub-Saharan Africa

Smallholder farmers in Sub-Saharan Africa encounter several persistent challenges that inhibit agricultural productivity and limit their participation in markets. Broadly speaking, these hurdles center around limited access to information, technologies, and financial services and are often aggravated by low and variable demand for their produce (Rajkhowa & Qaim, 2021). Conventional extension services, long promoted as a mechanism for improving both access to information and agricultural performance, have proven difficult to scale and, consequently, remain of limited effectiveness. This poor performance can be attributed, at least in part, to the fact that adequately funding these services generally proves difficult, coupled with the inability of existing services to provide the necessary site-specific information to meet local agricultural needs (Caine et al., 2016). Under these conditions, extensions delivered electronically via mobile phones or internet platforms have, in theory, the potential to circumvent other constraints and have been receiving increasing attention as a means of ameliorating agricultural challenges. Empirical evidence assessing the associated impacts remains, however, quite limited.

6.2. Emerging Markets in South Asia

Emerging markets in South Asia have witnessed considerable innovation in mobile-based agricultural services. Initiatives such as India's mKisan and Green Phablet have enhanced farmers' access to market information and technology. Projects in Tanzania, Kenya, and Ethiopia similarly employ ICT to provide agricultural extension, weather data, and market information, thereby improving decision-making. Mobile services like Farmerline's voice messaging and Weather Data integrations furnish farmers with real-time information. Research underscores mobile technologies' potential for reducing transaction costs and fostering sustainable practices; numerous programs have effectively leveraged ICT to bolster productivity and market access (Caine et al., 2016). Digital technologies can lower communication and transaction costs, enhance market efficiency, spur economic growth, and alleviate poverty. Mobile phones, in particular, increase market access, boost productivity and income, and improve welfare dimensions such as nutrition, gender equality, off-farm employment, and migration. The evolution of high-speed internet and smartphones further amplifies smallholders' livelihood prospects (Rajkhowa & Qaim, 2021).

6.3. Horticulture-centric Enterprises in Latin America

Horticulture plays a key role in food security, economic growth, and nutrition improvement, especially in developing countries where agriculture is the main economic activity and source of livelihood (Maginga et al., 2018). Horticulture-centric enterprises such as vegetable and flower production generate income throughout the year and support agribusiness activities like transport and packaging, improving local economies (Shepherd, 2018). An ICT-enabled extension support system for horticulture can guide farmers in selecting suitable vegetables based on location-specific climatic conditions and provide other advisory services on a timely basis. Timely advice on crop selection leads to better productivity and improves access to broader markets, thereby advancing the horticulture sector. Integrating mobile advisory into broader agribusiness initiatives accelerates adoption and enhances economy-wide benefits.

7. Implementation Roadmap for Stakeholders

Mobile-based farmer advisory services represent a promising approach to increasing farm productivity, incomes, and resilience. They deliver timely, location-specific recommendations that help farmers optimize decision-making while significantly lowering the cost of advisory services per user. User experiences across diverse contexts illustrate that such systems are feasible for a variety of crops and farming situations, with software components that can be widely reused. The evidence base for impact is building, with estimates indicating that adoption can yield economic benefits of \$20 to \$80 per hectare of crops including cereals, grains, and vegetables per farming season. Gains from mobile-based advisory appear to be especially valuable in the face of climate variability. Mobile-based advisory systems provide several options for outreach that can be tailored to specific user circumstances and are often able to achieve large-scale farmer uptake and cost-effective delivery across large geographic areas (Wani et al., 2016). Four differentiated components make advisory services more effective: (Caine et al., 2016). The first is improved data collection from alternative sensing technologies, which can enhance applicability and relevance. The second is development of robust decision support algorithms and models for better understanding of input–crop performance relationships.

Table 2. Implementation Roadmap for Stakeholders

Impact indicator	Reported value	Context
Addressable farmer base	> 500 million	Smallholders across the Global South
Scaled reach scenario	95 million farmers	Global extrapolation of advisory services
Yield gains	15–25%	Africa, Asia and Latin America
Net income gain at scale	> US\$10 farmer ⁻¹ month ⁻¹	≈ US\$1 billion additional income per year
Advisory benefit per hectare	US\$20–80 season ⁻¹	Cereals, grains and vegetables
Access to timely information	≈ 2× likelihood of yield rise	Plot crops during cultivation period
Long-term potential	Up to 30% yield / resource gain	≈ US\$100–360 billion yr ⁻¹ in staple crops

(Gallardo et al., 2021)

7.1. Government and Policy Interventions

Agricultural policies can help to facilitate the adoption and upscaling of digital advisory systems. Regulatory interventions that can stimulate these efforts include policies and investment assistance that encourage companies to develop advisory solutions; subsidies for farmers to purchase smartphones with strong connectivity; policies stimulating private sector capacity building for advisory service delivery; standards and frameworks that facilitate data sharing between different advisory systems; and third-party evaluation of advisory systems to inform farmers about content veracity and reliability (Rajkhowa & Qaim, 2021).

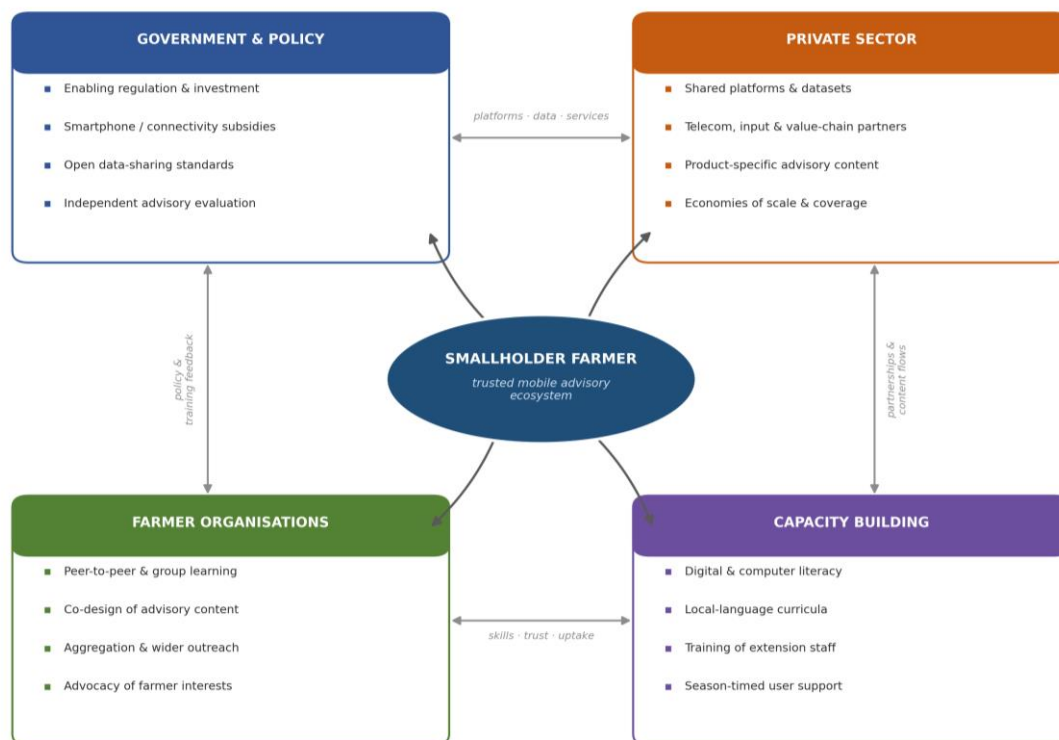


Figure 3. Multi-stakeholder implementation framework for mobile-based farmer advisory services.

Government

7.2. Private Sector Roles and Partnerships

The private sector plays an instrumental role in advisory systems by collaborating on platforms, contributing data sets, and providing services. Combining public and private datasets can immensely enrich the evidence base for advisory systems (Caine et al., 2016). Platforms developed or owned by the private sector such as those of telecommunications companies, seed and fertilizer businesses, and agricultural value chain firms can complement open-source platforms. When farmer consultations occur, companies can share advisory content specific to their products. Such arrangements can facilitate collaborations where governmental, non-governmental, and private institutions combine their respective platforms, data, and services to create a comprehensive advisory system. To increase farmer uptake, farmer organizations can assist in shaping the information transmitted through the private-sector platform (Quaye et al., 2018).

7.3. Farmer Organizations and Community Networks

Smallholder farmers are often constrained by limited access to information on agricultural practices and critical inputs. This deficiency leads to lower productivity, resource inefficiencies, reduced farm incomes, and heightened vulnerability to climate variability (Rajkhowa & Qaim, 2021). Consequently, many countries are investing in services that assist farmers in making the best possible decisions based on available information. Mobile-based digital advisory services provide recommendations on crop management practices, equipment procurement, and input rates, drafting contracts and linking farmers with buyers within the value chain (Caine et al., 2016). Recent evidence indicates these services offer considerable benefits to farmers and can transform rural economies.

Collective action and peer-to-peer learning through community organizations enhance the reach and effectiveness of advisory services. Although most advisory systems deliver inputs directly to farmers, learning from peers and with a group substantially increases the uptake of new practices and technologies. Collective learning is an effective mechanism, particularly in developing countries, where farmers often face similar agricultural constraints and technologies. In-depth dialogues within community or farmer organizations may be more productive than one-way guidance from public or private advisory systems. These organizations assume various roles, including information dissemination, experimentation, sharing knowledge and experiences, and fostering discussion and analysis. They can be community-based organizations, cooperatives, or farmer organizations.

7.4. Capacity Building and Training

Capacity building and training enable sustainable and wide-scale adoption of digital agriculture and mobile-based farmer advisory services. Many adopters require training to establish awareness and guidance on operations, and related costs involve travel expenses incurred by extension staff vis-à-vis rural areas (Shepherd, 2018). Training extends to staff and personnel with varying components, and the lack of computer literacy presents obstacles to implementation. Attention to requirements for new technologies and digital tools optimizes advisory implementation (Landmann, 2018). Tailored curricula that accommodate local language, seasonal timing, and diverse literacy levels further support sustained and impactful uptake. Capacity building and training can optimize sustainable and large-scale adoption of advisory systems. Awareness of tools, functionalities, and opportunities typically constitutes the initial phase, demanding significant investments of time and competing with other priorities. Subsequent training may engage varied audience segments tasked with implementation, ranging from policy and high-level personnel to extension field staff and user groups. Projects often confront computer literacy challenges among personnel on the ground, particularly in rural settings. Similarly, initial adoption of smartphones and web-based technologies triggers substantial demands on knowledge and skills across multiple system dimensions.

8. Challenges and Mitigation Strategies

Farmers in both intensively cultivated and marginal regions face a multitude of threats and challenges, including the destructive impacts of climate change, market volatility, and adverse political factors. Mobile-based technologies offer farmers a new way to obtain timely information on climatic conditions, pests and diseases, and prices. Digital farm advisory services assist farmers in adapting to climate shocks by providing early warning systems for rainfall, pest and disease outbreaks, and content output that integrates data on weather, pests, soil, and price risk at multiple spatial and temporal scales. Such services also help farmers to stabilize yields and improve linkages with supply chains, achieving greater income stability when external shocks occur (Lemeilleur et al., 2019). Farmers lacking advisory services can obtain information in more informal and ad hoc ways. Some farmers highly dependent on non-digital processes engage in what is termed “acquiring information without a degree of choice in the selection of information” (Caine et al., 2016). Within these operating environments, mobile-based advisory services can follow an offline-first strategy that facilitates information and services when connectivity is unavailable, covering farmers with inconsistent connectivity.

8.1. Connectivity and Digital Literacy Barriers

Mobile-based farmer advisory services have the potential to improve agricultural productivity and livelihoods on smallholder farms in developing countries, but connectivity and digital literacy limitations present major barriers to adoption (Rajkhowa & Qaim, 2021). Many farmers in poor countries have low-quality agricultural information available to them, and efforts to disseminate knowledge through traditional extension services have yielded mixed results. For many farmers, their first experience with digital information services occurs through mobile phones, which can enable improved knowledge dissemination and lower information retrieval and market search costs. Nevertheless, service uptake remains very low in many countries where the potential impact on productivity and welfare would be greatest. Farmers’ limited use of mobile agricultural services stems from a combination of low access to mobile phones, unreliable networks, poor literacy and education, high generalised input costs, supply chain inefficiencies, distrust in private-sector information sources, and in some settings, gender-and-age-based barriers. Advisory services can mitigate some of these challenges by offering pre-emptive information such as

call-in reminders, warning alerts, weather data, and market updates that reduce the ability of profiteers to conduct opportunistic practices against farmers.

8.2. Data Privacy, Ownership, and Trust

Data has become an essential enabler of productivity and resilience in agriculture. Digital technologies provide farmers all over the world with relevant data that can transform productivity, increase rural incomes, and address broader challenges such as climate change. Digital agriculture, defined as “the Internet of Things (IoT), artificial intelligence (AI) and blockchain for sustainable productivity and resilient livelihoods” (Ivanov, 2020, p. 72), supports the accurate and timely decision-making required to realize such gains. Mobile-based farmer advisory services, typically delivered via voice or SMS, have been widely demonstrated to provide such data effectively. By leveraging remote-sensed and crowd-sourced data with sophisticated algorithms, these systems guide farmers toward higher yields, lower costs, and better access to markets (Pacheco et al., 2022) in an era of increasingly uncertain climatic, economic, and disciplinary conditions. Though benefits may seem self-evident, a wide range of ethical considerations including trust, ownership, consent, and transparency hinder the large-scale adoption of digital agriculture solutions in low- and middle-income countries. Significant work is still required to create a market for data-driven decision-making in agriculture. Building such a market will not only provide direct economic benefits but also enable deeper adoption of other digitalization techniques, accelerate the development of critical digital infrastructure, and address widespread gaps in farmer knowledge.

9. The Future of Digital Agriculture and Mobile Advisory

Digital agriculture is a powerful means of improving productivity, enhancing resilience, reducing poverty, and promoting the economic empowerment of smallholder farmers. As conventional agricultural extension systems often lack reach, relevance, and timeliness, low-cost mobile-based advisory services have emerged as an attractive alternative. Accessible through mobile phones and other devices, these services deliver tailored, actionable, and timely pre- and post-planting agricultural advice, directly addressing farmers' needs (Rajkhowa & Qaim, 2021). Quantitative evidence from 23 digital agriculture projects globally indicates that mobile advisory services can significantly increase farm productivity, enhance incomes, and strengthen economic resilience (PWani et al., 2016). Further investigation suggests that global models offering targeted advisory services through mobile devices hold the greatest potential to stimulate agricultural transformation, specifically by improving smallholder farmer productivity, relieving operating capital shortages, enabling timely access to relevant market information, and addressing the escalating uncertainty and unpredictability caused by climate change.

9.1. Emerging Technologies on the Horizon

Digital agriculture coupled with mobile-based advisory services has the potential to drive a transformation in agricultural productivity, livelihoods and resilience. To assess this potential and how to achieve it, a comprehensive mapping of trends, technologies, business models and case studies is presented based on extensive empirical evidence collected from the literature and debates in international conferences. Detailed estimates of productivity and other impacts associated with these interventions are provided based on documented cases in a variety of contexts. Digital agriculture encompasses a far broader range of activities than mobile-based advisory services, but these services are one of the most mature and widely adopted intervention areas for which substantial evidence exists regarding their impact. Wide-ranging effects on productivity, income stability and risk mitigation are highlighted, together with robust case studies demonstrating success under diverse socio-economic conditions and stressing enabling roles played by government and the private sector (Rajkhowa & Qaim, 2021).

9.2. Scalable Models for Global Impact

Digital agriculture has the potential to transform millions of farmers' livelihoods, increase food production, enhance climate resilience, and drive economic growth. Yet a recent landscape analysis of global public and private advisory services has found that the commitment to expand mobile-based advisory services has waned significantly since the COVID-19 pandemic. Despite scalable models being available to address farmers' urgent challenges and conditions for sustainable impact largely understood, progress is limited. Targeted actions by governments, the private sector, and local organizations can reinvigorate momentum. The analytical framework presented in this guide provides a foundation for these actions. The concept of mobile-based digital agriculture links critical drivers of farmers' livelihoods field productivity, access to markets, and resilience to climate shocks

to a broader definition of digital agriculture that includes data management, data science, and analytics. Digital agriculture encompasses a wider range of technologies but is best understood by viewing these interdependent drivers as complementary. Likewise, mobile-based farmer advisory services including those delivered via SMS, voice calls, apps, and other modalities represent a particular subset of digital agriculture and connect directly to the advisory ecosystem recognised by practitioners globally (Rajkhowa & Qaim, 2021). Most of the farmer-oriented advisory services exist on closed proprietary platforms governed by either the government or private companies. The platforms are restricted to proprietary data exchange and engagement with the farmer. The closure of government-run platforms, or considerable reduction in the national coverage of Free and Open-Source Software (FOSS) platforms, means that rights, ownership, and privacy of the farmer-data is in question. Although protective measures can be put in place, the nature of permission granted for the use of farmer-generated data from proprietary platforms by the government and financial private sector, respectively, remains uncertain. It is felt that Open-Source-Science Platforms integrated with FOSS tools offer the only scalable route, envisaging the gradual collective building of national data silos with self-protective access and governance models scalable up to the national level (Caine et al., 2016).

9.3. Strategic Calls to Action for Readers

Digital agriculture, driven by innovations in mobile-based extension services, has the potential to transform productivity, improve livelihoods, and enhance resilience among farmers, SMEs, and rural communities. Projections indicate that such solutions could deliver gains of up to 30 percent in crop yields or resource use the equivalent of \$100 billion to \$360 billion annually across staple crops in developing countries. Despite uneven adoption rates across regions, a diverse array of successful models already exists, spanning sub-Saharan Africa, South Asia, and Latin America. These examples demonstrate that digital agriculture need not be limited by investment, infrastructural, or institutional challenges. Mobilizing investment, innovation, and partnerships to scale and replicate such models remains an urgent priority. Digital technologies, data-driven insights, and AI are but a starting point. Integrated advisory systems, bridging knowledge gaps across all farming activities, shape the service offerings that establish a foundation for agribusiness growth. Policymakers can create enabling environments, develop multi-actor partnerships, and establish integrated systems to empower farmers and drive broader transformation (Kropff et al., 2019). Empowering smallholder farmers remains essential to achieving farm- and sector-level outcomes. Collective action through farmer organizations fosters group learning, identifies common challenges, extends outreach for specialized services, and enables farmers to adopt innovative practices. Farmer organizations support partnerships, broker agreements, and advocate for farmers' voices in shaping advisory interventions. Public and private sector actors interested in advancing digital agriculture should consider the priority actions for governments, private sector entities, and farmer organizations (Caine et al., 2016).

10. Conclusion

Digital agriculture enhances agricultural productivity, farmer livelihoods, and rural resilience to shocks. Diverse evidence from different contexts quantifies the impact of mobile-based farming advisory services and indicates high returns. These services are also relevant in many developed economies, where they can boost farm efficiency, sustainability, and competitiveness. Nevertheless, to harness the transformative potential of digital agriculture through mobile-based advisory services and multiply the corresponding benefits, governments, the private sector, development organizations, and farmer organizations must take proactive action. Digital agriculture and mobile advisory services must scale-up to empower millions of farmers to transform their farming systems and agricultural practices. This guide has highlighted key principles for the design and implementation of farmer-focused mobile advisory services and the multi-stakeholder solutions necessary to establish and scale them. Digital agriculture allows farmers to address diverse challenges pragmatically and effectively by enabling timely insights and helping them learn adaptive practices based on past experiences. The guidance addressing climate variability, transforming dietary patterns, and exploring commodity diversification links with the 2030 Agenda for sustainable development, particularly goals.

References:

Rajkhowa, P., & Qaim, M. (2021). Personalized digital extension services and agricultural performance: Evidence from smallholder farmers in India. *PLoS one*, 16(10), e0259319.

- Wani, S. P., Bergvinson, D., Raju, K. V., Gaur, P. M., & Varshney, R. K. (2016). Mission India for transforming agriculture (MITrA).
- Bayih, A. Z., Morales, J., Assabie, Y., & De By, R. A. (2022). Utilization of internet of things and wireless sensor networks for sustainable smallholder agriculture. *Sensors*, 22(9), 3273.
- Peets, S., Mouazen, A. M., Blackburn, K., Kuang, B., & Wiebensohn, J. (2012). Methods and procedures for automatic collection and management of data acquired from on-the-go sensors with application to on-the-go soil sensors. *Computers and Electronics in Agriculture*, 81, 104-112.
- Thilakarathne, N. N., Bakar, M. S. A., Abas, P. E., & Yassin, H. (2022). A cloud enabled crop recommendation platform for machine learning-driven precision farming. *Sensors*, 22(16), 6299.
- Ibrahim, A., Senthilkumar, K., & Saito, K. (2024). Evaluating responses by ChatGPT to farmers' questions on irrigated lowland rice cultivation in Nigeria. *Scientific Reports*, 14(1), 3407.
- Tsoumas, I., Giannarakis, G., Sitokonstantinou, V., Koukos, A., Loka, D., Bartsotas, N., ... & Athanasiadis, I. (2023, June). Evaluating digital agriculture recommendations with causal inference. In *Proceedings of the AAAI Conference on Artificial Intelligence* (Vol. 37, No. 12, pp. 14514-14522).
- Shepherd, A. (2016). *Lessons for sustainability: Failing to scale ICT4Ag-enabled services*. CTA.
- Maru, A., Bourgeois, R., & Mayer, W. (2014). ICTs improving family farming. *Proceedings of AFITA, 2014*.
- Ali, M., Man, N., Abd Latif, I., Muharam, F. M., & Omar, S. Z. (2018). The use of information and communication technologies in agricultural risk management by the agricultural extension services in Malaysia. *International Journal of Agriculture Environment and Food Sciences*, 2(1), 29-35.
- Maginga, T., Nordey, T., & Dida, M. (2018). Extension system for improving the management of vegetable cropping systems.
- Quaye, W., Bist, R., Yeboah, A., Osei, C., Asafu-Adjaye, N. Y., & Fiafor, B. (2018). Private sector-led business model for meeting changing needs of agribusiness value chains actors in Ghana based on mobile-based ICT-enabled field agents.
- Landmann, D. H. (2018). *Capacity development of small-scale farmers in developing countries: Analysis of preferences and the role of information and communication technologies*. Niedersächsische Staats-und Universitätsbibliothek Göttingen.
- Lemeilleur, S., Maître-d'Hôtel, É., Lepiller, O., & Hobeika, A. (2019). Uncertain impacts of new technologies: The case of digital agriculture and blockchains. *FOOD SYSTEMS AT RISK*, 91.
- Fadul-Pacheco, L., Wangen, S. R., da Silva, T. E., & Cabrera, V. E. (2022). Addressing data bottlenecks in the dairy farm industry. *Animals*, 12(6), 721.
- Kropff, W., Pilgrim, V., & Neate, P. J. (2019). *Overcoming challenges to digital agribusiness start-ups*. CTA.

Gene Editing and Its Future in Agriculture



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Abstract

The motivation for gene editing is grounded in societal demands for environmental sustainability, nutritional enhancement, and improved productivity. Gene editing offers higher precision than conventional breeding methods, enabling fewer unintended mutations and thereby facilitating regulatory approval in some regions. For crops and livestock with complex, polygenic traits under established breeding programmes, gene editing can supplement conventional approaches. The technology addresses food-security challenges arising from population growth and climate change. Fundamental lines of inquiry are: (i) What agricultural gene-editing applications and traits have been reported in the literature? (ii) To what extent have gene-edited biocontrol agents, feed additives, production strains, ripening inhibitors, silage enhancers, and generation-time extensions been addressed? Emergent topics within agriculture and beyond include: a convergence of gene editing and synthetic biology, the interface with precision agriculture, and the impacts of public acceptance and science communication on development trajectories. Dietary patterns shape consumer health through their influences on obesity, diabetes, cardiovascular disease, and nutrition-related cancers. Food consumption carries both nutritional and environmental dimensions, and public pressures to reduce greenhouse gas (GHG) emissions are rising. Thus, gene editing could enhance traits supported by evolving societal perceptions a novel capability compared to earlier biotechnologies. Such improvements could also reduce agriculture's ecological footprint, with gene-edited input traits attracting attention alongside nutritious-output traits.

1. Introduction

Feeding the world amid climate change and declining biodiversity requires addressing population growth, dietary shifts, and food systems sustainability. Gene editing enables targeted genome improvements that accelerate breeding, meet selective pressure, and enhance emerging traits. Precision guidance shortens timelines and increases efficiency, as highlighted by the adoption of genome editing in crops and livestock. CRISPR/Cas14 applications represent a significant milestone in genome editing, thanks to simplicity and adaptability for targeted DNA modification, transcriptome regulation, nucleoprotein tagging, epigenome engineering, genome imaging, and transgene-free gene delivery (Lyzenga et al., 2021). Referred to as biotechnology 2.0, these technologies prompt ethical considerations, risk analysis, and equitable access to mitigate monopolistic practices and safeguard innovation (Zhang et al., 2018). Gene editing and regulation in crops, livestock, and fermentation systems closely link to population dynamics, dietary diversification, climate change, and biodiversity loss. Agricultural species represent the first globally adopted artificial intelligence platform, transforming agricultural production and connected human activities. Computer vision models support breeding processes, enabling automation of physiological trait analyses, herbivory damage detection, and the evaluation of variety adaptability to development-stage stress (Sprink et al., 2019).

2. Foundations of Gene Editing

Gene editing is an exciting new area of research for the specific modification of genomes in living organisms. In the past few years some major advances have taken place that led to a better understanding of the workings of gene editing and its applications, along with some substantial progress in agricultural uses (Zhang et al., 2018). Earlier technologies such as targeted gene replacement using homologous recombination, zinc finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs) have provided important insight, but such approaches have often proven relatively complex and quite slow to achieve a desired modification in a target organism or cell. The arrival of the Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology in 2012, an ingenious system exploited by bacteria to combat viruses, marked a game-changing shift

toward faster, less costly and more flexible genome target editing (Thomson et al., 2022). Subsequent refinements introduced base editing and prime editing (Koning, 2017). Still, the consideration of off-target modifications and the inevitable repair of DNA double strand breaks by non-homologous end joining remains relevant in any gene editing attempt. The main present gene editing mechanisms and progress in the agricultural field are now overviewed. Gene Editing and Its Future in Agriculture Research aiming to develop agricultural organisms that require fewer inputs or can better cope with climate change is gaining priority. Thanks to the continuous development of gene sequencing techniques, the genetic structures of many organisms are now fully described. Therefore, the identification of regions of interest (genes or genetic variants) that can improve specific functionalities has become easier. Such efforts may benefit from applying gene editing systems to either precisely disrupt the gene to study its impact or to introduce constructive mutations without generating transgene-derived sequences (introgressible transgene) (Prado et al., 2024).

CRISPR-Cas9 editing in a plant cell

A sequence-specific nuclease creates a targeted break; the cell repairs the break to create the edit.

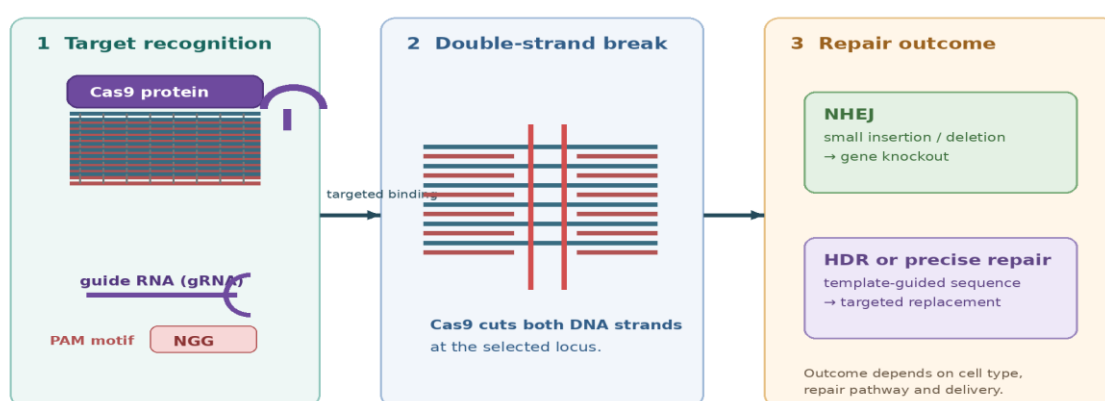


Figure 1. Targeted CRISPR–Cas9 editing Jinek et al. (2012) and Doudna and Charpentier (2014).

2.1. Historical Development

Gene editing originated with the advent of recombinant DNA technology in the early 1970s, which laid the foundation for genetic engineering. These pioneering efforts set the stage for various events representing technological improvement (such as sequence-specific nucleases) and a fundamental change in conceptual approach (from transgenic to genome editing). A comprehensive overview of the major developments in genome editing, beginning with the first DNA constructs containing a restriction enzyme, provides context for understanding the scientific advancements and issues that have emerged. The introduction of recombinant DNA technology allowed the construction of a DNA molecule containing the EcoRI restriction endonuclease gene (Thomson et al., 2022) followed by EcoRI recognition sites, significantly increasing the number of vectors available for cloning and providing an open-source option for molecular biologists in academia and industry. The introduction of λ -based vectors and the development of the ligation-independent cloning approach (Huang & Puchta, 2021) further simplified the introduction of foreign sequences into plasmids. The characterization of the first zinc finger nuclease (ZFN) that targeted a sequence-specific DNA double-strand break (DSB) (Souza Prado et al., 2024) marked the first genome-editing commercial application directed toward reducing the production of human-immune-response-inducing protein in mice for the development of therapeutic protein-secreting mice. The first potato and rice plants containing ZFN-modified resistance-increasing traits were successfully obtained in 2009 and 2010, respectively. These historical milestones set the stage for further exploration and assessment of the comparative advantages and disadvantages of ZFNs, transcription activator-like effectors (TALEs), and clustered regularly interspaced short palindromic repeat (CRISPR)-associated nucleases.

2.2. Core Technologies

Gene editing technologies have an unprecedented capacity for precise modifications in genomes of plants, animals, and microbes, and potential applications in agriculture are attracting increasing

interest. Discovery of the CRISPR/Cas mechanism revolutionized the genome-editing field, embedding a new paradigm of target search and discrimination into the technology landscape. Despite existing editing platforms, ongoing research on new technologies and improvements of CVR/Cas9 gene editing still represents a highly active field. Gene editing techniques promise significant improvements in productivity of agricultural systems, while addressing food security and environmental concerns (Thomson et al., 2022). Advancements in genome sequencing rapidly expanded the understanding of biological processes governing traits of interest, their location, and method of generational transmission. Methods enabling extraction and insertion of specific genetic information into genomes are available for early-stage and back-crossing methodologies. Genome editing broadens the scope of achievable targets, fulfilling market demand for high-end, nutritionally dense food products through classical, poorly standardised breeding methods well embedded in lengthy progress and investor scrutiny (Patel et al., 2023). New traits have been successfully engineered in crops through Integrated CRISPR/Cas9 editing, accessing both causal mutations and previously hidden alleles through integration of materials from closely related species. Reduction of genomic transformation stacks, saving time and resources for downstream building and subsequent regulatory hurdles, resolves some haplotype bottlenecks (Prado et al., 2024). Selection of traits heavily influenced by genome editing further accesses an improved bioproduction microbe facilitating straightforward production of ingredients such as organic acids at industrial scales.

Table 1: Gene-editing approaches relevant to agriculture

Approach	What it changes	Agricultural relevance	Main limitation
CRISPR–Cas9	Targeted DNA break; repair can disrupt a gene.	Fast, programmable editing of traits such as disease response. (Jinek et al., 2012)	Off-target edits and variable repair outcomes require screening.
Base editing	Single-base conversion without a conventional double-strand break.	Useful for fine-tuning proteins or regulatory sequences. (Komor et al., 2016)	Limited conversion types and editing windows.
Prime editing	“Search-and-replace” edits guided by a pegRNA.	Potential for precise small substitutions, insertions or deletions. (Anzalone et al., 2019)	Delivery and efficiency can be challenging in crops.
TALENs / ZFNs	Protein-guided, site-specific nuclease activity.	Established alternative when guide-RNA delivery is unsuitable. (Gaj et al., 2013)	Design is more laborious than CRISPR systems.

2.3. Mechanisms of Action

Gene editing techniques commonly rely on one or more nuclear-targeting elements to introduce changes in targeted genomic loci of a given organism. Nuclear-targeting elements allow gene editing tools to travel from the cytoplasm to the nucleus. Genome-targeting tools locate double-stranded breaks (DSB) or substituted nucleotides or groups within the host nuclear genome. After target recognition, the editing system executes either a DSB repair pathway or a precision base-modification process. When a DSB is generated, the editing machinery switches the target editing mechanism from base conversion to DSB repair. Subsequently, Base-excision repair (BER) operates on selected bases after cellular removal of the editing machinery. Both target repair systems evolve in a mutually exclusive manner that is independent of early target processing. Repair of DSBs represented by CRISPR systems depends on either non-homologous end joining (NHEJ) or homology-directed repair (HDR). The NHEJ repair pathway carries the highest efficiency among standard CRISPR systems for plant editing. Changes in NHEJ components directly reflect the type and efficiency of indels in crops; for example, mutations of key NHEJ factors in rice modulate target editing output from zero to nearly 100%. By contrast, selection of

HDR-competent plants with accurate point mutations or foreign DNA integration remains a substantial challenge (Thomson et al., 2022).

3. Applications in Agriculture

Gene editing has the potential to address many critical needs in agriculture that are otherwise difficult to resolve. Development of crops with enhanced resilience to abiotic and biotic stressors could significantly mitigate growing conditions and climate stresses linked to global warming (Zhang et al., 2018). The emergence of new strains of crop pathogens and pests threatens food security, necessitating the continuous breeding of new crop varieties that could avert significant losses. Such sustained breeding is extremely arduous, resource-demanding, and historically subject to extensive time lags. Gene editing may be utilized to introduce precision edits that modulate the expression of relevant immunity genes in diverse crops (Prado et al., 2024). Gene editing may also build on traditional breeding practices to enhance livestock breeding. Gene editing approaches such as CRISPR can introduce considerable genetic gains in livestock regardless of subsequent genomic selection adoption. Specific traits under consideration include disease resistance, welfare enhancement, feed utilization, and greenhouse gas emission reduction.

3.1. Crop Improvement

Historically, significant progress has been made since the domestication of crops through selective breeding and classical mutagenesis. Continued advances in plant breeding technologies, such as genomic selection, phenotyping, marker-assisted selection, and genome sequencing, have accelerated crop improvement. CRISPR/Cas gene editing can now leverage this accumulated investment to accelerate the precise modification of genetic targets and associated crop improvement (Thomson et al., 2022). Gene editing enables the addition, removal, or alteration of deoxyribonucleic acid (DNA) sequences at specific genomic locations. Within 10 years, CRISPR/Cas has become the pre-eminent technology for gene editing in plants, a field that also encompasses the techniques of transcription activator-like effector nucleases (TALENs) and zinc-finger nucleases (ZFNs). Compared with these alternatives, the CRISPR/Cas system is easier to implement, has fewer difficulties associated with component delivery, and has been established in a wider range of plant systems (J. Lyzenga et al., 2021). The two core components of the CRISPR/Cas system a single guide ribonucleic acid (sgRNA) that guides the associated endonuclease enzyme to a predetermined and complementary genomic target, and a Cas endonuclease that introduces DNA double-strand breaks (DSBs) can now be delivered reliably using established methods such as agrobacterium transformation, biolistic transformation, and particle bombardment. The most common editing outcomes consist of small insertions and deletions at the site of the DSB. Whereas many of the described interventions remain to be proven in the field, all expected performance benchmarks have been achieved at least in greenhouses.

3.2. Animal Breeding

Gene editing offers the opportunity to address many of the challenges facing livestock breeding while displacing few of the traits already under selection. The primary aim of animal breeding is to enhance the genetic value of livestock by selecting individuals with the greatest merit for their desired traits. Livestock breeding frequently confronts issues such as poor animal welfare that reduce production efficiency, and other challenges that require urgent solutions, including climate change, increasing the competition for food and feed sources caused by the world population growth, and an increased demand for animal protein globally. Furthermore, animal breeding faces the challenge of having to double food production to meet the demands of a growing population by 2050, even though most of the major quantitative traits are already being selected (Bhat et al., 2017).

3.3. Microbial and Fermentation Systems

Genetic cultivation lasts while producers must ward off contamination, spoilage, and hazards. Microbial and fermentation processes use greater volumes of crops than conventional production (Zhang et al., 2018). Gene editing uplifts microbial and fermentation systems by enhancing production strains, establishing process efficiencies, and relieving feedstock and energy constraints. Modifier and bypass traits coupled to editing support improved strains (Sprink et al., 2019). Consequently, more output derives from the same input. Microorganisms, such as bacteria, saccharomyces, and filamentous fungi, intervene, demanding considerable feedstock and energy, yet sustainability, global warming, and other climate-related stipulations spur research.

From edited sequence to an agronomic trait

A simplified development pathway linking molecular change, plant physiology and field validation.

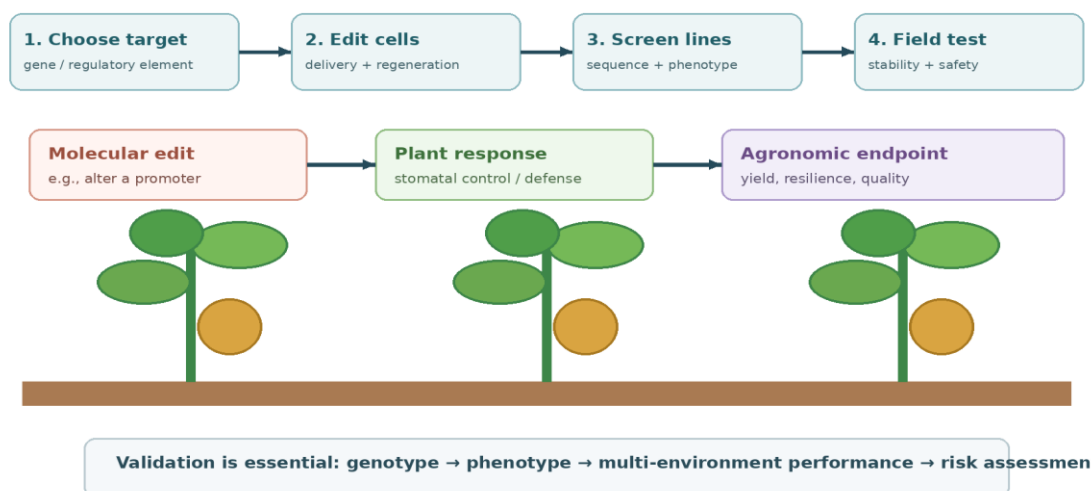


Figure 2. From edited sequence to an agronomic trait validation sequence reflects principles discussed by Gao (2021)

4. Benefits and Advantages

Precise genome editing holds substantial potential for enhancing agricultural productivity and sustainability. Gene-edited crops and livestock provide opportunities to mitigate climate change effects through increased resource-use efficiency and reduced greenhouse gas emissions. Wild-relatives gene editing can promote cultivation of underutilized species with resilient traits. Targeted improvements in microbial strains can boost fermentative processes and valorize agricultural byproducts (Matres et al., 2021). Advanced breeding techniques face challenges in implementing multi-trait improvements and compound crosses; by integrating gene editing, these limitations could be significantly alleviated. Addressing the twin climate and food crises will require diverse and synergistic approaches. As gene editing opens routes to sustainable intensification, it merits careful consideration and broader deployment throughout the food system.

4.1. Productivity and Efficiency

Gene editing, particularly using CRISPR/Cas, significantly enhances productivity and efficiency across agricultural breedings. As gene editing generates mutations and beneficial alleles in target loci directly without needing a pre-existing variant in the parental lines, it can create favorable alleles early in a breeding cycle. This reduces the risk of losing these alleles among the large number of remaining alleles during early selection, which ultimately helps maintain higher rates of genetic gain (Lyzenga et al., 2021). Leveraging the high throughput and precision of gene editing enables simultaneous improvement of multiple traits or integration of several different beneficial alleles into a single elite line. In sorghum, gene editing introduced genes for aflatoxin resistance, brown midrib, photoperiod sensitivity, and root-knot nematode resistance into an elite cultivar that was already widely cultivated in southern Africa.

4.2. Nutritional Enhancement

The nutritional quality of agricultural products affects consumers' health and vitality. Today's food supply cannot fully satisfy the demand for safer, more nutritious, and functional products. Molecular breeding techniques such as cisgenesis and intragenesis have shown potential to improve the nutritional quality of crops but nonetheless frequently face regulatory challenges. Compared to these technologies, CRISPR-Cas genome editing is not perceived as genetic modification and therefore presents a more promising and acceptable method for enhancing nutritional quality (Kumar et al., 2022). Gene editing combined with existing breeding methods can precisely alter the copy number of QTLs that are mutated in an array of crops, thereby improving protein, oil, or starch content. Several studies report success in boosting grain protein or lysine content in crops such as wheat, rice, and

barley. Fortifying grains with vitamins A, E, or D through CRISPR-induced mutagenesis can also promote consumer health (Ku & Ha, 2020).

Table 2: Priority trait areas and evidence questions

Trait area	Biological focus	Potential value	Evidence / caution
Drought resilience	Stomatal regulation, roots, osmotic balance	More stable productivity under water stress. (Gao, 2021)	Test across soils, climates and seasons; avoid growth penalties.
Disease resistance	Host susceptibility or immune-response genes	Reduced crop loss and pesticide dependence. (Zaidi et al., 2018)	Monitor pathogen evolution and non-target ecological effects.
Nutrition / quality	Pathways controlling vitamins, oils or shelf life	Improved nutritional value and reduced post-harvest loss. (Gao, 2021)	Confirm composition, stability and consumer-relevant outcomes.
Yield and efficiency	Plant architecture, flowering or nutrient use	Higher output per unit land or input. (Gao, 2021)	Yield is environment-dependent; multi-location trials are essential.

4.3. Environmental Sustainability

Within the European Union, agriculture is responsible for 10 % of gross greenhouse gas (GHG) emissions and 30 % of surface water pollution. Crop and animal production are dominant contributors to this environmental footprint generating the highest nitrogen and phosphorous runoff and GHG emissions, namely methane from manure (Lassoued et al., 2021). Gene editing is expected to favour sustainable agricultural practices through decreased fertilizer and pesticide input, improved efficiency in water use and nutrient uptake, reduced GHG production and enhanced on-farm animal welfare. Twelve years of experience with transgenic Bt cotton have shown a drastic reduction in pesticide use coupled with increased profitability and crop productivity (Brookes & J Smyth, 2024). Constraints on fertiliser and related agrochemical inputs are strongly supported by the EU's Farm to Fork Strategy which sets ambitious targets for the reduction of chemical pest control products. In the same respect gene editing could strongly contribute towards European Green Deal goals through reduced agricultural impact on biodiversity, soil health and pollutants in air, water and sediments (Patel et al., 2023). Low input solutions are urgently needed in the shortest timeframe and gene editing is positioned to deliver.

5. Risks, Challenges, and Ethical Considerations

The benefits of gene editing must be balanced with risks, which are highlighted in policy proposals (Brookes & J Smyth, 2024) that call for risk-appropriate regulations and in risk governance analyses that emphasize the challenges of assigning risks to gene-edited crops (Tenfen et al., 2018). These risks include the regulatory disadvantage faced by crops with gene-edited traits compared to conventionally bred crops, inequitable outcomes for resource-poor farmers, public perception and potential ecosystem consequences (Nawaz & Satterfield, 2022). The regulatory landscape varies widely among regions and countries, and the governance and regulation of gene editing remain contentious and unsettled. Gene editing is accompanied by important ethical considerations, as with any emerging technology. The ethical questions that are likely to arise relate broadly to equity, access, and societal impact; although existing efforts have sought to deliberately synthesize and articulate these questions, they have not yet systematically engaged the specific dimensions and implications that gene editing poses with respect to agriculture and food, where pressing technical challenges and diverse stakeholder perspectives persist.

5.1. Biosafety and Risk Assessment

Health and environmental risks associated with advanced gene-editing technologies are generally regarded as manageable, comparable to those posed by traditional seed breeding. However, the increased precision, speed, and availability of gene editing pose novel biosafety and regulatory challenges (Tenfen et al., 2018). Risk governance frameworks based on science and prioritizing societal concerns remain necessary, incorporating comprehensive screening and monitoring of potential effects and mitigating actions. Biosafety assessments of

gene-editing techniques, including CRISPR, TALENs, and ZFNs, aim to evaluate the likelihood of accidental mutations following targeted DNA modifications, delineate the boundaries of gene-editing protocols demanding minimized risk through particular agent selection or working under specific confines to avert biosecurity challenges, and assess the distinct hazards posed by gene editing relative to those associated with genomic alterations generated via other approaches. In the context of agriculture, the characterization of gene-edited plants further serves to inform evaluations.

5.2. Governance and Regulation

The emerging gene-editing technologies showcase new wave of gene-editing techniques, such as CRISPR and Gene Drive, is evolving fast. Various legislative responses to these innovative techniques and products raise the demand for flexible regulations, both internationally and domestically. To date, adequate regulatory frameworks that create a transparent process to assess gene-edited crops on a case-by-case basis are still lacking. Existing regulations governing many categories of products derived from crop genome editing are vague, inconsistent, unclear, and expected to evolve over time and accordingly. All these uncertainties on regulatory frameworks raise into the necessity of thoroughly considering the approaches for governing gene-edited crops that rely on established fertilisation techniques (Hartley et al., 2016).

5.3. Equity, Access, and Societal Impact

The global agricultural landscape continues to be affected by the rapid advances in technological innovations. In recent years, agricultural biotechnology, particularly gene editing technologies such as CRISPRs (Clustered Regularly Interspaced Short Palindromic Repeats), TALENs (Transcription Activator-Like Effector Nucleases), and ZFNs (Zinc Finger Nucleases), has provided opportunities to overcome several challenges in crop and livestock improvement (Patel et al., 2023). Many challenges that smaller producers or producers in developing regions face will not be solved by biotechnology alone, especially when the support of public institutions and researchers is lacking. Consequently, some of the most important gene editing applications involve addressing the climatic or health challenges that disproportionately impact less developed regions (Nawaz & Satterfield, 2022). Such applications face fewer restrictions and can proceed rapidly but often receive less funding and fewer technical resources (Lassoued et al., 2021).

6. Regulatory Landscape Across Regions

The regulatory landscape for genome editing technologies varies significantly worldwide. The European Union (EU) and some adjacent countries typically consider new breeding techniques (NBTs), including CRISPR-Cas9 and zinc-finger nucleases (ZFNs), under existing genetically modified organism (GMO) regulations (Lassoued et al., 2021). In the EU, NBTs are classified as GMO technology because they introduce synthetic nucleic acids (Eriksson et al., 2019). Therefore, products developed through NBTs must undergo a lengthy and costly approval process. By contrast, the United States Department of Agriculture–Animal and Plant Health Inspection Service (USDA–APHIS) generally does not regulate most genome-edited crops. The USDA–APHIS confirmed that crops edited with the CRISPR-Cas9 method are exempt from regulation when homologous repair or non-homologous end-joining pathways are used to introduce a targeted deletion that is indistinguishable from those resulting from conventional breeding. Similar exemptions exist for other targeted mutagenesis techniques without the addition of exogenous DNA. Argentina, Australia, Brazil, Canada, Chile, Colombia, Honduras, India, Israel, Japan, Kenya, Mexico, New Zealand, Philippines, Russia, Singapore, South Africa, South Korea, Switzerland, Tanzania, Ukraine, the United Kingdom, and Uruguay have adopted comparable positions or are engaged in discussions in that direction.

6.1. Americas

Gene-edited products are subject to differing assessment and approval requirements in North and South America. Argentina's Food Safety Agency classifies gene-edited products according to the same risk criteria as those developed using traditional techniques. The Canadian system does not focus on the technology applied to foods; instead, it assesses the safety of novel products based on the characteristics of individual food items. The United States treats gene editing similar to conventional plant breeding while Argentina regards gene-editing traits as non-transgenic (Patel et al., 2023). Ongoing discussions on the standards for regulating such products have taken place at several levels to outline a framework for regional harmonization. Mexico's regulatory framework allows

the application of gene-editing, the only biotechnological tool tested against transgene-like insertion, as emphasized by the “no rule” statement issued by the Ministry of Environment and Natural Resources. Gene-edited products that continue harvesting the Netherlands framework are exposed to regulatory asymmetry restrictions (Jones et al., 2022).

6.2. Europe and Eurasia

Gene-edited crops are regulated as genetically modified organisms (GMOs) in many European countries, thus imposing strict testing and labeling requirements (Nordberg et al., 2018). As of late 2022, gene-edited crops remain unapproved within the EU, although certain member states, including France, Spain, Hungary, Poland, the Czech Republic, and Italy, have begun development despite the extensive EU restrictions. Given the importance of Russia to global grain supplies, the weakened state of the agricultural sector since the Ukraine crisis, and the contrast between Western and Russian regulatory approaches that has emerged since sanctions and restrictions were imposed, the situation in Eurasia is also relevant (Jones et al., 2022).

6.3. Asia and Africa

The landscape of biotechnology and agricultural science in Asia and Africa is remarkably heterogeneous. Public awareness of biotechnology and bioengineering varies tremendously from one country to another. Resources for modern plant breeding differ significantly among countries and within various regions of the same country. Regional and country-specific priorities of policy trajectories vary widely as well. Many developing countries engaged in exploratory applications of biotechnology are seeking assistance from industrialized countries and international organizations to build sustainable agricultural biotechnology capacity. These countries also regard agriculture as an important sector of the economy where international technology transfer, trade, and research and development (R&D) cooperation are increasingly becoming significant issues (Lassoued et al., 2021). Despite these complexities, an attempt is made to summarize the emerging regulatory frameworks for plant gene editing across the selected countries and regions in Asia and Africa. The surveyed Asia and Africa regions include: • North Africa: Algeria and Egypt; • East Africa: Ethiopia, Kenya, and Uganda; • Southern Africa: South Africa; • West Africa: Ghana; • South Asia: India; • Southeast Asia: the Association of Southeast Asian Nations (ASEAN) and Malaysia; • East Asia: China, Japan, the Republic of Korea, and Taiwan (G. K. Jones et al., 2022).

7. Future Directions and Emerging Trends

The interdependence of gene editing and synthetic biology creates new opportunities for research, development, and commercialization. Such a race to integrate these disciplines raises ethical questions related to the dual-use nature of biotechnology, climate intervention, and sustainability, the possible repurposing of surveillance or military applications, and the possible application of gene drives to intentionally or unintentionally cause extinction (Sharma et al., 2022). The convergence of gene editing and synthetic biology will lead to creation of microbial and plant synthetic organisms with engineered properties, and to the genetic manipulation of complex traits based not just on knowledge of the genome but also on the quantified mapping of the precursors, intermediates, and products of defined perturbations (Patel et al., 2023). Based on stakeholders, three main avenues can be identified for further innovation: regulatory, societal, and technological. Precision agriculture is an evolving science that enables data-driven decision-making in agriculture at the plot, field, and farm levels. Sequencing the genomes of crops, livestock, pests and pathogens, and soil organisms provides enormous potential for agricultural applications by generating biological knowledge that can be translated into breeding, agronomy, water management, and fertilizer use. Gene editing combined with intelligent data management facilitates rapid deployment of breeding programs adapted to precision agriculture (Gan & Ling, 2022). Numerical agronomy is a further opportunity enabled through information technology to conduct massive simulations covering all environmental and genotypic influences involving cohorts of fields, with large-scale introduction to monitor bio-evolution and invasive maneuvers, and to provide foresight on climate adaptation.

7.1. Gene Editing and Synthetic Biology Convergence

A convergence between gene editing and synthetic biology brings new capability to manipulate plants and other organisms. An example of this integration leverages diverse enzymes to enhance the nutritional profiles of oil-producing crops such as *Arabidopsis thaliana* and *Camelina sativa* (Goold et al., 2018). Other strategies address competing demands for land by engineering microbes to bioremediate environmental toxins and by developing

crops able to grow in non-arable, saline, or contaminated environments through genome sequencing and reverse engineering. Such approaches support crop resilience to climate change while enabling active land regeneration, thereby contributing to global food security. A holistic framework integrates genome assembly, germplasm characterization, gene identification, genomic-assisted breeding, and gene editing with rapid-cycle breeding strategies. Non-transgenic gene-editing approaches that target causal genes and alleles are exempt from USDA SECURE regulations, granting public breeding programs wider access to gene editing without transgenic-deregulation hurdles (Thomson et al., 2022).

7.2. Precision Agriculture and Field Deployment

Data-driven decision-making is progressively reshaping agricultural practices worldwide. Farmers increasingly collect and analyze historical data about crop development and climate-sowing patterns to make well-informed adjustments to planting strategies and field-management practices. The shift towards digital agriculture also encompasses real-time monitoring of climate and soil conditions for judicious deployment of chemical, water, or energy inputs in the field (Zhang et al., 2018). Pioneering initiatives are underway to integrate genome-editing technology and precise interactive Agri-Platforms within monitoring data-tracking systems, addressing critical challenges in Asian agriculture such as decreasing farm workforce, rising chemical-input prices, and low crop productivities especially in pulses, oilseeds, and other under-utilized crops. Opportunities for new gene-edited plant development hinge on the simultaneous availability and accessibility of dozens of valuable genome-editing tools together with localized monitoring data tracking inputs, productivity, traits, and genes. In the 21st century, rapid digital plant-information technologies and data-driven decisions are becoming the hallmark of modern agriculture, enabling interactive options for placement in breeding, editing, trait-development, and geographical-controlled strategies (Sharma et al., 2022).

7.3. Public Acceptance and Science Communication

Gene editing, particularly using CRISPR technology, holds great promise to address food security and agricultural sustainability. Despite the potential benefits, public anxiety over gene editing interference with nature and possible negligence of unintended consequences presents significant challenges to the adoption of novel agricultural innovations. Mass media coverage and outreach activities underscore the importance of effective communication strategies to inform stakeholders about new developments and build public trust in the science that underpins gene editing (McFadden et al., 2021). Targeted public discussions have identified specific communication challenges, including information overload, improper framing of gene editing, and the need for sector engagement. These challenges highlight the relevance of embedding communication and outreach at the onset of any agricultural or biotechnological research project (Fleischmann, 2019). Continuing to anticipate and proactively address communication and consultation needs will be crucial to maintaining future momentum in agricultural gene editing.

8. Research Gaps and Priorities

Fulfilling food demand sustainably will require multiple approaches, which include embracing innovations in genetic technologies. Crop breeding remains critically important for meeting food-security objectives in Africa, where projected population growth presents serious challenges. Improvements in existing gene-editing technologies will be essential to enhance and accelerate crop-breeding efforts in under-utilized crops crucial for sustainable food, nutrition, and income security in the drylands. Enhanced efforts to improve breeding systems in the drylands should also concentrate on generating robust information to guide the cultivation of gene-edited products that best meet specific stakeholder preferences and regional priorities (Sharma et al., 2022). The continuous introduction of innovative gene-editing technologies such as base and prime editing, along with other fundamental biological advances in gene-editing technologies, provides a unique opportunity to overcome longstanding constraints and position plant breeding for a significantly enhanced impact on food security (Lassoued et al., 2021). Prioritizing information generation and technology improvement relevant to under-utilized crops under conditions where regulatory hurdles remain substantial and public acceptance widespread is vital to support accelerated deployment of gene-editing technologies through fully engineered or extensively validated governance models. An effective strategy entails also developing modular models that are readily

adaptable to changing science and regulatory environments and that support trait submissions where minimum foundational data enable initiation of fully engineered pathways (Nawaz & Satterfield, 2022).

10. Conclusion

Gene editing has emerged as a powerful and versatile technology that offers remarkable opportunities to improve crops and livestock to meet the ever-increasing global demand for safe and nutritious food while minimizing the deleterious environmental impacts of agriculture. It addresses adverse climatic conditions, emerging pests and pathogens, and other challenges exacerbated by climate change, population growth, and changing dietary preferences. The primary technology used in agriculture is CRISPR/Cas, which permits the precise editing of life forms without leaving unwanted traces. It is therefore positioned at the crossroad of multiple scientific advances: note the convergence with the synthetic biology movement, the emergence of precision agriculture, and the establishment of more informative and effective public awareness. As the promise of gene editing is becoming widely recognized, its regulation remains critical. Major advances have occurred in consensus on risk governance across both technical and policy fronts. Regulatory approaches are transitioning from uncertainty and debate to experimentation and guidance. Gene editing has experienced rapid development in food and agricultural systems; some applications have already crossed the experimental stage and reached commercial, marketable phases. An increasingly integrated and interdisciplinary research agenda can further strengthen gene editing in these systems;. Attention to public communications will help sustain support for cutting-edge scientific endeavors while minimizing the risk of misinformation.

References:

- Metje-Sprink, J., Menz, J., Modrzejewski, D., & Sprink, T. (2019). DNA-free genome editing: past, present and future. *Frontiers in plant science*, 9, 1957.
- Prado, G. S., Rocha, D. C., Santos, L. N. D., Contiliani, D. F., Nobile, P. M., Martinati-Schenk, J. C., ... & Souza, A. A. D. (2024). CRISPR technology towards genome editing of the perennial and semi-perennial crops citrus, coffee and sugarcane. *Frontiers in Plant Science*, 14, 1331258.
- Lyzenga, W. J., Pozniak, C. J., & Kagale, S. (2021). Advanced domestication: harnessing the precision of gene editing in crop breeding. *Plant Biotechnology Journal*, 19(4), 660-670.
- Zhang, Y., Massel, K., Godwin, I. D., & Gao, C. (2018). Applications and potential of genome editing in crop improvement. *Genome biology*, 19(1), 210.
- Thomson, M. J., Biswas, S., Tsakirpaloglou, N., & Septiningsih, E. M. (2022). Functional allele validation by gene editing to leverage the wealth of genetic resources for crop improvement. *International Journal of Molecular Sciences*, 23(12), 6565.
- de Koning, C. (2020). *The co-constitution of technologies, organisations, and institutions in the process of commercialisation: the case of CRISPR* (Doctoral dissertation, University of Oxford).
- Wang, J., Zhang, L., Pan, C., Lan, X., Xing, B., & Li, M. (2025). Application of gene editing technology in livestock: Progress, challenges, and future perspectives. *Agriculture*, 15(20), 2155.
- Huang, T. K., & Puchta, H. (2021). Novel CRISPR/Cas applications in plants: from prime editing to chromosome engineering. *Transgenic research*, 30(4), 529-549.
- Patel, A., Miles, A., Strackhouse, T., Cook, L., Leng, S., Patel, S., ... & Potlakayala, S. D. (2023). Methods of crop improvement and applications towards fortifying food security. *Frontiers in Genome Editing*, 5, 1171969.
- Bhat, S. A., Malik, A. A., Ahmad, S. M., Shah, R. A., Ganai, N. A., Shafi, S. S., & Shabir, N. (2017). Advances in genome editing for improved animal breeding: A review. *Veterinary world*, 10(11), 1361.
- Matres, J. M., Hilscher, J., Datta, A., Armario-Nájera, V., Baysal, C., He, W., ... & Slamet-Loedin, I. H. (2021). Genome editing in cereal crops: an overview. *Transgenic research*, 30(4), 461-498.
- Kumar, D., Yadav, A., Ahmad, R., Dwivedi, U. N., & Yadav, K. (2022). CRISPR-based genome editing for nutrient enrichment in crops: a promising approach toward global food security. *Frontiers in Genetics*, 13, 932859.
- Ku, H. K., & Ha, S. H. (2020). Improving nutritional and functional quality by genome editing of crops: status and perspectives. *Frontiers in plant science*, 11, 577313.

- Lassoued, R., Phillips, P. W., Macall, D. M., Hessel, H., & Smyth, S. J. (2021). Expert opinions on the regulation of plant genome editing. *Plant Biotechnology Journal*, 19(6), 1104-1109.
- Brookes, G., & Smyth, S. J. (2024). Risk-appropriate regulations for gene-editing technologies. *GM Crops & Food*, 15(1), 1-14.
- Agapito-Tenfen, S. Z., Okoli, A. S., Bernstein, M. J., Wikmark, O. G., & Myhr, A. I. (2018). Revisiting risk governance of GM plants: the need to consider new and emerging gene-editing techniques. *Frontiers in plant science*, 9, 1874.
- Nawaz, S., & Satterfield, T. (2022). Climate solution or corporate co-optation? US and Canadian publics' views on agricultural gene editing. *PLoS One*, 17(3), e0265635.
- Hartley, S., Gillund, F., van Hove, L., & Wickson, F. (2016). Essential features of responsible governance of agricultural biotechnology. *PLoS Biology*, 14(5), e1002453.
- Eriksson, D., Kershen, D., Nepomuceno, A., Pogson, B. J., Prieto, H., Purnhagen, K., ... & Whelan, A. (2019). A comparison of the EU regulatory approach to directed mutagenesis with that of other jurisdictions, consequences for international trade and potential steps forward. *New phytologist*, 222(4), 1673-1684.
- Jones, M. G., Fosu-Nyarko, J., Iqbal, S., Adeel, M., Romero-Aldemita, R., Arujanan, M., ... & Khoo, K. (2022). Enabling trade in gene-edited produce in Asia and Australasia: The developing regulatory landscape and future perspectives. *Plants*, 11(19), 2538.
- Nordberg, A., Minssen, T., Holm, S., Horst, M., Mortensen, K., & Møller, B. L. (2018). Cutting edges and weaving threads in the gene editing (R) evolution: reconciling scientific progress with legal, ethical, and social concerns. *Journal of Law and the Biosciences*, 5(1), 35-83.
- Gan, W. C., & Ling, A. P. (2022). CRISPR/Cas9 in plant biotechnology: applications and challenges. *Biotechnologia*, 103(1), 81.
- Hallerman, E. M., Bredlau, J. P., Camargo, L. S. A., Dagli, M. L. Z., Karembu, M., Ngure, G., ... & Wray-Cahen, D. (2022). Towards progressive regulatory approaches for agricultural applications of animal biotechnology. *Transgenic research*, 31(2), 167-199.
- Sharma, K. K., Palakolanu, S. R., Bhattacharya, J., Shankhapal, A. R., & Bhatnagar-Mathur, P. (2022). CRISPR for accelerating genetic gains in under-utilized crops of the drylands: Progress and prospects. *frontiers in genetics*, 13, 999207.
- Goold, H. D., Wright, P., & Hailstones, D. (2018). Emerging opportunities for synthetic biology in agriculture. *Genes*, 9(7), 341.
- McFadden, B. R., Rumble, J. N., Stofer, K. A., Folta, K. M., Turner, S., & Pollack, A. (2021). Gene editing isn't just about food: comments from US focus groups. *GM Crops & Food*, 12(2), 616-626.
- Fleischmann, S. (2019). Scientific Communication and CRISPR.
- Anzalone, A. V., Randolph, P. B., Davis, J. R., Sousa, A. A., Koblan, L. W., Levy, J. M., Chen, P. J., Wilson, C., Newby, G. A., Raguram, A., & Liu, D. R. (2019). Search-and-replace genome editing without double-strand breaks or donor DNA. *Nature*, 576, 149-157. <https://doi.org/10.1038/s41586-019-1711-4>
- Doudna, J. A., & Charpentier, E. (2014). The new frontier of genome engineering with CRISPR-Cas9. *Science*, 346(6213), 1258096. <https://doi.org/10.1126/science.1258096>
- Gao, C. (2021). Genome engineering for crop improvement and future agriculture. *Cell*, 184(6), 1621-1635. <https://doi.org/10.1016/j.cell.2021.01.005>
- Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., & Charpentier, E. (2012). A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. *Science*, 337(6096), 816-821. <https://doi.org/10.1126/science.1225829>
- Komor, A. C., Kim, Y. B., Packer, M. S., Zuris, J. A., & Liu, D. R. (2016). Programmable editing of a target base in genomic DNA without double-stranded DNA cleavage. *Nature*, 533, 420-424. <https://doi.org/10.1038/nature17946>
- Zaidi, S. S.-A., Mahfouz, M. M., & Mansour, A. M. M. (2018). CRISPR-Cpf1: A new tool for plant genome editing. *Trends in Plant Science*, 23(6), 550-553. <https://doi.org/10.1016/j.tplants.2018.02.004>

Role of Millets in Food and Nutritional Security



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Abstract

Millets have moved from the margins of the modern food market to the centre of conversations on nutrition, climate resilience and sustainable agriculture. India has a long tradition of growing and eating millets, and renewed interest in these crops offers an opportunity to connect traditional food knowledge with contemporary nutrition and food-processing practices. This article discusses the role of major millets in food and nutritional security, with emphasis on their nutritional diversity, suitability for dryland agriculture, value-addition potential and relevance to household nutrition. Different millet species provide different amounts of protein, dietary fibre and minerals; therefore, the strength of the millet group lies in its diversity rather than in any single “superfood” claim. Millets can broaden the cereal basket, support resilient production systems and create opportunities for local processing and rural enterprises. Their benefits are most meaningful when they are included in balanced meals alongside pulses, vegetables, fruits and other foods. The article also highlights the role of Krishi Vigyan Kendras and Home Science professionals in turning millet awareness into practical adoption through recipe demonstrations, nutrition education, processing training and community enterprise development. A people-centred approach that respects local food habits while improving convenience and market opportunities can help millets contribute more effectively to India’s food and nutritional security.

Keywords: Millets; food security; nutritional security; dietary diversity; climate resilience; nutri-cereals; value addition; Home Science; Krishi Vigyan Kendra; Odisha

1. Introduction

Food security is often measured by the amount of food produced, but a truly secure food system must answer a bigger question: does it provide people with enough safe, affordable and nutritious food, even when climate and markets are uncertain? This question has become increasingly important as agriculture faces irregular rainfall, rising temperatures, pressure on water resources and changing consumer preferences.

Millets offer a practical part of the answer. They are a diverse group of cereals that have been grown for centuries, particularly in dry and semi-arid regions. Their ability to perform under relatively difficult conditions has renewed interest in them at a time when farmers and consumers are looking for food crops that can serve more than one purpose. Millets can contribute to the farm, the kitchen and the local economy at the same time.

India has a particularly strong millet heritage. Sorghum, pearl millet, finger millet and small millets such as foxtail, little, kodo, proso and barnyard millet have long been part of regional food traditions. Yet the increasing dominance of rice and wheat in many diets has reduced the everyday visibility of these grains. The recent emphasis on “Shree Anna” and the International Year of Millets 2023 have helped bring millets back into public discussion, but awareness alone will not change food habits. People need foods that are tasty, affordable, easy to prepare and available throughout the year.

2. Why millets matter for the food basket

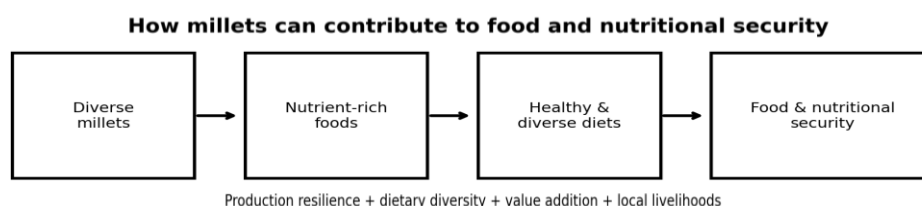


Figure 1. A practical pathway from millet diversity and value addition to food and nutritional security.

The strongest argument for millets is not that rice and wheat should disappear from Indian diets. Rather, millets can make the cereal basket more diverse. Different crops respond differently to weather, soils and market conditions. Similarly, different millet species offer different nutritional and culinary characteristics.

3. Nutritional strength lies in diversity

Millets are sometimes described collectively as though all species have the same nutritional composition. In reality, there is considerable variation. ICAR–Indian Institute of Millets Research data show differences in protein, dietary fibre, iron and calcium among commonly cultivated millets.

Table 1. Representative nutrient values of major millets per 100 g. Values may vary with variety, production conditions and processing.

Millet	Protein	Fibre	Iron	Calcium
Sorghum	10.0 g	4.0 g	2.6 mg	54 mg
Pearl millet	10.6 g	1.3 g	16.9 mg	38 mg
Finger millet	7.3 g	3.6 g	3.9 mg	344 mg
Foxtail millet	12.3 g	8.0 g	2.8 mg	31 mg
Proso millet	12.5 g	2.2 g	0.8 mg	14 mg
Kodo millet	8.3 g	9.0 g	0.5 mg	27 mg
Little millet	7.7 g	7.6 g	9.3 mg	17 mg
Barnyard millet	11.2 g	10.1 g	15.2 mg	11 mg

3.1 Protein and fibre

Protein content varies among millet species, with proso and foxtail millet among the higher values in the IIMR dataset. Several small millets are also notable for dietary fibre. This makes them useful additions to meals where greater cereal diversity and fibre intake are desired.

3.2 Calcium and iron

Finger millet is particularly well known for its calcium content. Pearl millet and barnyard millet show comparatively high iron values in the IIMR dataset. These characteristics are useful in nutrition education, but they should be presented in the context of a complete diet rather than as a promise that one grain can correct a nutritional deficiency on its own.

4. Millets and nutritional security

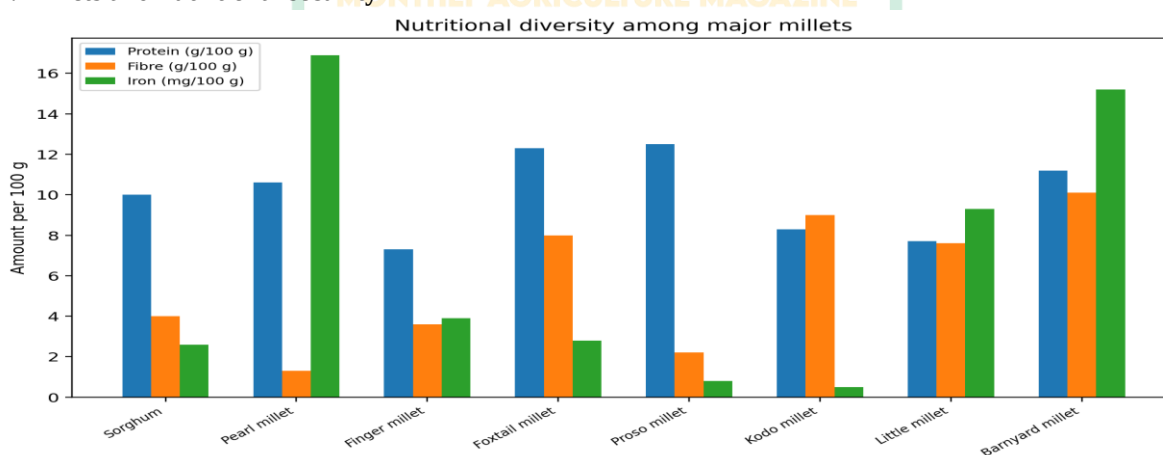


Figure 2. Comparative protein, fibre and iron content of selected millets.

Nutritional security means having regular access to food that is adequate in quantity and quality. Millets can support this objective by widening the range of cereals available to households and by adding useful nutrients to everyday meals.

4.1 Dietary diversification

Millets can be cooked as whole grains, ground into flour, made into porridges, fermented, malted or incorporated into mixed-cereal products. This flexibility allows families to use them without completely changing their

established eating habits. A portion of millet can be introduced into familiar foods such as roti, dosa-type preparations, porridge, upma, snacks or bakery products.

4.2 Processing matters

The way a grain is processed affects cooking time, texture, taste and the final food product. Dehulling, milling, germination, malting, fermentation, flaking and extrusion can all improve convenience and expand the range of millet foods. The growing portfolio of millet-based products developed by ICAR institutions shows how traditional grains can be adapted to modern consumers.

A simple message for nutrition education is more useful than complicated health claims: choose a suitable millet, prepare it well and combine it with other food groups.

5. Millets, climate resilience and food availability

Millets are particularly relevant to agriculture in areas where water is limited and rainfall is uncertain. FAO identifies them as crops that can tolerate heat, drought and poor soils and can continue to provide grain under conditions that may severely affect some other cereals. This does not mean that every millet will perform well everywhere; local soil, rainfall, variety and management still determine productivity.

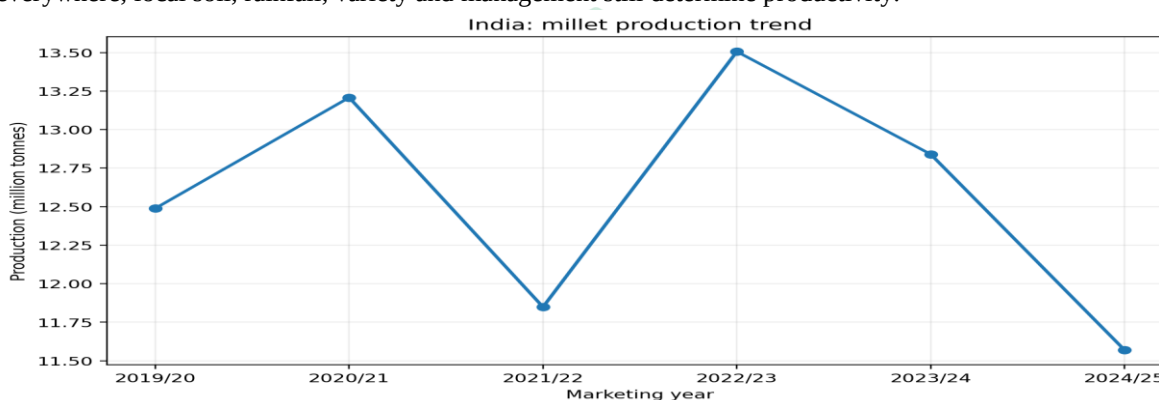


Figure 3. India's millet production trend, 2019/20–2024/25. Source: USDA Foreign Agricultural Service. Production figures fluctuate from year to year, reminding us that resilience is not the same as immunity to climate variability. Better varieties, timely sowing, appropriate nutrient management, moisture conservation and improved post-harvest practices remain important.

Table 2. Practical links between millet cultivation and food-security outcomes.

Food-security aspect	How millets can help	What is needed
Availability	Broaden the range of cereals produced	Quality seed and reliable production
Stability	Suitability for several dryland environments	Local agronomic recommendations
Access	Potential for local production and processing	Markets and infrastructure
Utilization	Nutrient-rich cereal options	Food preparation and nutrition education
Sustainability	Fit into diversified and resource-conscious systems	Integrated soil and water management

6. From grain to enterprise: value addition

A farmer benefits from millet cultivation only when the crop has a dependable market. Value addition can help close this gap. Cleaning, grading, milling, malting, flaking, extrusion, baking and packaging can convert raw grain into products that are easier to use and potentially more valuable.

Table 3. Practical value-addition routes for millet-based foods.

Value-addition route	Examples	Why it matters
Milling	Flour and multigrain flour	Easy household use
Malting	Malted ragi mixes	Convenient beverages and foods
Flaking	Breakfast flakes	Short preparation time
Extrusion	Ready-to-eat snacks	Convenience and shelf life
Bakery products	Biscuits, breads, muffins	Appeals to new consumers
Traditional foods	Roti, porridge, fermented foods	Maintains cultural familiarity

6.1 Opportunities for women and rural enterprises

Millet processing is well suited to small and community-level enterprises. Women's self-help groups, farmer producer organisations and local entrepreneurs can participate in cleaning, milling, recipe development, packaging and direct marketing. This creates a useful connection between nutrition work and livelihood development.

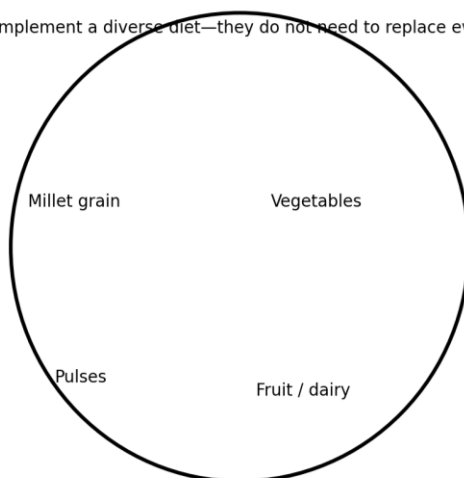
6.2 Building a stronger local value chain

The most sustainable model is one in which farmers, processors and consumers are connected. Local procurement can reduce transport and create a stronger identity around regional foods. Quality control, food safety, attractive packaging and consistent supply are essential if these enterprises are to grow.

7. Millets in household and community nutrition

A practical "millet plate" approach

Millets complement a diverse diet—they do not need to replace every staple.



Illustrative nutrition-education graphic

Figure 4. A practical millet-plate approach: millets as one part of a varied and balanced meal.

The success of a millet programme is ultimately decided in the kitchen. People choose foods because they taste good, fit their budget, are easy to prepare and are familiar to the family. Nutrition education therefore needs to be practical rather than purely theoretical.

Table 4. Suggested community approach for millet-based nutrition education.

Group	Useful focus	Possible activity
Women and caregivers	Meal planning and preparation	Recipe demonstrations and tasting
Children	Taste and variety	Breakfast and snack preparation
Farm families	Farm-to-kitchen connection	Use of locally grown millet
SHGs/FPOs	Processing and enterprise	Training in food safety and packaging
Consumers	Nutrition awareness	Simple nutrient comparison charts

7.1 Role of KVKs and Home Science professionals

Krishi Vigyan Kendras can provide an important link between farmers and households. Home Science professionals can add another dimension by demonstrating recipes, discussing dietary diversity, evaluating consumer acceptance and supporting women's groups in food processing.

For Odisha, this approach can be especially useful because locally available millets can be presented through familiar foods rather than as an unfamiliar "health product." Demonstrations can begin with one or two practical recipes and gradually introduce more varieties and processing methods.

A useful sequence is: identify local millet → demonstrate processing → prepare affordable foods → discuss nutrition → collect feedback → support enterprise development → connect producers with markets.

8. Challenges that need attention

Table 5. Major constraints and practical responses.

Challenge	Practical implication	Way forward
Processing difficulty	Long preparation time can discourage use	Local milling and ready-to-cook products
Consumer perception	Some consumers still associate millets with coarse traditional foods	Better recipes, presentation and tasting
Market uncertainty	Farmers may hesitate to expand acreage	Reliable buyers and value-chain linkages
Nutrition misinformation	Overstated claims can reduce credibility	Evidence-based communication
Post-harvest losses	Poor storage can reduce quality and value	Better drying, storage and packaging
Limited product range	Consumers may lose interest if choices are narrow	Diversified products and local innovation

8.1 The importance of honest nutrition communication

Millets are nutritious foods, but they are not medicines. A professional article should avoid presenting any millet as a cure for a disease or as a complete substitute for a balanced diet. Nutrition messages should remain species-specific, evidence-based and easy for households to understand.

8.2 Research priorities

Future research should focus on improving productivity, developing climate-resilient varieties, understanding nutrient retention during processing, studying consumer acceptance and strengthening the economics of millet value chains. Equally important is documenting successful local models that can be replicated through extension networks.

9. Future prospects

The next phase of millet development should move from awareness to adoption. Farmers need profitable production systems, processors need dependable raw material, consumers need convenient and appealing foods, and nutrition educators need clear evidence to communicate.

Table 6. Strategic priorities for stronger millet-based food systems.

Area	Priority for the future
Crop improvement	Stress-resilient, productive and nutritionally desirable varieties
Agronomy	Location-specific packages for rainfed and dryland farming
Nutrition	Clear, species-specific nutrition messages
Processing	Affordable and efficient small-scale technologies
Markets	Quality assurance, branding and stronger local demand
Extension	Closer coordination among KVKs, SHGs, FPOs and consumers
Research	Evidence on nutrition, processing, adoption and farm economics

Digital platforms can help with recipes, farmer advisories, enterprise information and consumer awareness, but field demonstrations remain important. People are more likely to adopt a new food when they can see it being prepared, taste it and understand how it fits into their existing meals.

10. Conclusion

Millets have a valuable place in India's future food system because they bring together three qualities that are increasingly important: nutritional diversity, resilience in challenging production environments and potential for local value addition. Their importance is not that they are superior to every other cereal, but that they give farmers and consumers another set of useful choices.

The nutritional differences among millet species make this diversity particularly valuable. Finger millet is well known for its calcium content, while pearl millet and barnyard millet show comparatively high iron values in the ICAR-IIMR dataset. Several small millets also contribute useful dietary fibre. These characteristics can strengthen the nutrient density of meals, but only when millets are part of a varied diet that also includes pulses, vegetables, fruits and other foods.

The larger opportunity is therefore to build a food system in which millets move naturally from field to kitchen. Farmers need suitable varieties, practical production technologies and dependable markets. Consumers need convenient, affordable and appealing products. Women's groups and rural enterprises need processing and marketing support. Extension institutions such as Krishi Vigyan Kendras can connect these needs through demonstrations, nutrition education, processing training and local market linkages.

For Odisha, this integrated approach is especially relevant. The combination of agricultural extension and Home Science expertise can help turn locally available millets into practical household foods and viable community enterprises. Instead of asking families to abandon familiar staples, extension programmes can show how millets can be introduced gradually into everyday meals in ways that respect taste, culture and affordability.

References

- Food and Agriculture Organization of the United Nations. (2023). About the International Year of Millets 2023. FAO, Rome.
- Food and Agriculture Organization of the United Nations. (2023). Millets: Climate Smart Seeds of the Future. FAO, Rome.
- Food and Agriculture Organization of the United Nations. (2023). Unleashing the potential of millets: Background paper for the International Year of Millets 2023. FAO, Rome.
- Food and Agriculture Organization of the United Nations. (2024). Showcasing millets' rich heritage and potential: Final report of the International Year of Millets 2023. FAO, Rome.
- Malathi, V. M., Venkateswarlu, R., Jacob, J., & Ratnavathi, C. V. (2023). Nutritional value of millets. *Indian Farming*, 73(1), 88–90.
- Venkateswarlu, R., Malathi, V. M., Jacob, J., Ratnavathi, C. V., & Kumar, M. (2023). Health benefits of millets. *Indian Farming*, 73(1), 91–93.
- ICAR–Indian Institute of Millets Research. (2026). Millet information and nutritional benefits. Hyderabad, India.
- ICAR–Indian Institute of Millets Research. (2026). Research, production technologies and value-added millet products. Hyderabad, India.
- USDA Foreign Agricultural Service. India: Millet area, yield and production. Country Summary.
- Government of India, Press Information Bureau. (2025). Shree Anna for Shreshta Bharat: Millet production and policy support.

Integrated Weed Management: Reducing Herbicide Dependence Through Eco-Friendly Practices



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Abstract

Weeds compete with crops for vital resources, causing significant yield losses and posing a serious threat to world agricultural productivity. Although synthetic herbicides have been a major component of conventional control due to their effectiveness, this over-reliance has led to a number of problems, such as the emergence of herbicide-resistant weed species, soil degradation, environmental contamination, and health issues for humans. The goal of Integrated Weed Management (IWM), a sustainable and knowledge-intensive paradigm shift, is to lessen the need for herbicides. In order to keep weed populations below economically detrimental levels, this paper offers a thorough overview of IWM as a multi-tactic framework that cooperatively integrates mechanical, biological, chemical, cultural, and preventive tactics. Crop diversification, cover crops, mulching, allelopathy, bioherbicides, and precision weeding technologies are among the fundamental eco-friendly methods that are summarized in this study. In order to improve agroecosystem resilience and guarantee long-term productivity and environmental health, it is concluded that a diverse IWM approach is essential. However, for this strategy to be successfully adopted, more research and innovation, efficient farmer education, and supportive policy measures are needed to promote IWM as a workable alternative for sustainable agricultural intensification.

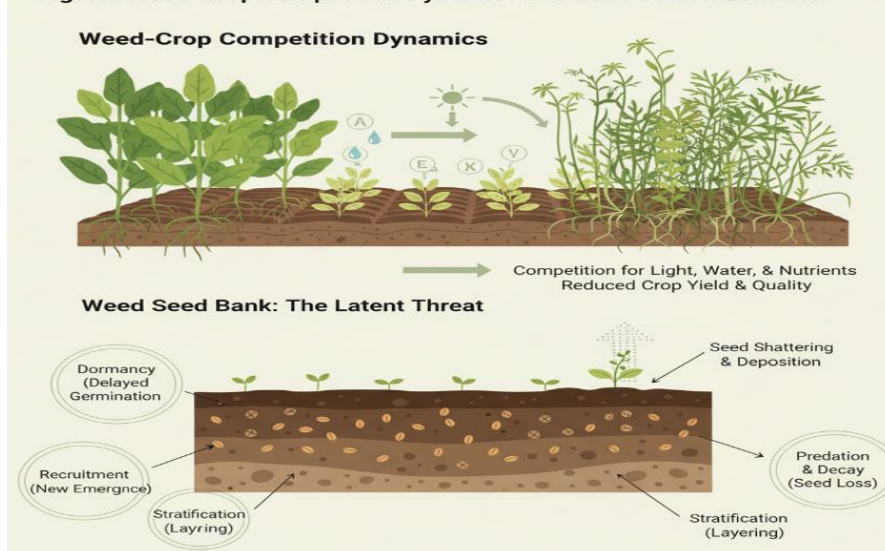
Keywords: Integrated Weed Management, Herbicide Resistance, Sustainable Agriculture, Cover Crops, Crop Rotation, Allelopathy, Biological Control, Precision Farming, Eco-friendly Weed Control, Cultural Practices, Ecological Balance, Weed Ecology, Bioherbicides.

1. Introduction

Weeds are one of the most serious biological restrictions to worldwide agricultural output, capable of producing yield losses of 34-40% if not controlled. As demonstrated by national-level figures, such as the more than Rs. 6,000 crores in annual crop losses in India, these losses are significant economically, amounting to billions of dollars annually. Synthetic herbicides have been the mainstay of weed control for many years because of their quick action, effectiveness, and affordability. But this over dependence has led to a number of unforeseen repercussions. Herbicide-resistant weed biotypes have evolved as a result of the over 500 reported examples worldwide that have been caused by the oversimplified and repetitive use of these compounds, making many important chemistries ineffective. Herbicide overuse and misuse have led to extensive environmental pollution, including soil degradation, water body contamination, harm to non-target creatures, and possible health hazards for humans, in addition to resistance.

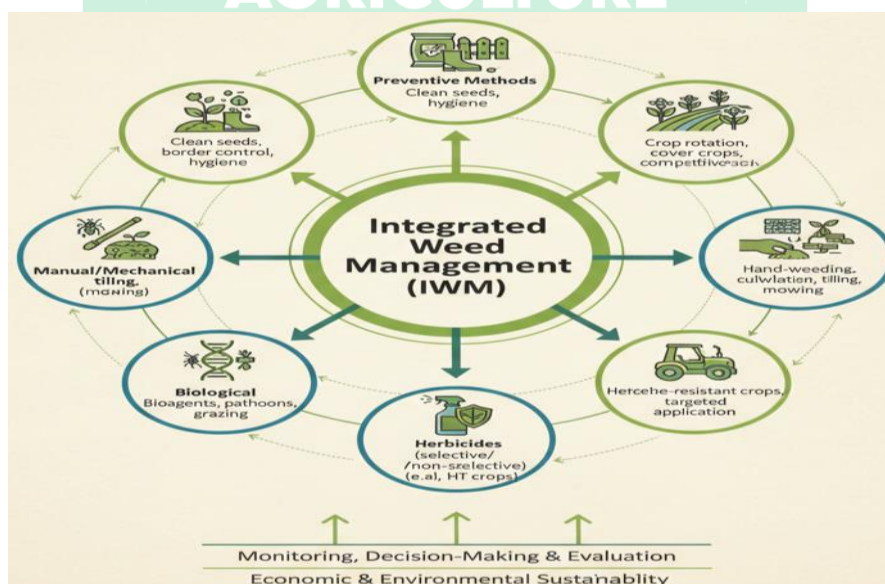
The global shift towards regenerative and sustainable agriculture, along with this unsustainable trend, has sparked a hunt for strong substitutes. As a crucial paradigm shift, Integrated Weed Management (IWM) moves away from a chemically intensive, single-method strategy and toward a comprehensive, multifaceted framework. IWM is the deliberate combining of several management strategies, including as mechanical, biological, cultural, preventative, and limited chemical methods, to keep weed populations below economically harmful levels. IWM's fundamental tenet is sustainable management of weeds by decreasing the weed seed bank and shifting the crop's competitive advantage, not the complete elimination of weeds. Long-term crop yield and farm profitability are the main goals, together with biodiversity preservation, agroecosystem resilience, and environmental impact reduction. In order to bring agricultural practices into line with the pressing need for ecological balance, this review attempts to clarify the fundamentals of integrated water management (IWM) and critically assess the range of environmentally friendly techniques that might be used to reduce reliance on herbicides.

Figure: Weed-Crop Competition Dynamics and Seed Bank Illustration



2. Weed Ecology and Biology

Effective management of weeds requires an understanding of their ecology. Weeds are able to survive in a variety of agroecosystems due to their exceptional flexibility, quick growth rates, abundant seed production, and dormancy mechanisms. Weeds can be propagated over an extended period of time using the soil seed bank. Early in crop establishment, frequently during the key phase of competition, which varies from crop to crop, weeds and crops compete for resources. For example, the critical period for wheat is between 20 and 50 days after sowing, but for rice it is between 15 and 45 days after transplanting. Effective timing of weed control activities is facilitated by an understanding of these processes. Allelopathic interactions, seed distribution methods, and resistance evolution are further aspects of weed biology. It is easier to identify weak points in their life history for focused control interventions when one is aware of whether the life cycle is annual, biennial, or perennial.



3. The Pillars of Integrated Weed Management (IWM)

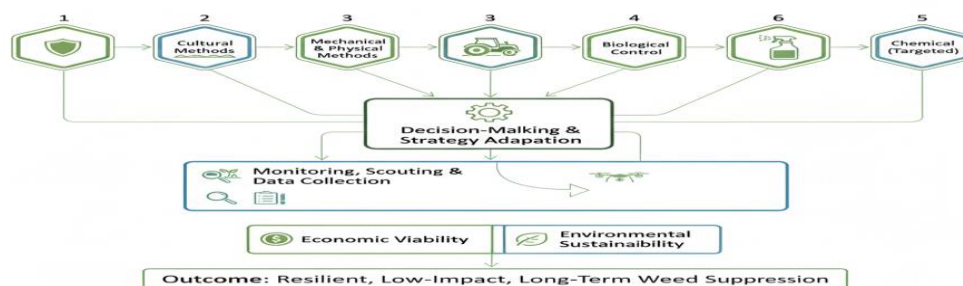
IWM is founded on the principle of diversity and integration. It moves away from a single-tactic approach and builds resilience through several interconnected pillars:

- **Prevention:** The most cost-effective method, focusing on stopping weed introduction and spread (e.g., using clean seeds, cleaning machinery).

- **Cultural Weed Control:** Manipulating the crop environment to make it less favorable for weeds and more competitive for the crop.
- **Mechanical/Physical Weed Control:** Using tools and machinery for direct weed removal.
- **Biological Control:** Utilizing living organisms (insects, pathogens, grazers) to suppress weeds.
- **Chemical Control:** The judicious and strategic use of herbicides, often at reduced rates and with a diversity of modes of action.

The synergy between these pillars is key to IWM's success.

Figure: Conceptual Flowchart of Integrated Weed Management (IWM)



4. Eco-friendly Components of Integrated Weed Management

Table 1. Emerging eco-friendly innovations for weed management.

Innovation	Principle	Advantages
Bioherbicides	Microbial metabolites target specific weeds	Safe, biodegradable, eco-friendly
Allelopathic crops	Natural suppression via secondary metabolites	Dual benefits: yield + weed control
AI-guided drones	Precision mapping and selective herbicide application	Reduced chemical use
Robotic weeders	Automated mechanical control	Labor-saving, high precision
Conservation agriculture	Soil cover and minimal tillage	Improved soil health, lower weed pressure

Integrated Weed Management (IWM) suppresses weeds in an economical and ecological manner by combining many management strategies in a synergistic manner. IWM improves the resilience and sustainability of agroecosystems by decreasing dependence on any one technique, especially herbicides. The essential elements are described in full below.

4.1. Cultural and Preventive Practices

Cultural methods are foundational to IWM, aiming to give the crop a competitive advantage over weeds by manipulating the cropping environment.

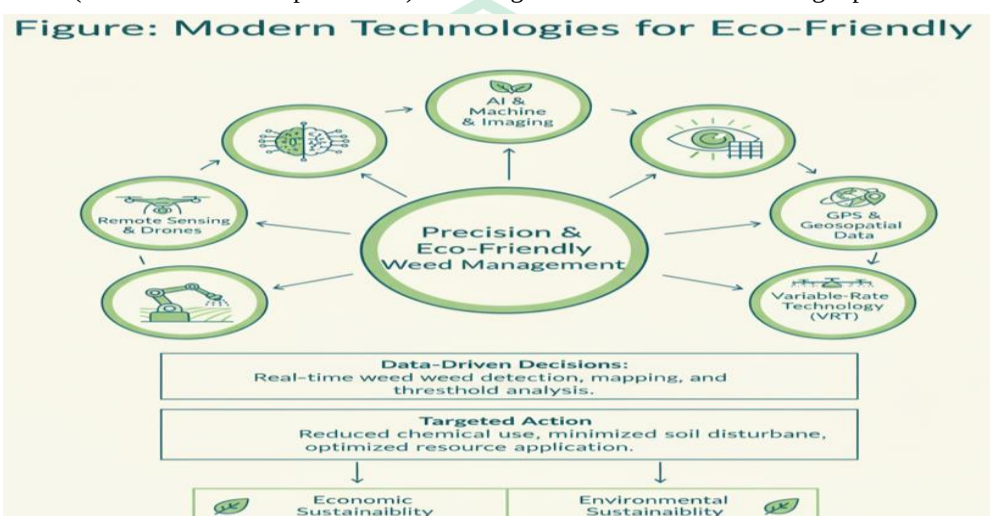
- **Cover Cropping:** Using physical smothering, light competition, and allelopathy, non-cash crops such as rye, clover, or vetch can be grown during the off-season to reduce weeds. When it is finished, the waste creates a long-lasting mulch that further prevents weeds from growing.
- **Diverse Crop Rotations:** By switching up crops with distinct life cycles, growth patterns, and phenologies (for example, summer annual corn and winter annual wheat), weeds' specialized life cycles are disrupted and no single species is allowed to take over.
- **Competitive Crop Cultivars:** By choosing cultivars with characteristics like high leaf area index, quick early growth, and tall stature, you can improve the crop's natural capacity to shade out and outcompete weeds for resources.

- **Allelopathy:** This method makes use of the natural biochemicals that some plants (including rye, sunflower, and sorghum) emit to prevent the growth and germination of weeds. Allelopathic cover crops, intercropping, or utilizing their residues are ways to take advantage of this.

4.2. Mechanical and Physical Control

These tactics involve the direct physical removal or suppression of weeds.

- **Strategic Tillage:** Conventional tillage can suppress perennials and bury weed seeds, but it can also awaken dormant seeds. On the other hand, no-till or conservation tillage systems, which are frequently combined with cover crops, maintain soil health but necessitate careful weed control at planting.
- **Precision Mechanical Weeding:** Cutting-edge technologies can now tell the difference between weeds and crops, such as robotic weeders with vision-based recognition and automated guidance systems. This greatly lowers labor expenses and crop damage by enabling high-precision mechanical control within the crop row.
- **Mulching:** Weed germination and growth are physically inhibited by applying a layer of organic material (such as straw or crop leftovers) or biodegradable films that restrict light penetration.



4.3. Biological Control

Biological control employs living organisms to regulate weed populations.

- **Classical Biocontrol:** To manage invasive weeds in new areas, this strategy introduces host-specific natural enemies (pathogens, insects) from the weed's natural range. Using *Zygogramma bicolorata* beetles to control *Parthenium hysterophorus* is a well-known example.
- **Bioherbicides:** These are plant pathogen formulations (fungi such as *Puccinia chondrillina* or *Phoma macrostoma*) that are sprayed in the same way as conventional herbicides. Although their limited host ranges and formulation problems have hindered their commercial development, they provide a selective and ecologically friendly alternative.

4.4. Judicious Chemical Control within an IWM Framework

IWM does not advocate for the complete elimination of herbicides but promotes their strategic and reduced use as a last resort.

- **Herbicide Rotation and Mixtures:** Herbicide resistance can be controlled and delayed by using herbicides with various modes of action sequentially or in combination.
- **Site-Specific Application:** Herbicides may now be applied only where weeds are present thanks to precision agricultural technology like GPS-guided and sensor-based sprayers, which significantly lowers the total amount of herbicide needed.
- **Economic Threshold-Based Application:** This theory suggests avoiding preventative, calendar-based programs and limiting the application of herbicides to situations in which weed densities are expected to result in financial losses.

5. Principles of Integrated Weed Management

The philosophy of IWM is rooted in ecological balance and sustainability. The main principles include: (i) Prevention rather than eradication, (ii) Diversification of control tactics, (iii) Maintenance of economic thresholds, (iv) Ecological harmony, and (v) Local adaptability. IWM acknowledges that complete elimination of weeds is neither feasible nor desirable; rather, maintaining weed populations at levels that do not cause economic damage is the goal.

These principles collectively ensure that weed management strategies remain flexible, location-specific, and sustainable over the long term.

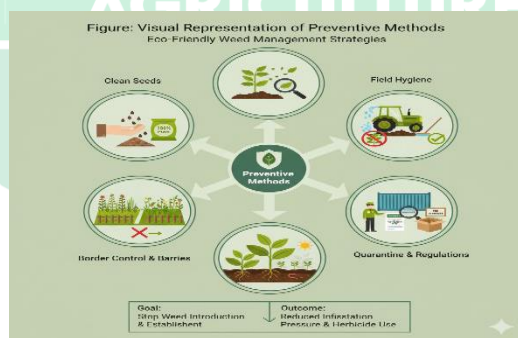
Table 2. Comparative overview of weed management methods and their characteristics.

Weed Management Approach	Description	Advantages and Limitations
Preventive	Avoid introduction/spread of weeds through hygiene and certified seeds	Reduces infestation risk but requires strict discipline
Cultural	Modifies cropping systems to suppress weeds	Improves soil health; moderate control level
Mechanical	Physical removal using tools or machinery	Immediate effect; labor-intensive
Biological	Uses natural enemies or allelopathic crops	Environmentally safe; slower action
Chemical	Application of herbicides	Fast and effective; risk of resistance and pollution

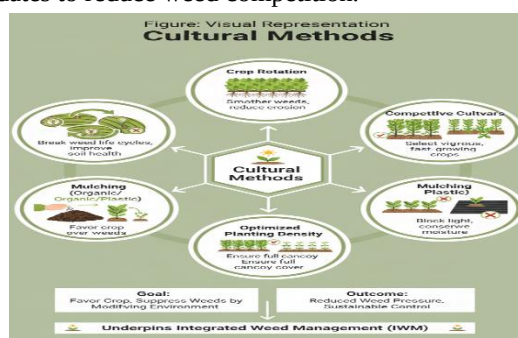
6. Components of Integrated Weed Management

IWM combines multiple compatible strategies. Its major components include preventive, cultural, mechanical, biological, and chemical methods applied in a site-specific and knowledge-based manner.

- **Preventive Methods:** Involves preventing weed introduction through clean seeds, field sanitation, irrigation management, and early detection.

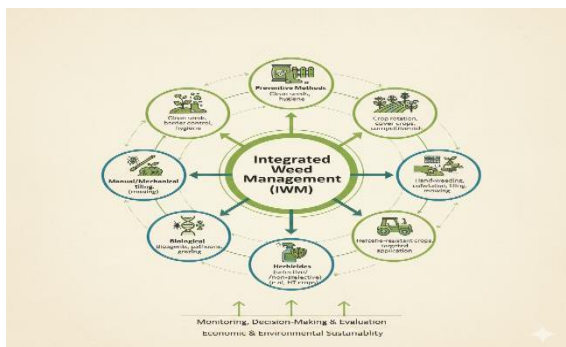


- **Cultural Methods:** Includes crop rotation, intercropping, cover cropping, mulching, and adjusting sowing density or dates to reduce weed competition.



- **Mechanical and Physical Methods:** Involves tillage, hoeing, mowing, and thermal control such as flaming or solarization.

- **Biological Methods:** Uses insects (e.g., *Zygogramma bicolorata* for *Parthenium*), pathogens, and allelopathic crops (e.g., sorghum, rye).



- **Chemical Methods:** Selective herbicide use within IWM ensures effectiveness while minimizing ecological impact.

7. Advances in Technological Interventions for IWM

Technological innovation is revolutionizing Integrated Weed Management by enabling precision, efficiency, and a reduced environmental footprint. Key advances include:

- **Precision Weeding:** AI-driven robots and drones with sophisticated sensors can now tell the difference between weeds and crops in real time. This significantly lowers the need for chemicals by enabling the targeted mechanical removal of weeds or the direct administration of micro-dose herbicides to specific weeds.
- **Smart Mapping & DSS:** Drones and geospatial techniques are used to provide comprehensive maps of the distribution of weeds. Instead of using standard field-wide applications, this data can be integrated with Decision Support Systems (DSS) to enable proactive, site-specific management methods.
- **Integration of Renewable Energy:** The use of electric weed control tools (such as laser weeding) and solar-powered autonomous weeders is lowering the carbon footprint of weed control and promoting safer, non-chemical alternatives.

8. Case Studies and Success Stories

The successful implementation of Integrated Weed Management (IWM) in a variety of agricultural systems across the globe demonstrates its practical effectiveness. These case studies demonstrate how customized, multi-pronged approaches yield substantial financial and ecological advantages.

- **In North America,** the combination of high-tech solutions with traditional techniques has produced significant outcomes. The use of AI-guided spot spraying, for example, in the US soybean-maize system enables herbicides to be administered solely to weed areas, lowering overall chemical consumption by more than 70% while preserving effective control.
- **In Australia,** where pesticide resistance is rampant, novel harvest-time methods have proved critical. In order to collect and concentrate weed seeds and stop them from returning to the soil seedbank, chaff lining and residue retention are often used during harvest. In cereal systems, this method has decreased the use for post-emergence herbicides by as much as 60%.
- **In South Asia,** IWM has proven critical for addressing specific weed concerns in intensive cropping systems. The integrated management of the resistant weed *Phalaris minor* is a noteworthy achievement in the wheat-rice system of India. Farmers have effectively prevented the development of resistance and maintained productivity by combining timely mechanical weeding, strategic crop rotation, and the switching up of herbicide modes of action. Also, the traditional biological treatment of *Parthenium hysterophorus* in Karnataka, India, with the help of the host-specific leaf beetle *Zygogramma bicolorata*, demonstrates a low-cost, sustainable approach that has dramatically decreased infestation levels without the use of chemicals.

- **In Europe**, especially in organic systems, the use of a combination of mechanical and biological approaches has increased soil health and biodiversity while also managing weeds more successfully and increasing farm sustainability.

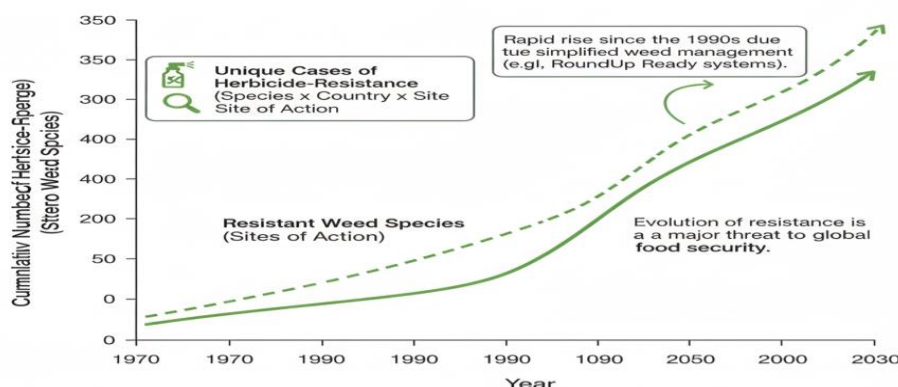
These real-world instances demonstrate that IWM is a useful and flexible framework rather than a theoretical idea. The purposeful blending of techniques to produce a strong, long-lasting, and financially feasible weed control system is the unifying factor.

Country/Region	Crop/System	Main IWM Strategies	Outcome
India	Wheat–rice system	Crop rotation, mechanical weeding, herbicide alternation	Reduced resistance in <i>Phalaris minor</i>
Australia	Cereal systems	Residue retention, harvest weed seed control	Lower herbicide use, improved yields
USA	Soybean–maize	AI-guided spraying, cover crops	Reduced herbicide consumption by 70%
Europe	Organic systems	Mechanical and biological methods	Higher biodiversity and soil health

9. Challenges and Future Prospects of IWM

Integrated weed management has several advantages, but there are also major obstacles to its broad use. For the purpose of directing future research and extension initiatives, a thorough grasp of these difficulties is necessary.

Global Herbicide Resistance Trends: An Increasing Challenge



9.1. Benefits of IWM Adoption

There are several benefits to implementing a well-thought-out IWM strategy:

- **Mitigates Herbicide Resistance:** IWM considerably slows the evolution of herbicide-resistant weed biotypes by varying selection pressure through a variety of control strategies.
- **Improves Environmental Health:** By lowering the chemical load in agroecosystems, IWM improves soil biodiversity, water quality, and non-target organism safety.
- **Enhances Soil and System Resilience:** Fundamental techniques such as reduced tillage and cover crops improve soil organic matter, structure, and water infiltration, laying a stronger basis for crop production.
- **Encourages Long-Term Economics:** By creating a self-regulating system, IWM can eventually result in more stable and lucrative yields while reducing dependency on costly herbicide inputs, despite the possibility of higher initial expenses.

9.2. Key Challenges to Widespread Adoption

Despite its potential, there are a number of obstacles to the switch to IWM:

- **Knowledge and Complexity Barrier:** IWM is more complicated than calendar-based herbicide spraying since it necessitates a thorough understanding of weed ecology and the cooperative management of several techniques.

- **Socio-Economic Barriers:** Farmers are discouraged, especially in areas with a shortage of manpower, by the perceived and actual increases in work, time, and initial investment required for new equipment or bio-control agents.
- **Technological and Input Limitations:** Depending on soil and climate conditions, the effectiveness of biological and cultural techniques might vary, and there are currently few commercially available effective bioherbicides.
- **Inadequate Research and Support:** Localized implementation is hampered by a lack of region-specific, readily adoptable IWM packages and fragmented research on weed ecology under climate change.

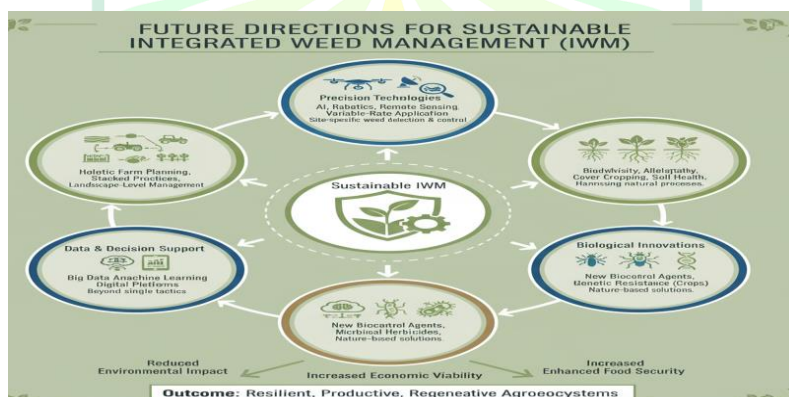
9.3. Future Directions

Future initiatives must concentrate on the following in order to overcome these obstacles and realize IWM's full potential:

- **Creating Region-Specific IWM Models:** Studies should produce customized packages that take into consideration regional weeds, dominant agricultural systems, and socioeconomic circumstances.
- **Developing Bioherbicide Technology:** To provide efficient, non-chemical substitutes, it is essential to make investments in the formulation, stability, and large-scale manufacturing of microbial bioherbicides.
- **Combining Digital and Precision Tools:** By combining artificial intelligence (AI), robotics, and decision-support systems, IWM's labor and management complexity can be decreased, increasing accessibility to precision weeding.
- **Enhancing Knowledge Transfer:** To close the knowledge gap and show the long-term agronomic and economic advantages of IWM, strong extension initiatives and farmer-participatory research are required.

Conclusion

The evidence is clear: the days of controlling weeds primarily with chemical pesticides are becoming less and less effective and are not sustainable for the environment. With its strong approach to balancing environmental stewardship and agricultural output, Integrated Weed Management (IWM) is emerging as the future's essential, science-based paradigm. IWM offers a workable framework to significantly lessen reliance on herbicides, reduce environmental contamination, and proactively handle the growing problem of herbicide-resistant weeds by simultaneously integrating preventative, cultural, mechanical, biological, and targeted chemical approaches.



IWM's fundamental strength is its all-encompassing methodology. It cultivates robust agroecosystems, going beyond straightforward weed management. In addition to reducing the need of chemical inputs, IWM actively promotes biodiversity, improves soil health, and ensures farm profitability and production over the long run. In the future, IWM's development will be fueled by the combination of enhanced bioherbicides, robotics, AI-driven precision weeding, and a deeper comprehension of weed ecology. But technological progress isn't enough on its own. It takes a coordinated and cooperative effort to implement IWM widely. It necessitates a fundamental change in perspective from a "silver bullet" mentality to a systems-thinking approach. Three crucial pillars will determine future success:

1. **Continuous Research and Innovation:** Focusing on region-specific IWM models, novel bio-based solutions, and the refinement of precision technologies.
2. **Comprehensive Farmer Capacity Building:** Through effective education and extension services to overcome knowledge barriers and demonstrate economic benefits.
3. **Supportive Policy Frameworks:** That incentivize ecosystem services and the adoption of sustainable practices.

References

- Food and Agriculture Organization of the United Nations. (2023). *The impact of disasters on agriculture and food security*. FAO. <https://doi.org/10.4060/cc7900en>
- Gharde, Y., Singh, P. K., Dubey, R. P., & Gupta, P. K. (2018). Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection*, 107, 12–18. <https://doi.org/10.1016/j.cropro.2018.01.007>
- Heap, I. (2024). *The International Herbicide-Resistant Weed Database*. Retrieved March 15, 2024, from <https://www.weedscience.org>
- Bajwa, A. A., Walsh, M., & Chauhan, B. S. (2017). Eco-biology and management of *Parthenium hysterophorus*: A global perspective. *Crop Protection*, 92, 21–31. <https://doi.org/10.1016/j.cropro.2016.10.003>
- Booth, B. D., Murphy, S. D., & Swanton, C. J. (2010). *Weed ecology in natural and agricultural systems* (2nd ed.). CABI Publishing.
- Chauhan, B. S., & Mahajan, G. (Eds.). (2014). *Recent advances in weed management*. Springer. <https://doi.org/10.1007/978-1-4939-1019-9>
- Davis, A. S., & Frisvold, G. B. (2017). Are herbicides a once in a century method of weed control? *Pest Management Science*, 73(11), 2209–2220. <https://doi.org/10.1002/ps.4643>
- Farooq, M., Jabran, K., Cheema, Z. A., Wahid, A., & Siddique, K. H. M. (2011). The role of allelopathy in agricultural pest management. *Pest Management Science*, 67(5), 493–506. <https://doi.org/10.1002/ps.2091>
- Liebman, M., Mohler, C. L., & Staver, C. P. (2001). *Ecological management of agricultural weeds*. Cambridge University Press.
- Monaco, T. J., Weller, S. C., & Ashton, F. M. (2002). *Weed science: Principles and practices* (4th ed.). John Wiley & Sons.
- Neve, P., Barney, J. N., Buckley, Y., & Cousens, R. D. (2018). Reviewing research priorities in weed ecology, evolution, and management. *Weed Research*, 58(4), 245–258. <https://doi.org/10.1111/wre.12304>
- Slaughter, D. C., Giles, D. K., & Downey, D. (2008). Autonomous robotic weed control systems: A review. *Computers and Electronics in Agriculture*, 61(1), 63–78. <https://doi.org/10.1016/j.compag.2007.05.008>
- Swanton, C. J., & Weise, S. F. (1991). Integrated weed management: The rationale and approach. *Weed Technology*, 5(3), 657–663. <https://doi.org/10.1017/S0890037X00033752>
- Walsh, M. J., & Powles, S. B. (2014). High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. *Weed Technology*, 28(3), 486–493. <https://doi.org/10.1614/WT-D-13-00183.1>
- Westwood, J. H., Charudattan, R., Duke, S. O., Fennimore, S. A., Marrone, P., Slaughter, D. C., Swanton, C., & Zollinger, R. (2018). Weed management in 2050: Perspectives on the future of weed science. *Weed Science*, 66(3), 275–285. <https://doi.org/10.1017/wsc.2017.78>
- Jhala, A. J., & Knezevic, S. Z. (2018). Integrated weed management strategies for herbicide resistance mitigation. *Agronomy Journal*, 110(5), 1630–1640. <https://doi.org/10.2134/agronj2018.02.0121>
- Kremer, R. J. (2021). Bioherbicides: A review of current and emerging strategies. *Weed Biology and Management*, 21(3), 78–90. <https://doi.org/10.1111/wbm.12210>
- Moss, S. R. (2019). Integrated weed management (IWM): Why are farmers reluctant to adopt non-chemical alternatives? *Pest Management Science*, 75(5), 1205–1211. <https://doi.org/10.1002/ps.5267>
- Duke, S. O. (2015). Perspectives on transgenic, herbicide-resistant crops in the United States almost 20 years after introduction. *Pest Management Science*, 71(5), 652–657. <https://doi.org/10.1002/ps.3863>
- Chauhan, B. S., Mahajan, G., & Gill, M. S. (2017). Role of cultural methods in integrated weed management. *Crop Protection*, 95, 98–104. <https://doi.org/10.1016/j.cropro.2016.09.012>

From Fresh to Dried: Choosing the Right Fish for Quality and Shelf Life



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Introduction

Fish is a highly perishable food because of its high moisture content, nutrient-rich muscle, endogenous enzymes and susceptibility to microbial growth. Rapid preservation is therefore essential, particularly in tropical coastal regions where high temperature and humidity accelerate quality deterioration. Drying is one of the oldest and most widely practiced methods of fish preservation, enabling reduction of moisture availability, inhibition of microbial growth and extension of storage life. It also facilitates transportation and marketing of fish beyond periods of peak landings (Fitri et al., 2022).

Fish drying is essentially a simultaneous heat- and mass-transfer process. Heat supplied to the fish promotes evaporation of water, while moisture migrates from the interior of the muscle towards the surface and is removed by the surrounding air. The efficiency of drying depends on temperature, relative humidity, air velocity, solar radiation, product thickness, surface area, initial moisture content and fish composition. Traditional sun drying is inexpensive and requires limited infrastructure, but it is strongly influenced by weather and may expose the product to insects, dust and other contaminants. Modern approaches include solar, hot-air, hybrid, microwave-assisted and freeze-drying systems, each requiring appropriate process optimization (Fitri et al., 2022).

The selection of a suitable fish species is therefore a critical preliminary step in fish drying. Species differ considerably in moisture, protein and lipid contents, muscle structure, body size, thickness, seasonal availability and susceptibility to oxidation. Consequently, the same drying conditions cannot necessarily be applied to all species. Selection should consider not only the ability of a fish to lose moisture but also nutritional retention, sensory quality, microbiological safety, storage stability, processing yield and economic feasibility.

Criteria for Selection of Fish Species for Drying

Moisture Content and Water Activity

Moisture content is a major determinant of drying time and energy requirement. Fish muscle contains both relatively mobile free water and more strongly associated water. Free water is removed more readily during evaporation, whereas bound water is more difficult to remove (Fitri et al., 2022).

However, water activity (a_w) is more useful than total moisture content for assessing microbial stability because it indicates the availability of water for microbial growth and chemical reactions. A suitable species should be capable of reaching a sufficiently low water activity within a reasonable drying period. Excessively prolonged drying increases energy consumption and may promote undesirable changes in colour, flavour, texture and lipid oxidation.

Lipid Content and Fatty Acid Composition

Lipid content is one of the most important criteria for species selection. Lean and moderately fatty species generally have greater oxidative stability, whereas highly fatty species require greater attention to oxidation during drying and storage. Fish lipids, particularly polyunsaturated fatty acids, are susceptible to oxidation in the presence of oxygen, heat and light. Oxidation can produce undesirable flavours and odours and reduce nutritional quality.

Tenyang et al. (2020) demonstrated that traditional drying of fish reduced moisture but increased indicators of lipid oxidation and altered fatty-acid composition, including changes in polyunsaturated fatty acids. Similarly, Zeng et al. (2023) identified lipid oxidation as a major quality concern in dried aquatic products and emphasized the importance of controlling excessive oxidation through suitable processing and storage technologies.

Thus, fatty species such as sardines and mackerel can be dried successfully, but may require controlled temperature, reduced oxygen exposure, appropriate antioxidants or pretreatments, and oxygen-barrier packaging.

Protein Content and Muscle Characteristics

Protein is an important nutritional component of dried fish because dehydration concentrates the protein fraction. Species with firm and cohesive muscle are generally preferred because they can withstand washing, salting, cutting and drying with less physical damage.

Muscle structure also affects moisture migration and drying rate. Very soft fish may be difficult to handle and can develop undesirable texture during dehydration. Excessive drying temperatures can cause protein denaturation and produce excessively hard or tough products. Therefore, protein content, muscle firmness and drying conditions should be considered together.

Body Size, Thickness and Morphology

Small and thin fish are generally advantageous for drying because they have a high surface-area-to-volume ratio and a shorter moisture-diffusion distance. They can frequently be dried whole, reducing labour and processing losses. Larger fish require gutting, splitting, filleting or cutting to increase the exposed surface area.

The morphology of the species consequently determines the amount of preparation required and influences drying time. Fitri et al. (2022) noted that processing practices differ according to species, size and geographical origin, with medium- and large-sized fish generally requiring more extensive dressing before drying.

Initial Microbial Quality

The quality of the raw material is essential because drying cannot compensate for advanced spoilage. Fish should be fresh, hygienically handled and processed rapidly after landing. Open-air drying can expose fish to insects, dust, animals and other sources of contamination.

Research comparing traditional and improved drying of Bombay duck demonstrated that improved drying produced better microbiological and sensory quality than traditionally dried products, highlighting the importance of controlled and hygienic drying conditions.

Sensory Quality

A dried fish should have acceptable colour, aroma, flavour, texture and appearance. Excessive lipid oxidation can produce rancid odours, whereas excessive dehydration may produce an undesirable hard texture. Consumer familiarity is also important; species traditionally consumed in dried form generally have an established market.

Availability and Economic Considerations

A technically suitable species may not be economically suitable if it is expensive or seasonally scarce. Selection should therefore consider landing volume, seasonal abundance, raw-material price, processing yield, labour requirement, drying time, energy consumption, packaging cost and market demand.

Small fish that can be dried whole may have an economic advantage because they require less preparation. Conversely, larger species can provide profitable products when processed into higher-value dried or semi-dried products.

Suitable Fish Species for Drying

Sardines

Sardines, particularly Indian oil sardine (*Sardinella longiceps*), are important small pelagic resources and can be dried whole with minimal preparation. Their relatively small size facilitates moisture removal. However, their lipid content can increase susceptibility to oxidative rancidity. Consequently, sardines are suitable for drying but require careful control of temperature, drying duration and storage conditions.

Anchovies

Anchovies, particularly *Stolephorus* spp., are among the most suitable species for drying because of their small size, thin body and high surface-area-to-volume ratio. They can generally be dried whole, reducing processing costs. Studies on *Stolephorus commersonnii* have demonstrated the influence of drying technology on moisture removal, water activity, drying time and product characteristics.

Advanced drying approaches such as hot-air-assisted infrared drying have also been investigated for anchovies, demonstrating the potential for controlled drying systems when higher process consistency is required.

Bombay Duck

Bombay duck (*Harpodon nehereus*) is particularly important for the western coast of India and Maharashtra. Historical fisheries literature identifies Maharashtra and Gujarat as major regions supporting the Bombay duck fishery, and the species has long been utilized in dried and semi-dried forms.

The species has high moisture content and relatively delicate muscle, making rapid processing important. Solar and hybrid drying systems have demonstrated considerable potential. Alfiya et al. (2022) reported that solar-LPG hybrid drying substantially reduced drying time while producing microbiologically acceptable dried Bombay duck.

More recent comparative work also showed improved colour, texture, microbiological quality and storage characteristics in Bombay duck processed using an improved dryer compared with traditionally dried samples.

Indian Mackerel

Indian mackerel (*Rastrelliger kanagurta*) is another commercially important marine fish that can be dried or salted and dried. Its nutritional value makes it attractive; however, its relatively high lipid content requires careful oxidation control. It is therefore better suited to controlled drying and protective packaging when a standardized, high-quality product is required.

Ribbonfish

Ribbonfish (*Trichiurus* spp.) possesses an elongated body and can be dried after splitting or cutting. Its morphology allows increased surface exposure following preparation. It is suitable for both traditional and controlled drying systems. Solar tunnel drying studies involving commercially important marine species, including ribbonfish and Bombay duck, demonstrate the feasibility of controlled solar drying for marine fish products (Reza et al., 2009).

Small Demersal Fish

Small croakers, silver bellies and other demersal species can also be suitable, particularly when they have firm muscle and low-to-moderate lipid content. Their suitability varies by species and size, and experimental evaluation of drying rate, final moisture, lipid oxidation, microbial quality and sensory acceptability is recommended.

Small Shrimps

Small shrimps, including *Acetes* spp., are particularly appropriate for drying because their small size permits rapid moisture removal. Dried shrimp is widely used as a traditional food ingredient and has potential for further value addition as shrimp powder, seasoning and protein-rich ingredients.

Indian dried-fish value-chain studies have reported the drying of small shrimps, anchovies, prawns and other small fish, demonstrating the importance of species size and processing practices in determining the final product.

Suitability of Major Species

Species/group	Overall suitability	Major advantage	Major limitation
Anchovies	Very high	Small size and rapid drying	Contamination during open drying
Small shrimps	Very high	Rapid drying and value-addition potential	Storage deterioration
Bombay duck	Very high	Strong traditional market	Soft muscle and high initial moisture
Sardines	High	Abundance and nutritional value	Lipid oxidation
Ribbonfish	High	Suitable elongated morphology	Cutting/splitting required
Small demersal fish	High	Firm muscle	Seasonal availability
Indian mackerel	Moderate-high	Nutritional value	Higher oxidation risk

This comparison indicates that no single species is universally optimal. The most appropriate species depends on the intended product, drying technology, season, raw-material cost and target market.

Drying Technology and Species Selection

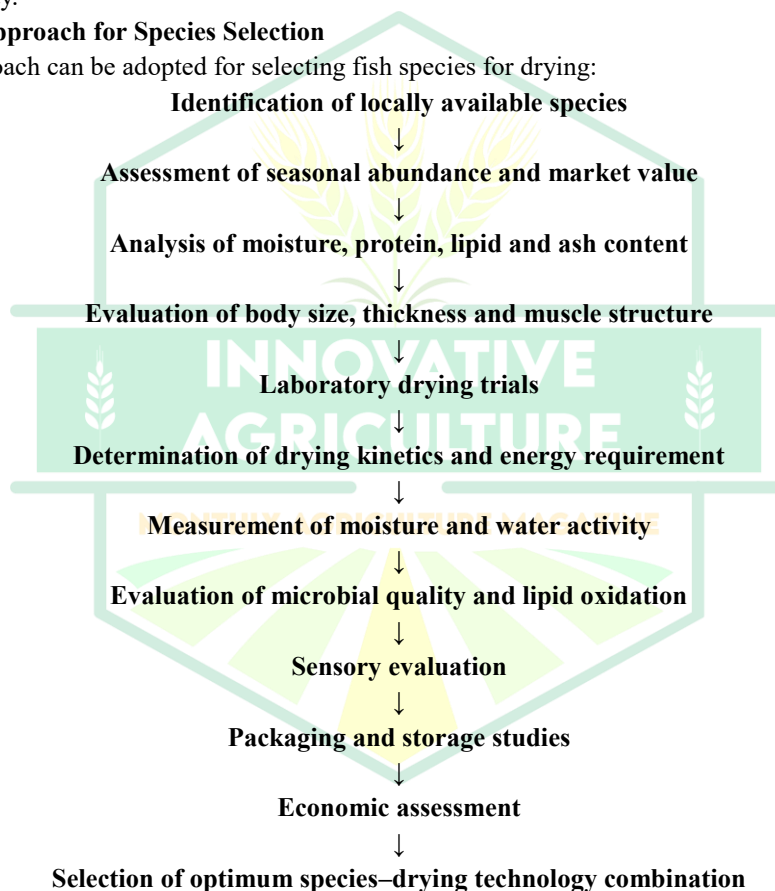
Drying technology should match species characteristics and economic value. Sun drying suits small fish and shrimps but is weather-dependent and contamination-prone. Solar drying offers better protection with low energy use, while hot-air drying provides greater process control but may accelerate oxidation at high temperatures. Hybrid solar-assisted systems are promising for coastal regions; solar-LPG drying has improved Bombay duck processing (Alfiya et al., 2022). Vacuum, microwave-assisted and freeze drying offer better control but require higher capital and energy, making them suitable mainly for high-value products.

Quality, Packaging and Storage

Successful fish drying depends on raw-material quality, drying, packaging and storage. Key indicators include moisture, water activity, microbial load, TVB-N, lipid oxidation, colour, texture and sensory quality. Lipid oxidation can reduce nutritional and sensory quality, especially in fatty fish. Moisture absorption may increase water activity and microbial deterioration. Therefore, adequate drying and oxygen- and moisture-resistant packaging, including vacuum or high-barrier systems where suitable, are essential for maintaining safety, quality and storage stability.

Recommended Approach for Species Selection

A systematic approach can be adopted for selecting fish species for drying:



Such an approach allows species selection to be based on measurable technological and economic parameters rather than traditional preference alone.

Future Prospects

Future research should emphasize species-specific drying kinetics, climate-resilient technologies, oxidation control, energy efficiency, predictive quality modelling and improved packaging. Solar and hybrid dryers can reduce fuel dependence and contamination risks in coastal communities. Value addition through fish powders, flakes, seasonings and protein-rich ingredients can enhance economic returns and reduce post-harvest losses.

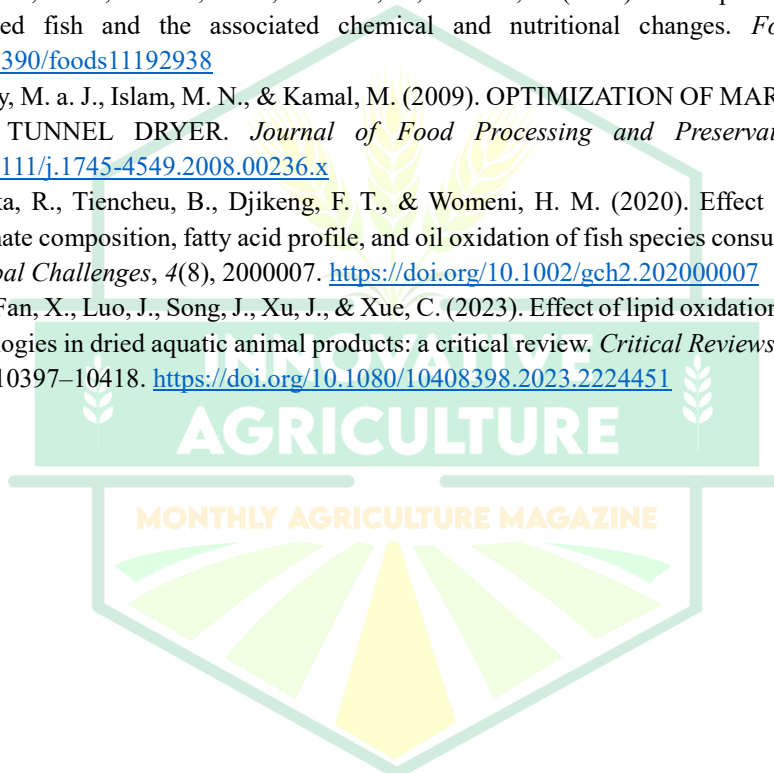
Conclusion

Suitable fish selection is essential for efficient and sustainable drying. Key factors include moisture, lipid and protein content, muscle structure, body size, microbial quality, sensory attributes, seasonal availability, yield and

economic value. Small fish such as anchovies and shrimps dry rapidly, while Bombay duck is particularly important along Maharashtra's western coast. Sardines and mackerel offer high nutritional value but require oxidation control. For Konkan, combining traditional practices with solar, hybrid and mechanical drying, along with hygienic handling and protective packaging, can improve quality, safety and profitability. The ideal species balances drying efficiency, nutrition, acceptability, stability, availability, energy use and economic return.

References

- Alfiya, P., Murali, S., Delfiya, D. A., Sreelakshmi, K., Sivaraman, G., & Ninan, G. (2022). Kinetics, modelling and evaluation of Bombay duck (*Harpodon nehereus*) dried in solar-LPG hybrid dryer. *Solar Energy*, 242, 70–78. <https://doi.org/10.1016/j.solener.2022.07.006>
- Delfiya, D. S. A., Sneha, R., Prashob, K., Murali, S., Alfiya, P. V., & Samuel, M. P. (2021). Hot air-assisted continuous infrared dryer for anchovy fish drying. *Journal of Food Process Engineering*, 45(6). <https://doi.org/10.1111/jfpe.13824>
- Fitri, N., Chan, S. X. Y., Lah, N. H. C., Jam, F. A., Misnan, N. M., Kamal, N., Sarian, M. N., Lazaldin, M. a. M., Low, C. F., Hamezah, H. S., Rohani, E. R., Mediani, A., & Abas, F. (2022). A comprehensive review on the processing of dried fish and the associated chemical and nutritional changes. *Foods*, 11(19), 2938. <https://doi.org/10.3390/foods11192938>
- Reza, M. S., Bapary, M. a. J., Islam, M. N., & Kamal, M. (2009). OPTIMIZATION OF MARINE FISH DRYING USING SOLAR TUNNEL DRYER. *Journal of Food Processing and Preservation*, 33(1), 47–59. <https://doi.org/10.1111/j.1745-4549.2008.00236.x>
- Tenyang, N., Ponka, R., Tiencheu, B., Djikeng, F. T., & Womeni, H. M. (2020). Effect of traditional drying methods on proximate composition, fatty acid profile, and oil oxidation of fish species consumed in the Far-North of Cameroon. *Global Challenges*, 4(8), 2000007. <https://doi.org/10.1002/gch2.202000007>
- Zeng, J., Song, Y., Fan, X., Luo, J., Song, J., Xu, J., & Xue, C. (2023). Effect of lipid oxidation on quality attributes and control technologies in dried aquatic animal products: a critical review. *Critical Reviews in Food Science and Nutrition*, 64(28), 10397–10418. <https://doi.org/10.1080/10408398.2023.2224451>



Low-Cost Goat Housing for Small Farmers



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Abstract

Goat farming is an important source of income and livelihood for small and marginal farmers, particularly because goats require comparatively less space, feed and initial investment than large livestock. However, proper housing is essential for maintaining animal health, reducing disease risk and improving productivity. Expensive housing systems are often difficult for small farmers to afford, but a well-planned low-cost goat shed can provide adequate protection using locally available materials. Proper site selection, good ventilation, adequate floor space, protection from rain and extreme temperatures, suitable feeding and watering arrangements, and regular cleaning are the basic requirements of economical goat housing. Raised floors can be particularly useful in areas with high rainfall and humidity by keeping animals away from moisture and accumulated waste. Separate spaces for kids, pregnant animals and sick goats can further improve management and reduce health problems. Low-cost housing should not mean poor-quality housing; rather, it should focus on maximum animal comfort and hygiene with minimum investment. Adoption of simple, scientific and locally suitable housing practices can help small farmers reduce production losses, improve goat health and contribute to more profitable and sustainable goat farming.

Keywords: Goat farming, Goat shed, Housing, Locally available materials.

Introduction

Goat farming is one of the easiest livestock enterprises for small and marginal farmers because goats require comparatively less space, feed and investment than large animals. However, good housing is essential for healthy goats, faster growth, better reproduction and lower disease losses. Many farmers think that a goat house must be expensive or constructed with cement and bricks. In reality, a safe and comfortable goat shed can be prepared at relatively low cost using locally available materials.

Why is Good Housing Important?

Goats are hardy animals, but they do not perform well when they are continuously exposed to rain, cold winds, excessive heat, damp floors or poor sanitation. A poorly designed shed can increase the risk of pneumonia, diarrhoea, parasitic infections, foot problems and kid mortality.

A good goat house should provide:

- Protection from rain, wind and extreme temperatures
- Adequate ventilation and sunlight
- A dry and clean resting area
- Protection from predators
- Easy feeding and watering
- Proper drainage of urine and wastewater
- Sufficient space for movement
- Easy cleaning and manure collection

The objective of a low-cost shed is not to make the cheapest possible structure, but to construct a practical shelter that provides maximum benefit with minimum investment.

Choose the Right Location

The location of the goat shed is the first important decision. Select a raised and well-drained site that does not become waterlogged during the rainy season. The shed should preferably receive morning sunlight while being protected from strong winds. It is better to keep the shed slightly away from stagnant water, garbage pits and other

sources of contamination. A location close to the farmer's house is also useful because goats can be observed regularly, especially during kidding.

Use Locally Available Materials

Small farmers do not necessarily need costly construction materials. Depending on availability and climate, the shed can be made using-bamboo, wooden poles, locally available timber, bricks, mud or clay, thatch, corrugated sheets, tiles, gi sheets, locally available roofing materials.

Bamboo and wooden poles can be particularly useful for low-cost construction. However, materials that remain in direct contact with moisture should be properly treated or protected to increase their life.

Raised Floor: A Smart Investment

One of the most useful features of a goat shed, particularly in areas with heavy rainfall or high humidity, is a raised floor.

Instead of keeping goats directly on a damp earthen floor, the resting platform can be raised above ground level. Wooden or bamboo slats can be used where locally suitable.

A raised floor helps:

- ❖ Keep goats away from wet manure and urine.
- ❖ Improve ventilation below the animals.
- ❖ Reduce moisture accumulation.
- ❖ Keep the sleeping area cleaner.
- ❖ Make manure collection easier.

However, the floor should be strong, safe and comfortable. Slats should not have gaps large enough for a goat's hoof or a kid's leg to become trapped.

Adequate Space is Essential

Overcrowding is a common mistake in small goat farms. When too many goats are kept in a small area, competition for feed increases and the risk of disease transmission becomes higher. The space requirement depends on the age, size, breed, production stage and housing system. Adult goats require more space than kids, while pregnant and lactating animals may need additional room.

Therefore, farmers should avoid designing a shed only according to the present herd size. If possible, some provision should be made for future expansion.

Proper Roof Design

The roof is the main protection against rain and heat. A roof with a sufficient slope allows rainwater to drain quickly. In hot regions, a very thin metal sheet can become extremely hot during the afternoon. A simple solution is to provide insulation or an additional layer using locally available material. Adequate roof height and ventilation also help reduce heat accumulation. The roof should have enough overhang to prevent rainwater from entering the shed.

Ventilation and Sunlight

A goat house should be airy but not exposed to strong cold drafts. Good ventilation removes excess moisture, ammonia, heat, dust, unpleasant odours. The shed should have open sides or properly positioned windows covered with suitable mesh or fencing. Natural sunlight is also beneficial for maintaining a cleaner and healthier housing environment. During winter, however, young kids need additional protection from cold winds.

Feeding and Watering Arrangements

Feeders should be designed so that goats can eat comfortably without standing inside the feed trough. Fresh and clean drinking water should be available regularly. Water containers should be placed at a convenient height and cleaned frequently. Dirty water can quickly become a source of disease, especially when several animals use the same container.

Separate Areas for Different Goats

If the herd is large enough, keeping all animals together is not ideal. Simple partitions can be made using bamboo or wooden fencing. Separate areas can be provided for adult males, adult females, pregnant or kidding goats, young kids, sick animals. A separate kidding area is particularly useful. It provides the mother and newborn kid with a cleaner and quieter environment during the critical period around birth.

Special Care of Newborn Kids

Newborn kids are more vulnerable to cold, dampness and infections than adult goats. Their housing should therefore receive special attention. The kidding and kid area should be dry, clean, well ventilated, protected from cold drafts, easy to disinfect.

The newborn kid should receive colostrum as soon as possible after birth. Good housing alone cannot prevent kid mortality; proper nutrition, hygiene, vaccination and disease prevention must accompany good housing.

Cleanliness: The Cheapest Disease Prevention

Farmers sometimes spend money on medicines while neglecting the cleanliness of the shed. Regular cleaning is one of the simplest ways to reduce disease problems. Manure and wet bedding should be removed regularly. Feed that has become contaminated with urine or faeces should not be offered to goats. The shed should be periodically cleaned and disinfected, particularly before introducing new animals. A clean shed also reduces flies, bad odour and parasite problems.

Low-Cost Housing Does Not Mean Poor Housing

There is an important difference between low-cost housing and poor-quality housing.

A poor shed may save money during construction but increase expenses later through:

- Higher disease incidence
- Increased kid mortality
- Feed wastage
- Poor growth
- More labour requirements
- Frequent repairs

A properly planned low-cost shed can actually reduce the long-term cost of goat farming.

Important Points

Before constructing a goat shed, remember these simple rules: Dry floor + fresh air + shade + sunlight + clean water + proper drainage + adequate space = healthier goats.

Farmers should also remember that housing requirements change according to local climate. A design suitable for a hot and dry area may not be ideal for a region receiving heavy rainfall. Therefore, local materials, weather conditions and herd size should always be considered.

Conclusion

Low-cost goat housing is an excellent option for small and marginal farmers. A good goat shed does not have to be expensive. With proper site selection, locally available materials, adequate space, good ventilation, a dry floor, proper drainage and regular cleaning, farmers can create a healthy environment for their goats at relatively low cost. The real goal of goat housing is not simply to provide a roof over the animals. It is to create an environment in which goats can eat, rest, grow, reproduce and remain healthy. A well-planned low-cost shed can therefore become an important investment in profitable and sustainable goat farming.

Herbicide Residues in Agriculture: Causes, Impacts, and Management



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Abstract

Herbicides have become an essential component of modern agriculture because they provide effective, economical and timely weed control. However, using herbicides incorrectly or repeatedly might leave residues in the soil, water, or harvested produce. These residues can persist for varying periods depending on the herbicide, soil properties and environmental conditions. Herbicide residues may injure succeeding crops, reduce soil microbial activity, contaminate water resources and pose environmental concerns. Fortunately, crop rotation, approved application rates, appropriate herbicide selection, and integrated weed management practices can reduce majority of the residue-related issues.

Keywords: Crop safety, Herbicide degradation, Herbicide residues, Soil health

Introduction

Weeds are among the most important biological constraints limiting agricultural productivity worldwide. In India, uncontrolled weed infestation can reduce crop yields by **15–80%**, depending on the crop, weed species, and management practices. Besides reducing yield, weeds compete with crops for nutrients, water, light, and space, interfere with harvesting operations, and may act as alternate hosts for insect pests and diseases (Rao & Chauhan, 2015). Effective weed management is therefore essential for achieving higher crop productivity and ensuring food security.

Over the past few decades, herbicides have become an integral component of modern agriculture because they provide timely, effective, and economical weed control while reducing dependence on manual labour. Their use has increased considerably due to labour shortages, rising wages, and the expansion of intensive cropping systems and conservation agriculture (Sondhia, 2014). However, improper or repeated use of herbicides may result in the persistence of small amounts of these chemicals in the soil, water, crop plants, or harvested produce. These remaining quantities are known as **herbicide residues**.

Under normal conditions, most herbicides degrade naturally through microbial activity, sunlight, moisture, and chemical reactions. However, repeated application, excessive doses, and unfavourable environmental conditions can delay their degradation, causing residues to persist for longer periods (Janaki et al., 2015). Persistent residues may injure succeeding crops, affect beneficial soil microorganisms, contaminate water resources, and, in some cases, contribute to residue accumulation in harvested produce (Sondhia, 2014).

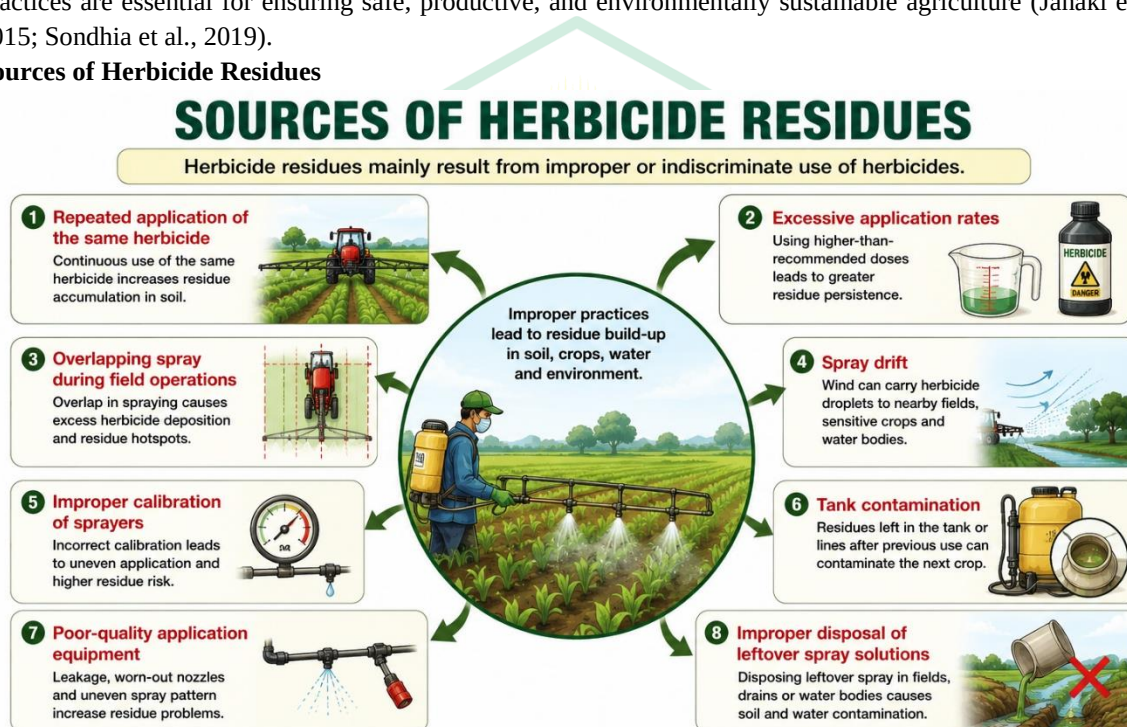
It is important to note that the presence of herbicide residues does not necessarily indicate a health or environmental risk. When herbicides are used according to recommended doses and good agricultural practices, residue levels generally decline to safe limits. Scientific herbicide selection, proper crop rotation, improved soil health, precision application, and integrated weed management can effectively minimize residue-related problems and ensure sustainable crop production (Janaki et al., 2015; Sondhia et al., 2019). This article discusses the causes, effects, and practical management strategies of herbicide residues for safe and sustainable agriculture.

What Are Herbicide Residues?

Herbicide residues refer to the traces of herbicides and their transformation products that remain in agricultural soils, crops, irrigation water, harvested produce, or crop residues after application. The persistence of these residues varies according to the chemical characteristics of the herbicide and prevailing environmental conditions. (Janaki et al., 2015).

It is important to understand that the presence of herbicide residues does not necessarily indicate contamination or pose a threat to crop production, human health, or the environment. Most herbicides gradually break down through natural processes such as microbial degradation, sunlight, moisture, and chemical reactions, and their residues decline to safe levels within the recommended waiting period (Sondhia, 2014). However, when persistent herbicides are applied repeatedly, used at higher-than-recommended doses, or when unfavourable environmental conditions slow their degradation, residues may remain biologically active for longer periods. Such persistent residues can injure sensitive succeeding crops, affect beneficial soil microorganisms, or contaminate nearby water resources. Therefore, understanding herbicide residues and adopting recommended management practices are essential for ensuring safe, productive, and environmentally sustainable agriculture (Janaki et al., 2015; Sondhia et al., 2019).

Sources of Herbicide Residues



How Do Herbicide Residues Develop?

After application, herbicides undergo several physical, chemical, and biological processes that determine their persistence in the environment. A portion of the applied herbicide is absorbed by weeds and crop plants, while some binds to soil particles and organic matter. Simultaneously, herbicides begin to degrade through microbial activity, sunlight (photodegradation), and chemical reactions such as hydrolysis, which gradually reduce their concentration in the soil (Janaki et al., 2015).

Some herbicides may also be lost through volatilization, surface runoff, or leaching into deeper soil layers and groundwater, depending on their chemical properties and prevailing environmental conditions (Sondhia, 2014). Under favourable conditions, including adequate soil moisture, warm temperatures, and active microbial populations, most herbicides degrade rapidly and their residues decline to safe levels.

However, degradation may slow under dry or cold conditions, in soils with low microbial activity, or when persistent herbicides are repeatedly applied. In such situations, herbicide residues may remain biologically active for longer periods and can affect sensitive succeeding crops, beneficial soil microorganisms, or nearby water resources. Therefore, understanding the fate of herbicides after application is essential for minimizing residue-

related problems and ensuring their safe and sustainable use in modern agriculture (Janaki et al., 2015; Sondhia et al., 2019).

Factors Affecting Herbicide Persistence

The persistence of herbicide residues in the environment depends on the interaction of several factors related to the herbicide, soil, and climate. Among these, the chemical nature of the herbicide plays a major role. Herbicides with longer half-lives remain active in the soil for extended periods and are more likely to cause carryover injury to succeeding crops (Janaki et al., 2015).

Soil properties also influence herbicide persistence. Clay soils and soils rich in organic matter adsorb herbicides more strongly than sandy soils, reducing their immediate availability but sometimes prolonging their persistence. In contrast, sandy soils allow herbicides to move more easily into deeper soil layers, increasing the risk of groundwater contamination. Soil pH further affects degradation, with some herbicides persisting longer in alkaline soils and others under acidic conditions (Sondhia, 2014).

Environmental conditions such as soil moisture, temperature, and rainfall are equally important. Adequate moisture and warm temperatures promote microbial activity, accelerating herbicide degradation. Conversely, dry conditions and low temperatures slow down degradation, allowing residues to persist for longer periods. Excessive rainfall or irrigation may transport herbicides through runoff or leaching into nearby water bodies or groundwater (Janaki et al., 2015).

The soil microbial population is one of the most important factors governing herbicide breakdown. Healthy soils rich in beneficial microorganisms degrade herbicides more rapidly than degraded soils with low biological activity. Therefore, maintaining soil health through balanced nutrient management and the addition of organic amendments not only improves crop productivity but also accelerates herbicide degradation, thereby reducing the risk of residue-related problems (Sondhia et al., 2019).

Effects of Herbicide Residues

1. Injury to Succeeding Crops

One of the most common consequences of persistent herbicide residues is carryover injury, where biologically active residues remaining in the soil affect crops planted in the following season. Sensitive crops such as pulses, oilseeds, vegetables, and some horticultural crops are more susceptible than cereals. Depending on the herbicide and residue level, affected crops may exhibit poor seed germination, delayed emergence, yellowing (chlorosis), stunted growth, malformed leaves, restricted root development, and ultimately reduced yield. Such symptoms are often mistaken for nutrient deficiencies or disease, making proper diagnosis essential (Janaki et al., 2015).

2. Effects on Soil Health

Herbicide residues may temporarily influence soil health by affecting beneficial microorganisms involved in nutrient cycling, decomposition of organic matter, and biological nitrogen fixation. Although most herbicides degrade over time and microbial populations generally recover, repeated application of persistent herbicides or excessive doses can disturb soil biological activity and reduce soil fertility in the long term (Sondhia, 2014).

3. Water Pollution

Herbicides may move from agricultural fields into nearby ponds, rivers, reservoirs, and groundwater through surface runoff or leaching, particularly after heavy rainfall or excessive irrigation. Contaminated water can affect aquatic plants, fish, and other non-target organisms, besides reducing water quality for agricultural and domestic use. The risk is generally greater in sandy soils and areas receiving high rainfall (Sondhia et al., 2019).

4. Crop Quality and Food Safety

If recommended application rates and pre-harvest intervals are not followed, herbicide residues may remain in harvested produce. Excessive residues can reduce market acceptability, affect export potential, and may exceed the Maximum Residue Limits (MRLs) prescribed for food safety. Adherence to label recommendations is therefore essential to ensure safe agricultural produce (FAO & WHO, 2025).

5. Impact on Biodiversity

Persistent herbicide residues may also influence biodiversity by affecting non-target vegetation growing along field boundaries and irrigation channels. The reduction in plant diversity can indirectly decrease habitats and food sources for beneficial insects, pollinators, birds, and other organisms that contribute to ecosystem stability.

Maintaining judicious herbicide use and adopting integrated weed management practices can help conserve biodiversity while ensuring effective weed control (Sondhia et al., 2019).

Management of Herbicide Residues

Effective management of herbicide residues requires an integrated approach that combines proper herbicide use with good agronomic practices. The following measures can significantly reduce residue-related problems:

1. **Apply Herbicides at the Recommended Dose:** Never exceed the label-recommended application rate. Higher doses increase residue persistence without substantially improving weed control.
2. **Select the Appropriate Herbicide:** Choose herbicides based on the crop, soil type, climatic conditions, and cropping sequence. Avoid persistent herbicides when sensitive crops are planned in the following season.
3. **Follow Crop Rotation Restrictions:** Observe the recommended waiting period before planting the next crop to prevent carryover injury, particularly in pulses, vegetables, and oilseeds.
4. **Improve Soil Organic Matter:** Incorporate farmyard manure (FYM), compost, green manures, or crop residues to stimulate microbial activity and accelerate herbicide degradation.
5. **Maintain Adequate Soil Moisture:** Proper irrigation after herbicide application promotes microbial degradation, whereas prolonged dry conditions increase herbicide persistence.
6. **Enhance Soil Microbial Activity:** Maintain healthy soils through balanced fertilization, residue recycling, and organic amendments to encourage natural herbicide degradation.
7. **Calibrate Sprayers Regularly:** Use the correct nozzle, spray pressure, and travel speed to ensure uniform application and prevent excessive herbicide deposition or spray overlap.
8. **Prevent Spray Drift:** Apply herbicides during calm weather and use drift-reducing nozzles and the recommended boom height to avoid contamination of neighbouring crops.
9. **Clean Spray Equipment Thoroughly:** Wash spray tanks, hoses, filters, and nozzles after each application to prevent accidental injury to subsequent crops.
10. **Adopt Integrated Weed Management (IWM):** Combine cultural, mechanical, biological, and chemical weed management practices to reduce herbicide dependence and minimize long-term residue accumulation.

Conclusion

Herbicides are valuable tools for improving agricultural productivity, but their benefits depend on responsible use. Herbicide residues become problematic mainly when herbicides are misused or when environmental conditions delay their degradation. Sound agronomic practices, proper herbicide selection, adherence to recommended doses, planned crop rotations and integrated weed management can greatly reduce residue-related problems. Emerging precision technologies and improved stewardship will further enhance safe herbicide use while protecting soil health, water resources and crop productivity. Sustainable management of herbicide residues is therefore essential for ensuring profitable farming and environmental protection.

References

- Das, T. K. (2021). *Weed science: Basics and applications* (3rd ed.). Jain Brothers.
- Food and Agriculture Organization of the United Nations, & World Health Organization. (2025). *Pesticide residues in food: Joint FAO/WHO meeting on pesticide residues*. World Health Organization.
- Janaki, P., Sharma, N., Chinnusamy, C., Sakthivel, N., & Nithya, C. (2015). Herbicide residues and their management strategies. *Indian Journal of Weed Science*, 47(3), 329–344.
- Rao, A. N., & Chauhan, B. S. (2015). Weeds and weed management in India—A review. In A. N. Rao & N. T. Yaduraju (Eds.), *Weed Science in the Asian-Pacific Region* (pp. 87–118). Indian Society of Weed Science.
- Sondhia, S. (2014). Herbicides residues in soil, water, plants and non-targeted organisms and human health implications: An Indian perspective. *Indian Journal of Weed Science*, 46(1), 66–85.
- Sondhia, S., Choudhury, P. P., & rao, A. R. (Eds.). (2019). *Herbicide residue research in India*. Springer.

Fast-Track Breeding: A Futuristics Technique for Improvement of Vegetable Crops



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Abstract

Fast-track breeding has produced more vigorous simulations than genomic selection with the high rate of genetic gain in its crops. In order to overcome the enormous barrier of the protracted varietal development process, speed breeding has given rise to the prospect of more inventive breeding techniques and programme redesigns that reduce the difficulties and seize any chances that may present themselves in the course of plant breeding.

Introduction

The world's agriculture has significant challenges in producing enough food to feed the expanding population (According to United Nation current world population is around 8.0 billion and is estimated to reach nearly 9.9 billion by 2050), particularly due to the exponential rise of the human population and the acceleration of climate change. In order to feed the world's expanding population, plant breeding is essential for improving productivity and solving agricultural issues. However, the rate at which important vegetable crops like potatoes (*Solanum tuberosum* L), tomatoes (*Solanum Lycopersicon* L), peas (*Pisum sativum* L) and other legumes and leafy vegetables like lettuce (*Lactuca sativa* L) are being produced is not sufficient to fulfil future demand.

Crop breeding is traditionally a laborious process that takes years to complete and requires numerous generations of crossbreeding, selection and evaluation. But by creating environments that resemble ideal growth environments-such as prolonged light exposure and regulated humidity and temperature-fast track breeding transforms this procedure. Fast track breeding is a cutting-edge agricultural technique designed to accelerate the breeding process of crops, enabling faster development of new varieties. Various selection methods can be integrated into speed breeding, such as the single seed descent (SSD), single pod descent (SPD), single plant selection (SPS), clonal selection and marker assisted selection (MAS) to shorten the breeding cycle and for efficient resource use. Fast track breeding results in 3 to 9 generations per year compared to 1 to 2 generations per year achieved with conventional selection approaches. As a result, speed breeding offers opportunities to rapidly develop homozygous and stable genotypes and to facilitate rapid generation advancement, resulting in accelerated development and release of new cultivars. By controlling the photoperiod (the amount and quality of light), temperature (which depends on the crop) and CO₂ surrounding the crop, fast track breeding may reduce the time it takes for seeds to mature and be harvested, which in turn shortens the time it takes for crops to grow.

For the first time, Lee Hickey used fast track breeding technique to create a wheat variety. "DS Faraday" is the first wheat variety which was released during 2017 in Australia has high protein content, good milling quality and tolerance for pre-harvest sprouting. The industries are also adopting it widely at the present time. The National Aeronautics and Space Administration (NASA) of the United States initially observed and employed this innovative technology or technique in the 1980s for space crop cultivation. They were able to grow crops far more quickly by using this strategy. Speed breeding can be done in many species like wheat, barley, canola, chickpea, garden pea, cauliflower, tomato, carrot etc. It started with agronomical crops. But now it can be possible in horticultural crops also.

Understanding the Need for Innovation in Vegetable Cultivation

- Challenges in Traditional Vegetable Cultivation
- Growing Demand for Improving Varieties
- Climate Change and Environmental Pressure
- Nutritional and Quality Consideration
- Sustainability and Resources Efficiency

- Global Food Security Imperatives
- Alignment with Sustainable Development Goals (SDGs)
- Urgency for Innovation and Collaboration
- Pest and Disease Management

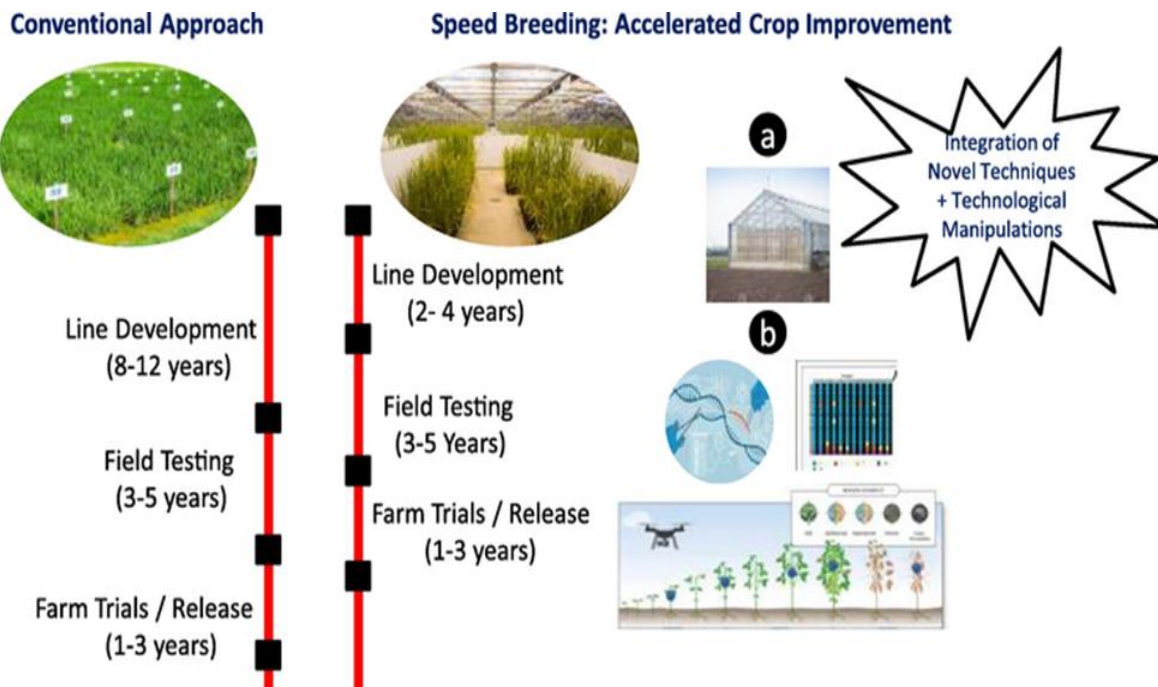


Fig: 1 Difference between conventional breeding and speed breeding

Basic Setup for Fast-track Breeding

- Temperature: 17°C during the two-hour dark period and 22°C during the light time.
- Photoperiod: Research has indicated that the best conditions for speedy reproduction are 22 hours of sunshine interspersed with 2 hours of darkness.
- Light: Any type of lighting that focuses on the blue, red and far-red ranges of the Photosynthetic Active (PAR) zone (400-700 nm) will help plants reproduce quickly.
- Humidity: A humidity of 60-70% has been maintained during the speed breeding programme.

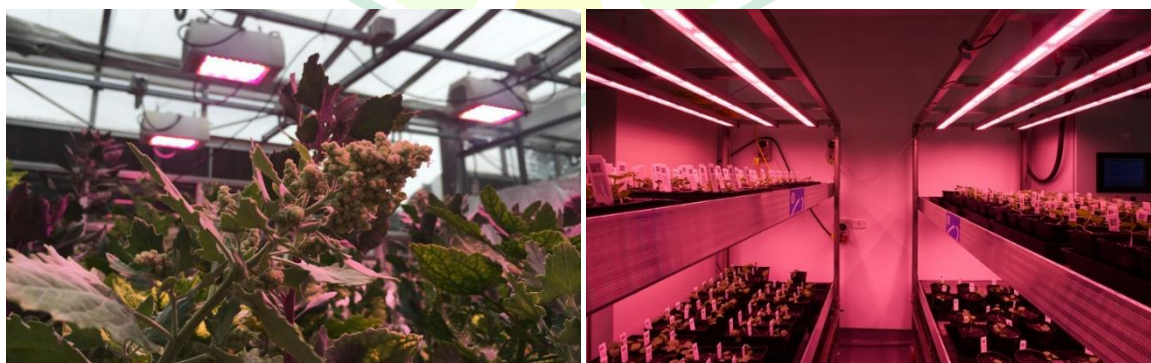


Fig: 2 Speed breeding chambers

Opportunities of Fast-track Breeding Techniques

1. Rapid development of homozygous lines for accelerated breeding:

Speed breeding techniques have been used on various crops to rapidly develop homozygous lines after initial crosses of selected parents with complimentary traits. The technique depends on the manipulation of photoperiod, light intensity, temperature, soil moisture, soil nutrition and high-density planting. These methods have been used

to induce early flowering and seed set, reducing the time taken to generate each breeding generation. The method allows for the production of 3 to 9 breeding generations per year. This is ideal for accelerated breeding and population evaluation across the target production environments involving various selection methods such as SSD, SPD and SPS.

2. Amenability with selection methods

The combination of speed breeding and effective selection methods should allow for the maintenance of a good breeding population and genetic diversity in the environments that restrict plant growth and for maximum yield production. The most appropriate selection methods amenable with speed breeding are single seed descent (SSD), single pod descent (SPD) and single plant selection (SPS) methods.

- **Single seed descent method**

Single seed descent (SSD) is geared towards achieving homozygous populations through continuous inbreeding of segregating population by retaining one seed from each F₂ plant and advancing these individuals to the next generation. The advantages of the SSD selection method include less growing area and labour being required for the handling of early generations. It allows for the advancement of progeny under high-density plantings in small nurseries, growth chambers or greenhouses.

- **Single pod descent method**

Single pod descent (SPD) method involves selection of one pod per plant from each F₂ - F₄ plant instead of a single seed. Due to there being more than one seed per pod in most legume crops, SPD has a higher chance of maintaining each F₂ plants in the advanced generations than SSD selection. advantage of SPD is that it allows for the early selection of pods, so a smaller population can be advance

- **Single plant selection method**

The single plant selection (SPS) method advances each F₂ plant by harvesting all the seeds of each selected plant. Hence the next generation will be advanced as plant-to-row. The SPS involves early selection of plants based on a smaller population than SSD and SPD.

Advantage of Fast-track Breeding

- Rapid Generation Turnover
- Reduced Breeding Cycle Time
- Enhanced Trait Selection Efficiency
- Increased Genetic Diversity
- Seasonal Independence
- Accelerated Response to Emerging Challenges
- Optimal Resource Utilization:
- Facilitated Trait Stacking and Trait Introgression
- Improved Breeding Program Productivity
- Contribution to Food Security and Sustainability

Constraints of Fast-track Breeding

- A major challenge that can hamper the adoption of Fast track breeding in the public sector is a lack of trained and active plant breeders and plant breeding technicians in developing countries.
- Fast track breeding platforms require sophisticated infrastructure to regulate environmental factors, particularly soil moisture, temperature and photoperiod. Institutional support is limited in public plant breeding programmes in many developing countries. This limits the adoption of state-of-the-art breeding methods such as speed breeding and biotechnological tools.
- There is a need for active collaboration between national and regional organizations in the development of infrastructure and for resource and knowledge sharing once the infrastructure is in place.

Fast track breeding in vegetable crops: A Future Prospectus

- Development and standardization of “speed breeding” protocol in several vegetable crops such as radish, pea, tomato, Amaranthus, Cassava, Potato, Brassica, Sugar beet, pea and some other leafy vegetables are in progress.

- Fast track breeding is likely to reduce generation time for other crops like tomato, potato, Amaranthus (can produced eight-generations per year instead of two in the field)
- Pepper: Early flowering and fruiting under continuous light.
- Onion: is biennial bulb formation in one year and flowering and seed setting takes place in the next year, cross-pollinated (due to the presence of protandry) and suffer serve inbreeding depression which took 10 - 12 years for varietal development. In onion, Fast track breeding can be hastened by breaking bulb dormancy and subjected with 22-hour photoperiod using Far-red light accelerate bulb initiation within 45 days and caused rapid bulb maturity within 80 days instead of required 5 - 6 months for bulb development.
- Tomato: is sensitive against continuous light supplement, hence identification and mapping of continuous light tolerant locus CAB-13 at the short arm of chromosome 7 and CAB-13 (Soly07g063600.2) gene linked with marker 7-20-1B responsible for light tolerant and its role in continuous light tolerant.
- Fast track breeding protocol has been standardized for growing of potato with continuous supplementation of long photoperiod in controlled greenhouse conditions accelerated faster plant growth and produced earlier flowering, fruiting and faster seed maturity. Fast track breeding integrated with aeroponics technology-facilitated year-round production of disease-free mini tubers suitable for planting purpose.

Conclusion

Breeding of vegetables is one of the crucial and difficult parts of agriculture. For agricultural crops, both conventional and molecular methods are useful in breeding. Developing improved and well-developed germplasm is essential to creating F₁ hybrids. The inclusion of strategies like gene pyramiding, MAGIC population and the introgression of wild species can improve the quality of segregating populations. All of these tactics add the necessary variation to the germplasm population, which makes it easier for breeders to examine the flow of characters within populations that are being separated and the behaviour of genes in relation to their surroundings- two extremely significant aspects of breeding.

Organic Farming and it's Impacts on Soil Health



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Abstract

Organic farming is an environmentally friendly agricultural system that relies on natural inputs and ecological processes to produce food while maintaining soil fertility and biodiversity. It avoids the use of synthetic fertilizers, pesticides, and genetically modified organisms (GMOs). Healthy soil is the foundation of sustainable agriculture, and organic farming plays a crucial role in improving soil physical, chemical and biological properties. Practices such as crop rotation, green manuring, compost application, mulching, and biological pest management enhance soil structure, nutrient availability, water-holding capacity and microbial activity. This article discusses the principles of organic farming, its influence on soil health, benefits, challenges and future prospects in promoting sustainable agriculture.

Introduction

Agriculture is essential for food security and economic development. However, excessive use of chemical fertilizers and pesticides has resulted in soil degradation, nutrient imbalance, declining soil fertility and environmental pollution. Organic farming has emerged as a sustainable alternative that focuses on improving soil health while conserving natural resources. By encouraging biological activity and reducing chemical inputs, it helps maintain soil productivity and supports long-term agricultural sustainability.



Concept of Organic Farming

Organic farming is a holistic production system that promotes ecological balance, biodiversity, and sustainable resource management. Instead of relying on synthetic chemicals, it uses organic manures, crop residues, biofertilizers and natural pest control methods. The primary aim is to maintain soil fertility naturally, produce safe and nutritious food, protect the environment and conserve soil and water resources for future generations.

Principles of Organic Farming

Organic farming is based on four fundamental principles: health, ecology, fairness, and care. It emphasizes maintaining the health of soil, plants, animals and humans while working in harmony with natural ecosystems.

The system promotes fairness among farmers, consumers and the environment and encourages responsible management of natural resources to ensure sustainability for future generations.

Organic Farming Practices Beneficial to Soil Health

Organic farming improves soil health through several natural practices. Organic manures such as farmyard manure, compost and vermicompost enrich the soil with organic matter and nutrients. Green manuring using leguminous crops increases nitrogen content and improves soil fertility. Crop rotation maintains nutrient balance while reducing pest and disease incidence. Mulching conserves soil moisture, minimizes erosion and increases soil organic carbon. Biofertilizers enhance nutrient availability through beneficial microorganisms, and biological pest management reduces the need for chemical pesticides by using natural enemies and botanical products.

Impacts of Organic Farming on Soil Health

Organic farming significantly improves the physical, chemical, and biological properties of soil. It enhances soil structure, increases porosity, improves water-holding capacity and reduces erosion and compaction. Chemically, it increases soil organic carbon, promotes efficient nutrient cycling, maintains balanced soil pH and improves cation exchange capacity. Biologically, it encourages the growth of beneficial microorganisms, increases earthworm populations, enhances soil enzyme activity and supports greater biodiversity, resulting in healthier and more productive soils.

Environmental Benefits

Organic farming contributes to environmental protection by reducing chemical pollution in soil and water. It improves groundwater quality, promotes carbon sequestration, conserves biodiversity and lowers greenhouse gas emissions. These benefits make organic farming an important approach for mitigating climate change and maintaining ecological balance.

Economic and Social Benefits

Organic farming reduces farmers' dependence on expensive chemical fertilizers and pesticides, lowering production costs over time. Organic products often receive premium market prices, increasing farmers' income. The system also improves farmers' health by reducing exposure to harmful chemicals and creates additional employment opportunities because organic farming practices require more skilled labor.

Challenges of Organic Farming

Despite its advantages, organic farming faces several challenges. Crop yields may decline during the initial transition period, and organic inputs are sometimes difficult to obtain. The farming system is labor-intensive and obtaining organic certification can be costly and time-consuming. Limited consumer awareness and restricted market access continue to hinder wider adoption in some regions.

Future Perspectives

Organic farming has great potential to address global issues such as climate change, soil degradation and food safety. Future progress depends on increased research in organic nutrient management, the development of improved biofertilizers and biopesticides and the adoption of digital technologies in organic agriculture. Greater government support through subsidies, certification assistance, farmer training and stronger market development will further encourage organic farming. Integrating organic farming with precision agriculture and climate-smart practices can enhance sustainability and productivity.

Conclusion

Organic farming is a sustainable agricultural system that enhances soil health while protecting the environment and producing safe, nutritious food. By improving soil organic matter, microbial diversity, nutrient cycling and water retention, it restores soil fertility and supports long-term agricultural productivity. Although challenges such as lower initial yields and certification costs remain, continued research, policy support, and farmer awareness can promote its widespread adoption. Organic farming is therefore an effective strategy for achieving sustainable agriculture, conserving natural resources and ensuring healthy soils for future generations.

Reference

Rani, M., Kaushik, P., Bhayana, S., & Kapoor, S. (2023). Impact of organic farming on soil health and nutritional quality of crops. *Journal of the Saudi Society of Agricultural Sciences*, 22(8), 560-569.

Wijesinghe, J., Botheju, S. M., Nallaperuma, B., & Kanuwana, N. (2023). Organic farming: the influence on soil health. *One Health: Human, Animal, and Environment Triad*, 185-197.

Schonbeck, M., & Jerkins, D. (2017). Soil health and organic farming. Organic Farming Research Foundation: Santa Cruz, CA, USA.

Kumar, S., Ansari, M. A., Choudhary, J., Ravisankar, N., Singh, R., & Mehta, P. (2024). Organic farming: long-term influence on soil health and produce quality. Special issue on in commemoration of, 1134.



THE EFFECT OF FOLIAR NUTRITION MANAGEMENT ON GROWTH AND YIELD OF COWPEA



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Abstract

Cowpea (*Vigna unguiculata* (L.) Walp.) is an important pulse crop valued for its high protein content, adaptability to diverse climatic conditions and multiple uses as a grain, vegetable, fodder and green manure crop. Improving its productivity is essential to meet the increasing demand for nutritious food. Among the various crop management practices, foliar nutrition has emerged as an effective technique for supplying nutrients directly to plant leaves during critical growth stages, particularly flowering and pod development, when nutrient demand is high and soil nutrient uptake may be limited. Foliar application of fertilizers such as Diammonium Phosphate (DAP), Mono Ammonium Phosphate (MAP), Potassium Nitrate (KNO_3) and water-soluble fertilizer (19:19:19), along with plant growth regulators like Salicylic Acid and Naphthalene Acetic Acid (NAA), has been reported to enhance physiological activities, improve nutrient use efficiency and reduce flower drop. These treatments promote plant growth, increase chlorophyll content, improve photosynthesis, enhance pod setting, seed filling and ultimately increase seed yield. The use of foliar nutrition also improves economic returns by increasing productivity with efficient nutrient utilization. This review highlights the role of different foliar nutrient sources and plant growth regulators in improving the growth, yield attributes, yield and profitability of cowpea cultivation, emphasizing the importance of adopting suitable foliar nutrition management practices for sustainable pulse production.

INTRODUCTION

Pulses play a vital role in ensuring food and nutritional security, particularly in developing countries. They are rich sources of protein, carbohydrates, vitamins and minerals and constitute an important component of the daily diet of millions of people. Among the pulse crops, cowpea (*Vigna unguiculata* (L.)) is one of the most important grain legumes cultivated in tropical and subtropical regions of the world. Cowpea is commonly referred to as “vegetable meat” because of its high protein content and nutritional value. It is cultivated for dry seeds, green pods and fodder and green manure purposes. Nutrient management plays a significant role in enhancing crop growth, flowering, pod development and seed yield in cowpea. Although basal fertilizer application supplies nutrients to the crop, nutrient uptake through roots may be limited during critical growth stages due to moisture stress, nutrient fixation and other soil-related factors. Under such situations, foliar nutrition becomes an effective approach to supply nutrients directly to plant leaves, ensuring rapid absorption and utilization. Foliar application of nutrients at flowering and pod development stages has been reported to improve physiological processes such as photosynthesis, chlorophyll synthesis, enzyme activity and assimilate translocation.

USES OF FOLIAR NUTRIENTS

Among the nutrient sources, Diammonium Phosphate (DAP) provides readily available nitrogen and phosphorus required for flowering and seed development. Mono Ammonium Phosphate (MAP) serves as an efficient source of phosphorus and nitrogen, promoting root growth and reproductive development. Potassium nitrate (KNO_3) supplies both potassium and nitrogen, which are essential for photosynthesis, enzyme activation and translocation of photosynthates. Foliar application of KNO_3 has been reported to improve flower retention, pod setting and seed filling in pulse crops. Water-soluble fertilizer 19:19:19 contains balanced proportions of nitrogen, phosphorus and potassium and provides immediate nutrition during critical growth stages, thereby improving crop growth and productivity.

Plant growth regulators also play an important role in enhancing crop performance. Salicylic acid is a phenolic growth regulator that improves physiological efficiency, stress tolerance and nutrient utilization. It

enhances flowering and reduces flower drop under field conditions. Naphthalene Acetic Acid (NAA), a synthetic auxin, promotes flower retention, pod setting and translocation of assimilates towards developing reproductive structures, ultimately improving yield attributes and seed yield. Several studies have reported that foliar application of nutrients and growth regulators during flowering and pod formation stages significantly improves growth parameters, yield attributes and economic returns in pulse crops. However, the response of cowpea to different foliar nutrient sources and plant growth regulators varies with variety, environment and management practices. Therefore, identifying an effective foliar nutrition schedule is essential for maximizing productivity and profitability.

EFFECT OF FOLIAR NUTRITION ON CROP GROWTH

Foliar nutrition is an efficient method of nutrient application in which nutrients are sprayed directly onto plant foliage. Foliar feeding helps in correcting nutrient deficiencies quickly and improves physiological activities such as chlorophyll formation, photosynthesis and translocation of assimilates. Foliar application is especially beneficial during periods of moisture stress or when nutrient uptake from soil is restricted.

Several researchers have reported that foliar spray of nutrients significantly improves growth parameters such as plant height, number of branches, leaf area index and dry Matter production in pulse crops. Foliar application of urea, DAP, potassium nitrate and micronutrients at flowering and pod initiation stages has shown positive effects on vegetative growth and reproductive development in cowpea and other legumes.

EFFECT OF FOLIAR NUTRITION ON FLOWERING AND YIELD ATTRIBUTES

Flowering and pod development are critical stages in cowpea cultivation. Nutrient deficiency during these stages often results in flower shedding and poor pod formation. Foliar application of nutrients during flowering enhances pollen viability, flower retention and pod setting, thereby increasing yield attributes.

Researchers have observed that foliar spray of DAP and potassium nitrate improves the number of pods plant⁻¹, pod length, seeds pod⁻¹ and 100 seed weight in cowpea. Pulse wonder, a nutrient mixture containing macro and micronutrients along with plant growth regulators, has also been found effective in improving flowering, reducing flower drop and enhancing grain yield in pulse crops.

Observe Micronutrients such as zinc and boron play an important role in reproductive growth and seed development. Foliar spray of zinc sulphate improves enzyme activity and chlorophyll synthesis, while boron enhances pollen germination and seed setting. Balanced foliar nutrition therefore contributes significantly to higher productivity in cowpea cultivation.

INFLUENCE OF FOLIAR SPRAY ON YIELD AND ECONOMICS

Foliar nutrient application has been reported to increase pod yield, seed yield and haulm yield in cowpea. The increase in yield may be attributed to improved nutrient availability, enhanced photosynthetic efficiency and better translocation of assimilates towards reproductive parts. Foliar feeding also improves nutrient use efficiency compared to conventional soil application methods.

Economic analysis conducted by several researchers indicated that foliar nutrition treatments provide higher gross returns, net returns and benefit cost ratio due to increased productivity and efficient nutrient utilization. Application of pulse wonder, potassium nitrate and DAP sprays at flowering and pod initiation stages were found economically viable in cowpea cultivation.

CONCLUSION

Foliar nutrition management is an effective and practical approach to improving the growth, yield and profitability of cowpea cultivation. The direct application of nutrients to plant foliage ensures rapid absorption and utilization, especially during critical stages such as flowering and pod development when nutrient demand is high and soil nutrient uptake may be restricted. Foliar sprays of DAP, MAP, Potassium Nitrate (KNO₃), water-soluble fertilizer (19:19:19) and plant growth regulators such as Salicylic Acid and NAA have been shown to enhance plant height, branching, chlorophyll content, flowering, pod setting and seed development. These treatments reduce flower shedding, improve photosynthetic efficiency and promote better translocation of assimilates to developing pods, resulting in higher seed yield and improved yield attributes. In addition to increasing productivity, foliar nutrition enhances nutrient use efficiency and provides higher gross returns, net returns and benefit-cost ratio, making it an economically viable practice for farmers. Therefore, adopting an appropriate foliar nutrition schedule based

on crop growth stage and nutrient requirement can significantly contribute to sustainable cowpea production, improved resource use efficiency and enhanced farm income.

REFERENCES

- Anitha, S., Sreenivasan, E., & Purushothaman, S. M. (2005). Response of cowpea (*Vigna unguiculata* L. Walp.) to foliar nutrition of zinc and iron. *Legume Research*, 28(4), 294–296.
- Brady, N. C., & Weil, R. R. (2017). *The Nature and Properties of Soils* (15th ed.). Pearson.
- Choudhary, G. L., & Yadav, L. R. (2011). Effect of fertility levels and foliar nutrition on cowpea productivity. *Journal of Food Legumes*, 24(1), 67–68.
- Havlin, J. L., Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (2014). *Soil Fertility and Fertilizers* (8th ed.). Pearson.
- Jackson, M. L. (1973). *Soil Chemical Analysis*. Prentice Hall of India.
- Kavitha, M. P., Balakumbahan, R., & Prabukumar, G. (2019). Effect of foliar spray and fertilizer levels on growth and yield of vegetable cowpea (*Vigna unguiculata* L. Walp.). *Indian Journal of Agricultural Research*, 53(6), 745–748. <https://doi.org/10.18805/IJARE.A-5074>



Hybridization in Crop Improvement



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ABSTRACT

Hybridization is a fundamental technique in plant breeding that involves crossing genetically dissimilar plants to produce improved offspring with desirable traits. This method has significantly contributed to increasing agricultural productivity, enhancing crop quality, and improving resistance to biotic and abiotic stresses. The present article discusses the principles, objectives, types, and procedures of hybridization, along with its advantages, limitations, and role in modern agriculture. Furthermore, it highlights the future prospects of hybridization in the context of technological advancements and global food security challenges. Hybridization continues to be a vital strategy for sustainable crop improvement and agricultural development.

Keywords: hybridization, crop improvement, heterosis, plant breeding, agriculture

INTRODUCTION

Agriculture plays a critical role in sustaining human life, and continuous improvement in crop productivity is essential to meet the demands of a rapidly growing global population. Plant breeding techniques have evolved over time to enhance crop performance, and hybridization stands out as one of the most effective and widely practiced methods. Hybridization refers to the deliberate crossing of two genetically diverse plants to produce offspring that exhibit desirable characteristics from both parents. The concept of hybridization is closely associated with the phenomenon of heterosis, or hybrid vigor, where hybrid offspring show superior qualities compared to their parents. These qualities may include increased yield, better resistance to diseases and pests, improved adaptability to environmental conditions, and enhanced nutritional value. As agricultural challenges such as climate change, soil degradation, and water scarcity intensify, hybridization has become increasingly important in developing resilient crop varieties. This paper explores the role of hybridization in crop improvement by examining its objectives, types, methodology, benefits, and limitations. It also discusses its significance in modern agriculture and future prospects in the face of global challenges.

OBJECTIVES OF HYBRIDIZATION

The primary objective of hybridization is to develop improved crop varieties that meet specific agricultural and economic needs. One of the main goals is to achieve higher yield potential. Hybrid crops often produce significantly more than traditional varieties due to heterosis, making them essential for ensuring food security. Another important objective is the improvement of crop quality. Hybridization can enhance various quality traits such as taste, texture, size, nutritional value, and shelf life. For example, hybrid fruits and vegetables are often more uniform in appearance and have better market value. Resistance to diseases and pests is also a key objective. By combining resistant traits from different parent plants, breeders can develop hybrids that are less susceptible to infections and infestations, thereby reducing the need for chemical pesticides. In addition, hybridization aims to improve tolerance to abiotic stresses such as drought, salinity, extreme temperatures, and flooding. This is particularly important in the context of climate change, which poses significant challenges to agricultural productivity. Early maturity is another desirable trait that can be achieved through hybridization. Early-maturing crops allow farmers to harvest sooner and potentially grow multiple crops within a single growing season, increasing overall productivity.

TYPES OF HYBRIDIZATION

Hybridization can be classified into different types based on the genetic relationship between the parent plants.

INTRASPECIFIC HYBRIDIZATION

Also known as inter varietal hybridization, this involves crossing different varieties within the same species. It is the most common type used in crop improvement because it is relatively easy to perform and produces fertile offspring. For example, crossing two varieties of rice to combine high yield with disease resistance.

INTERSPECIFIC HYBRIDIZATION

This type involves crossing two different species within the same genus. Although more complex than intraspecific hybridization, it can introduce valuable traits that are not present within a single species. However, fertility issues may arise in the offspring.

INTERGENERIC HYBRIDIZATION

Intergeneric hybridization involves crossing plants from different genera. This is the most challenging type due to genetic incompatibility, but it can produce unique and valuable hybrids. A well-known example is triticale, a hybrid of wheat and rye, which combines the high yield of wheat with the hardiness of rye.

PROCEDURE OF HYBRIDIZATION

The process of hybridization involves several carefully controlled steps to ensure successful crossing and seed production. The first step is the selection of suitable parent plants. These parents are chosen based on the traits that breeders wish to combine, such as yield potential, resistance to diseases, or environmental adaptability. The next step is emasculation, which involves the removal of anthers from the flower of the female parent to prevent self-pollination. This step is crucial in ensuring that only the desired pollen is used for fertilization. Following emasculation, the flower is covered with a protective bag to prevent contamination from unwanted pollen. This process is known as bagging. Once the flower is ready, pollen from the selected male parent is carefully transferred to the stigma of the female parent in a process called pollination. After pollination, the flower is re-bagged and labeled with details of the cross, including the names of the parent plants and the date of pollination. This helps in maintaining accurate records for future evaluation. Finally, the seeds produced from the hybridization process are collected, grown, and evaluated for their performance. Superior hybrids are selected for further testing and potential release as new crop varieties.

ADVANTAGES OF HYBRIDIZATION

Hybridization offers several advantages that make it a valuable tool in crop improvement. One of the most significant benefits is hybrid vigor, which results in improved growth, yield, and overall performance of the hybrid plants. This increased productivity is essential for meeting global food demands. Another advantage is the ability to combine desirable traits from different parent plants into a single variety. This allows breeders to develop crops that are not only high-yielding but also resistant to diseases and adaptable to various environmental conditions. Hybridization also increases genetic diversity, which is important for the long-term sustainability of agriculture. Greater genetic variation provides a broader base for selection and adaptation to changing conditions. Furthermore, hybrid crops often exhibit uniformity in growth and development, which is beneficial for mechanized farming and commercial production. Uniform crops are easier to manage and harvest, leading to improved efficiency.

LIMITATIONS OF HYBRIDIZATION

Despite its many advantages, hybridization has certain limitations. One of the major drawbacks is that it is a time-consuming process. Developing a stable and superior hybrid variety may take several years of research and testing. Another limitation is the high cost associated with hybrid seed production. The process requires skilled labor, controlled conditions, and careful management, which can increase the overall cost of seeds. Hybrid breakdown is another concern, as the desirable traits observed in the first generation (F1) may not be maintained in subsequent generations. As a result, farmers often need to purchase new seeds each season rather than saving seeds from previous crops. In some cases, genetic incompatibility between parent plants can lead to unsuccessful crosses or sterile offspring, particularly in interspecific and intergeneric hybridization.

ROLE OF HYBRIDIZATION IN MODERN AGRICULTURE

Hybridization has played a transformative role in modern agriculture. The development of hybrid crops has significantly increased agricultural productivity and contributed to food security worldwide. Crops such as maize, rice, wheat, and various vegetables have benefited greatly from hybrid breeding programs. Hybrid maize, for

example, has shown remarkable improvements in yield and adaptability, making it one of the most widely grown crops globally. Similarly, hybrid rice varieties have helped increase rice production in many countries, addressing food shortages and improving livelihoods. In vegetable crops, hybridization has led to the development of varieties with better quality, uniformity, and resistance to pests and diseases. These improvements have enhanced both farmer income and consumer satisfaction. Moreover, hybridization is often integrated with modern biotechnological tools such as molecular markers and genetic engineering. These technologies enable more precise selection of desirable traits and accelerate the breeding process.

FUTURE PROSPECTS

The future of hybridization in crop improvement looks promising, especially with the integration of advanced technologies. Techniques such as marker-assisted selection, genomic selection, and genome editing are enhancing the efficiency and accuracy of hybrid breeding. Climate change poses significant challenges to agriculture, including increased temperatures, irregular rainfall, and the spread of pests and diseases. Hybridization will play a crucial role in developing climate-resilient crops that can withstand these stresses. In addition, there is growing interest in developing hybrids with improved nutritional quality to address malnutrition and health issues. Bio fortified hybrid crops with higher levels of essential nutrients can contribute to better public health outcomes. Sustainable agriculture is another important focus area, and hybridization can help develop crops that require fewer inputs such as water, fertilizers, and pesticides. This will reduce environmental impact and promote long-term agricultural sustainability.

CONCLUSION

Hybridization is a powerful and essential tool in crop improvement that has significantly contributed to the advancement of agriculture. By combining desirable traits from different parent plants, it enables the development of high-yielding, resilient, and high-quality crop varieties. Although it has certain limitations, ongoing advancements in science and technology are addressing these challenges and enhancing the effectiveness of hybridization. As the world faces increasing food demands and environmental challenges, hybridization will continue to play a vital role in ensuring sustainable agricultural development and global food security.

REFERENCES

- Allard, R. W. (1999). *Principles of plant breeding* (2nd ed.). John Wiley & Sons.
- Acquaah, G. (2012). *Principles of plant genetics and breeding* (2nd ed.). Wiley-Blackwell.
- Singh, B. D. (2015). *Plant breeding: Principles and methods* (10th ed.). Kalyani Publishers.
- Poehlman, J. M., & Sleper, D. A. (1995). *Breeding field crops* (4th ed.). Iowa State University Press.

Impact of Nutrigenomics on Lifestyle of Today's Youth



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Abstract

Nutrigenomics is an emerging field that examines the interaction between nutrients and genes to understand how dietary components influence gene expression and individual health outcomes. In today's rapidly changing lifestyle, young people are increasingly affected by unhealthy eating habits, physical inactivity, stress, and the growing consumption of ultra-processed foods, leading to a rise in obesity, diabetes, and other lifestyle-related disorders. Nutrigenomics offers a personalized approach to nutrition by identifying genetic variations that affect nutrient metabolism and disease susceptibility, enabling tailored dietary recommendations. This approach has the potential to improve physical and mental well-being, enhance disease prevention, and promote long-term health among today's youth. However, challenges such as high testing costs, limited awareness, ethical concerns, and data privacy issues restrict its widespread adoption. With continuous advancements in genomic technologies and precision nutrition, nutrigenomics is expected to play a significant role in promoting healthier lifestyles and preventing chronic diseases in future generations.

Keywords: Nutrigenomics, Personalized Nutrition, Precision Nutrition, Gene–Nutrient Interaction, Lifestyle Diseases, Youth Health, Genomics, Dietary Intervention, Chronic Disease Prevention, Epigenetics, Metabolic Health, Precision Medicine, Healthy Lifestyle, Nutritional Genomics, Public Health.

Introduction

The prevalence of lifestyle-related diseases among today's youth has increased considerably due to rapid urbanization, unhealthy dietary habits, sedentary lifestyles, stress, and the widespread consumption of ultra-processed foods. Conditions such as obesity, type 2 diabetes, cardiovascular diseases, and metabolic syndrome are now being diagnosed at younger ages, posing a significant public health challenge. Conventional dietary recommendations often follow a generalized approach and may not adequately address individual differences in nutrient metabolism and disease susceptibility. This has led to growing interest in personalized nutrition as a more effective strategy for disease prevention and health promotion.

Nutrigenomics is an emerging field that studies the interaction between nutrients and genes, focusing on how dietary components influence gene expression and how genetic variations affect an individual's response to food. By integrating genomics with nutritional science, nutrigenomics enables the development of personalized dietary interventions tailored to an individual's genetic profile. Such precision nutrition can optimize nutrient utilization, improve metabolic health, and reduce the risk of chronic diseases.

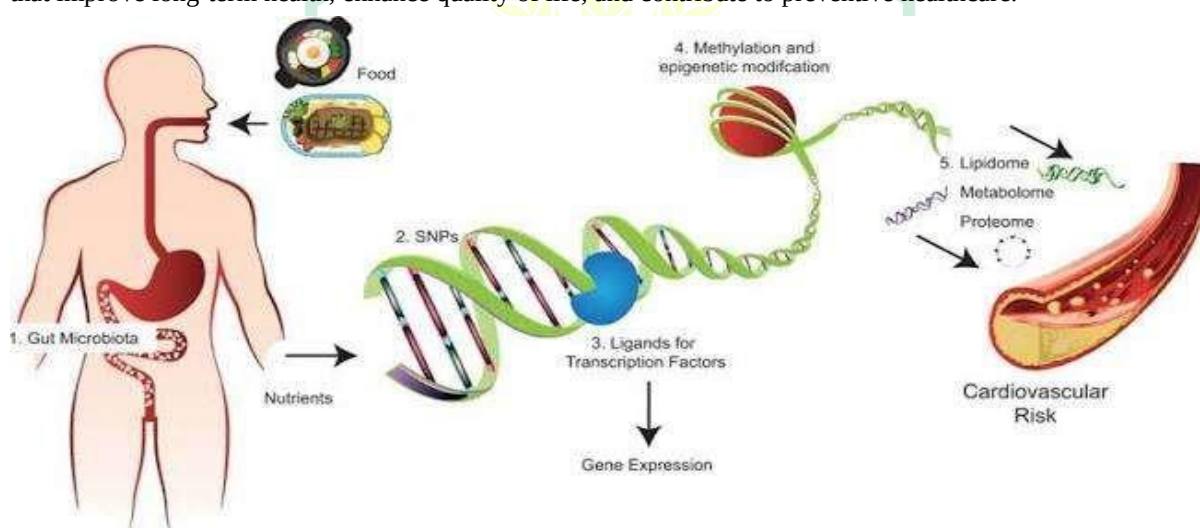
For today's youth, nutrigenomics has significant potential to promote healthier lifestyles by encouraging informed food choices, improving physical and mental well-being, and preventing nutrition-related disorders at an early stage. Advances in genetic testing, bioinformatics, artificial intelligence, and digital health technologies have further enhanced the practical application of nutrigenomics in preventive healthcare. Although challenges such as high costs, ethical concerns, limited awareness, and data privacy remain, nutrigenomics represents a promising approach to improving the health and quality of life of future generations through evidence-based, personalized nutrition.

Concept of Nutrigenomics

Nutrigenomics is a multidisciplinary field that integrates nutrition, genetics, molecular biology, and genomics to understand how nutrients and other bioactive food components influence gene expression and how genetic variations affect an individual's response to diet. The term is derived from the words nutrition and genomics, emphasizing the interaction between dietary factors and the human genome. Unlike traditional nutrition, which provides generalized dietary recommendations, nutrigenomics focuses on personalized nutrition by recognizing that individuals respond differently to the same foods because of their unique genetic makeup.

The central concept of nutrigenomics is that nutrients act not only as sources of energy but also as molecular signals that regulate the expression of genes involved in metabolism, growth, immunity, and disease prevention. At the same time, genetic variations, particularly single nucleotide polymorphisms (SNPs), influence how nutrients are absorbed, metabolized, transported, and utilized by the body.

These gene–nutrient interactions determine an individual's nutritional requirements, susceptibility to chronic diseases, and response to specific dietary interventions. Nutrigenomics aims to develop evidence-based, personalized dietary strategies that promote optimal health and reduce the risk of lifestyle-related diseases such as obesity, type 2 diabetes, cardiovascular diseases, and certain cancers. Advances in genome sequencing, bioinformatics, artificial intelligence, and precision medicine have accelerated the application of nutrigenomics in healthcare. By combining genetic information with nutritional assessment and lifestyle factors, nutrigenomics supports the concept of precision nutrition. This approach enables individuals to make informed dietary choices that improve long-term health, enhance quality of life, and contribute to preventive healthcare.



Lifestyle Challenges Among Today's Youth

Today's youth face numerous lifestyle challenges due to rapid urbanization, technological advancements, and changing dietary patterns. Increased consumption of fast foods, sugar-sweetened beverages, and ultra-processed foods, combined with reduced physical activity, has contributed to rising rates of obesity, diabetes, and other metabolic disorders. Excessive screen time, sedentary behavior, irregular sleep patterns, and academic or work-related stress further increase the risk of poor physical and mental health. Many young individuals also skip meals, particularly breakfast, and consume nutritionally inadequate diets, leading to deficiencies of essential vitamins and minerals. These unhealthy habits negatively affect growth, immunity, cognitive performance, and overall well-being. Additionally, exposure to alcohol, tobacco, and substance abuse among some youth further increases the burden of chronic diseases. Addressing these challenges requires a shift toward healthier lifestyles through balanced nutrition, regular physical activity, stress management, and personalized dietary interventions. Nutrigenomics offers a promising approach by providing gene-based nutritional recommendations that support disease prevention and promote long-term health.

Mechanism of Gene–Diet Interaction

The mechanism of gene–diet interaction explains how nutrients and bioactive food compounds influence gene expression and how genetic variations affect an individual's response to different foods. Nutrients act as signaling molecules that regulate the activation or suppression of specific genes involved in metabolism, growth, immunity, and disease prevention. This regulation occurs through molecular pathways that control the production of proteins and enzymes essential for normal physiological functions.

Genetic variations, particularly single nucleotide polymorphisms (SNPs), can alter the way nutrients are absorbed, metabolized, transported, and utilized in the body. As a result, individuals may respond differently to the same diet. For example, some people may require higher amounts of folate due to variations in the MTHFR gene, while others may have altered lipid metabolism because of variants in the APOE gene, increasing their susceptibility to cardiovascular diseases.

Diet also influences epigenetic mechanisms, such as DNA methylation, histone modification, and microRNA regulation, which modify gene expression without altering the DNA sequence. These epigenetic changes can affect metabolic health and disease risk throughout life. Understanding these gene–diet interactions enables the development of personalized nutrition plans that optimize health, prevent chronic diseases, and support precision healthcare based on an individual's genetic profile.

Impact of Nutrigenomics on Youth Lifestyle

Nutrigenomics is transforming the way young people approach health and nutrition by promoting personalized dietary recommendations based on an individual's genetic makeup. Instead of following the same diet plan for everyone, nutrigenomics helps identify the foods and nutrients that best suit a person's body. This approach encourages healthier eating habits and supports long-term well-being.

One of the major impacts of nutrigenomics is the prevention of lifestyle-related diseases. By understanding genetic risk factors for conditions such as obesity, type 2 diabetes, cardiovascular disease, and hypertension, young individuals can adopt appropriate dietary changes at an early stage, reducing the likelihood of developing these disorders.

Nutrigenomics also contributes to improved physical and mental performance. A personalized diet ensures that the body receives the right balance of nutrients, leading to better energy levels, stronger immunity, improved concentration, enhanced memory, and greater academic and athletic performance. It also helps maintain a healthy body weight by recommending foods that match an individual's metabolism.

Another important benefit is the promotion of healthy lifestyle habits. Young people become more aware of the relationship between food, genes, and health, encouraging them to make informed choices regarding diet, physical activity, and overall wellness. Personalized nutrition plans can also improve digestive health and address nutrient deficiencies more effectively than generalized dietary advice.

Furthermore, advances in genetic testing, mobile health applications, wearable devices, and artificial intelligence have made personalized nutrition more accessible. These technologies enable young individuals to monitor their health, track dietary intake, and receive customized nutrition guidance.

Despite its promising benefits, nutrigenomics faces challenges such as high costs of genetic testing, limited awareness, ethical concerns regarding genetic information, and unequal access to advanced healthcare services. Nevertheless, as research and technology continue to advance, nutrigenomics is expected to play a vital role in promoting healthier lifestyles, preventing chronic diseases, and improving the overall quality of life of today's youth.

Applications in Personalized Nutrition

Nutrigenomics has become an important tool in personalized nutrition, where dietary recommendations are tailored according to an individual's genetic profile rather than following a general diet plan. This approach helps improve health and prevent diseases by recognizing that people respond differently to the same foods.

One of its major applications is the prevention of lifestyle-related diseases such as obesity, type 2 diabetes, hypertension, and cardiovascular diseases. By identifying genetic risk factors, healthcare professionals can recommend specific dietary changes that help reduce disease risk. Nutrigenomics also helps in the management of nutrient deficiencies. Genetic testing can identify individuals who may require higher amounts of nutrients

such as folate, vitamin D, iron, calcium, or vitamin B12. Personalized dietary advice or supplementation can then be provided to meet these individual needs.

Another important application is weight management. Since metabolism differs among individuals, nutrigenomics helps design customized diet plans that improve weight loss, maintain a healthy body weight, and enhance metabolic health.

In addition, nutrigenomics supports sports and fitness nutrition by recommending diets that improve energy levels, muscle recovery, endurance, and athletic performance based on genetic characteristics. It also contributes to better digestive health by identifying food intolerances or sensitivities, such as lactose intolerance or gluten sensitivity, allowing individuals to modify their diets accordingly.

Overall, personalized nutrition through nutrigenomics enables individuals to make informed food choices, adopt healthier lifestyles, improve overall well-being, and reduce the risk of chronic diseases throughout life.

Role of Nutrigenomics in the Prevention of Lifestyle Diseases

Nutrigenomics plays an important role in preventing lifestyle diseases by providing personalized dietary recommendations based on an individual's genetic makeup. Since each person responds differently to food, nutrigenomics helps identify the nutrients and eating patterns that best support individual health. This enables people to adopt healthier lifestyles before diseases develop.

One of the key benefits of nutrigenomics is the early identification of genetic risk factors for diseases such as obesity, type 2 diabetes, cardiovascular disease, hypertension, and certain types of cancer. With this knowledge, individuals can make appropriate dietary and lifestyle changes to reduce their risk. Nutrigenomics also promotes healthy weight management by recommending diets that match a person's metabolism and nutritional needs. It helps improve blood sugar control, maintain healthy cholesterol levels, and regulate blood pressure, thereby lowering the risk of metabolic disorders.

In addition, personalized nutrition helps correct nutrient deficiencies, strengthens the immune system, reduces inflammation, and supports overall metabolic health. It also encourages long-term healthy habits such as balanced eating, regular physical activity, and informed food choices.

By combining genetic information with nutrition, nutrigenomics shifts healthcare from treating diseases to preventing them. As genetic testing becomes more affordable and accessible, nutrigenomics has the potential to become an effective strategy for reducing the burden of lifestyle-related diseases and improving the health and quality of life of today's youth.

Benefits of Nutrigenomics

Nutrigenomics offers several benefits by helping individuals make informed dietary choices based on their genetic profile. It promotes a personalized approach to nutrition that improves health and reduces the risk of disease.

1. **Personalized Nutrition:** Provides diet plans tailored to an individual's genetic makeup, making nutritional advice more effective than a one-size-fits-all approach.
2. **Prevention of Lifestyle Diseases:** Helps reduce the risk of obesity, type 2 diabetes, hypertension, cardiovascular diseases, and certain cancers through early dietary interventions.
3. **Improved Nutrient Utilization:** Identifies how the body processes different nutrients, ensuring better absorption and efficient use of vitamins and minerals.
4. **Healthy Weight Management:** Supports personalized weight-loss or weight-maintenance strategies based on an individual's metabolism and genetic characteristics.
5. **Better Physical and Mental Performance:** Enhances energy levels, concentration, memory, immunity, and overall physical fitness through appropriate nutritional choices.
6. **Early Detection of Health Risks:** Identifies genetic predisposition to certain diseases, allowing preventive measures before symptoms develop.
7. **Improved Management of Nutrient Deficiencies:** Helps identify increased requirements for nutrients such as iron, folate, vitamin D, calcium, and vitamin B12, enabling timely dietary modifications.
8. **Supports Precision Healthcare:** Combines genetic information with nutrition to provide targeted dietary recommendations that improve overall health and quality of life.
9. **Promotes Healthy Lifestyle Habits:** Encourages balanced eating, regular physical activity.

Challenges and Ethical Considerations of Nutrigenomics Challenges

1. **High Cost of Genetic Testing:** Genetic tests and personalized nutrition services are expensive, limiting access for many people.
2. **Limited Awareness:** Many individuals and healthcare professionals have limited knowledge about nutrigenomics and its benefits.
3. **Insufficient Scientific Evidence:** Some gene–diet interactions require further research before they can be widely applied in clinical practice.
4. **Lack of Trained Professionals:** There is a shortage of experts who can accurately interpret genetic test results and provide personalized dietary advice.
5. **Limited Accessibility:** Genetic testing facilities and personalized nutrition services are not equally available in all regions, particularly in rural areas.
6. **Complex Gene–Diet Interactions:** Health is influenced by multiple genes, lifestyle, and environmental factors, making personalized recommendations challenging.

Ethical Considerations

1. **Privacy and Confidentiality:** Genetic information is highly sensitive and must be securely stored to prevent unauthorized access.
2. **Informed Consent:** Individuals should fully understand the purpose, benefits, and possible risks before undergoing genetic testing.
3. **Risk of Genetic Discrimination:** Misuse of genetic information could lead to discrimination in employment, education, or insurance.
4. **Equal Access:** Personalized nutrition services should be affordable and accessible to people from all socioeconomic backgrounds.
5. **Data Security:** Strong cybersecurity measures are necessary to protect genetic data from misuse or cyberattacks.
6. **Responsible Use of Genetic Information:** Genetic results should be used only to improve health and nutrition, not for unethical or commercial exploitation.

Recent Advances

1. **Affordable Genetic Testing:** The cost of genetic testing has decreased, making personalized nutrition more accessible.
2. **Artificial Intelligence (AI):** AI helps analyze genetic data and provides personalized dietary recommendations more accurately.
3. **Wearable Health Devices:** Smartwatches and fitness trackers monitor health parameters and support customized nutrition plans.
4. **Mobile Health Applications:** Nutrition apps now combine genetic information with lifestyle data to offer personalized diet and health advice.
5. **Precision Nutrition:** Researchers are developing individualized diet plans based on genetic makeup, age, lifestyle, and health status.
6. **Gut Microbiome Research:** Studies on the interaction between gut bacteria, diet, and genes are improving personalized nutrition strategies.
7. **Advances in Genomic Technologies:** Faster and more accurate DNA sequencing has enhanced the understanding of gene–nutrient interactions.

Future Scope

1. **Personalized Diet Plans:** Nutrigenomics is expected to become a routine part of healthcare, providing individualized dietary recommendations for disease prevention and health promotion.
2. **Early Disease Prevention:** Genetic screening will help identify individuals at risk of obesity, diabetes, cardiovascular diseases, and other lifestyle disorders at an early stage.
3. **Integration into Clinical Practice:** Hospitals and nutrition clinics are likely to include genetic testing as part of regular nutritional assessment and counseling.

4. **Development of Functional Foods:** Foods designed to meet specific genetic and nutritional needs will become more widely available.
5. **Public Health Programs:** Governments may incorporate nutrigenomics into national nutrition policies to improve population health.
6. **Improved Quality of Life:** Personalized nutrition will support healthy ageing, better physical performance, stronger immunity, and improved mental well-being.
7. **Greater Accessibility:** As technology advances and costs decrease, nutrigenomic services are expected to become more affordable and available to a larger population.

Overall, recent technological developments and ongoing research indicate that nutrigenomics has the potential to transform nutrition and preventive healthcare by providing personalized dietary solutions that improve the health and lifestyle of future generations.

Conclusion

Nutrigenomics is transforming the field of nutrition by providing personalized dietary recommendations based on an individual's genetic profile. Unlike conventional nutrition, it recognizes that people respond differently to foods due to genetic variations, making nutrition more precise and effective. For today's youth, nutrigenomics offers significant potential to prevent lifestyle-related diseases such as obesity, diabetes, hypertension, and cardiovascular diseases by encouraging healthy eating habits and early dietary interventions. The integration of genetic testing, artificial intelligence, and digital health technologies has further expanded the scope of personalized nutrition, enabling individuals to make informed lifestyle choices. However, challenges such as high costs, limited awareness, ethical concerns, data privacy, and unequal access to genetic testing must be addressed for its successful implementation.

With continued scientific research, technological advancements, and supportive public health policies, nutrigenomics is expected to become an integral part of preventive healthcare and precision nutrition. By promoting individualized nutrition and healthier lifestyle practices, nutrigenomics has the potential to improve the overall health, well-being, and quality of life of today's youth while reducing the burden of chronic lifestyle diseases in the future.

References (APA 7th Edition)

- Afman, L. A., & Müller, M. (2006). Nutrigenomics: From molecular nutrition to prevention of disease. *Journal of the American Dietetic Association*, 106(4), 569–576. <https://doi.org/10.1016/j.jada.2006.01.001>
- Corella, D., & Ordovás, J. M. (2014). Aging and cardiovascular diseases: The role of gene–diet interactions. *Ageing Research Reviews*, 18, 53–73. <https://doi.org/10.1016/j.arr.2014.08.002>
- Ferguson, L. R. (2014). Nutrigenomics approaches to functional foods. *Journal of the American College of Nutrition*, 33(6), 436–447. <https://doi.org/10.1080/07315724.2013.875508>
- Kassem, N. M., Abdelmegid, Y. A., El-Sayed, M. K., Sayed, R. S., Abdel-Aalla, M. H., & Kassem, H. A. (2023). Nutrigenomics and microbiome shaping the future of personalized medicine: A review article. *Journal of Genetic Engineering and Biotechnology*, 21(1), Article 134. <https://doi.org/10.1186/s43141-023-00599-2>
- Lagoumintzis, G., & Patrinos, G. P. (2023). Triangulating nutrigenomics, metabolomics and microbiomics toward personalized nutrition and healthy living. *Human Genomics*, 17, Article 109. <https://doi.org/10.1186/s40246-023-00561-w>
- Malcomson, F. C., & Mathers, J. C. (2023). Translation of nutrigenomic research for personalised and precision nutrition for cancer prevention and cancer survivors. *Redox Biology*, 62, 102710. <https://doi.org/10.1016/j.redox.2023.102710>
- Minihane, A. M., Livingstone, K. M., Cecil, J. E., et al. (2015). The genetic contribution to disease risk and variability in response to diet: Where is the evidence? *Proceedings of the Nutrition Society*, 74(4), 430–444. <https://doi.org/10.1017/S0029665115003326>
- Ordovás, J. M., Ferguson, L. R., Tai, E. S., & Mathers, J. C. (2018). Personalised nutrition and health. *BMJ*, 361, k2173. <https://doi.org/10.1136/bmj.k2173>
- Phillips, C. M. (2013). Nutrigenetics and metabolic disease: Current status and implications for personalised nutrition. *Nutrients*, 5(1), 32–57. <https://doi.org/10.3390/nu5010032>

Rusu, I. G., Popa, D. S., & Crişan, G. (2023). Current challenges and future implications of exploiting omics data into nutrigenetics and nutrigenomics for personalized diagnosis and nutrition-based care. *Nutrition*, 110, 112002. <https://doi.org/10.1016/j.nut.2023.112002>

Sales, N. M. R., Pelegrini, P. B., & Goersch, M. C. (2014). Nutrigenomics: Definitions and advances of this new science. *Journal of Nutrition and Metabolism*, 2014, Article 202759. <https://doi.org/10.1155/2014/202759>

World Health Organization. (2022). Healthy diet. <https://www.who.int/news-room/fact-sheets/detail/healthy-diet>

World Health Organization. (2023). Noncommunicable diseases. <https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases>



"IMPACT OF EL NIÑO ON RAINFALL VARIABILITY IN TAMIL NADU"



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Background

El Niño is a naturally occurring climatic phenomenon associated with the warm phase of the El Niño–Southern Oscillation (ENSO), characterized by above-normal sea surface temperatures in the central and eastern equatorial Pacific Ocean. It is one of the most influential drivers of global climate variability, affecting atmospheric circulation, precipitation patterns, temperature, and the frequency of extreme weather events. In India, El Niño has historically been linked with weakened Southwest Monsoon rainfall, prolonged dry spells, droughts, and reduced agricultural productivity. Tamil Nadu, which depends predominantly on the Northeast Monsoon for nearly half of its annual rainfall, experiences unique climatic responses to El Niño compared with many other Indian states. Variations in rainfall distribution, delayed monsoon onset, increased temperature, water scarcity, and changes in crop-growing conditions significantly influence agricultural production, food security, and rural livelihoods. Understanding the influence of El Niño on Tamil Nadu's climate is therefore essential for developing climate-resilient agricultural and water management strategies.

Keywords: El Niño, ENSO, Rainfall Variability, Tamil Nadu, Northeast Monsoon, Southwest Monsoon, Climate Change, Agricultural Productivity, Drought, Water Resources, Climate-Smart Agriculture, Food Security, Adaptation Strategies.

1. Introduction

1.1 Climate Variability and Global Warming

Climate variability is one of the major environmental challenges affecting agricultural sustainability, water resources, and food security worldwide. Variations in rainfall, temperature, and atmospheric circulation occur naturally over seasonal to decadal time scales and are further intensified by anthropogenic climate change. The increasing concentration of greenhouse gases has resulted in rising global temperatures, altered precipitation patterns, and more frequent extreme weather events such as droughts, floods, heat waves, and tropical cyclones (IPCC, 2023). These climatic changes significantly influence agricultural production and ecosystem stability, particularly in tropical and monsoon-dependent countries like India.

The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual climate variability influencing weather systems across the globe. El Niño, the warm phase of ENSO, is characterized by anomalous warming of sea surface temperatures in the central and eastern equatorial Pacific Ocean, leading to changes in atmospheric circulation and global rainfall distribution (McPhaden et al., 2020; IPCC, 2023). ENSO affects monsoon systems, drought occurrence, flood frequency, and agricultural productivity through complex ocean–atmosphere interactions.

India is highly sensitive to ENSO because the country's agriculture depends largely on seasonal monsoon rainfall. Several studies have shown that strong El Niño events are generally associated with below-normal Southwest Monsoon rainfall, reduced soil moisture, water shortages, and lower crop yields, although regional responses vary depending on the Indian Ocean Dipole (IOD) and other climate drivers (Roxy et al., 2017; Mishra et al., 2020; IPCC, 2023).

Tamil Nadu exhibits a unique rainfall regime compared with most Indian states because nearly half of its annual rainfall is received during the Northeast Monsoon (October–December). Consequently, the influence of El Niño on Tamil Nadu differs from that observed over northwest and central India. Recent research has demonstrated that ENSO significantly affects Northeast Monsoon rainfall over Tamil Nadu through changes in

atmospheric circulation, sea surface temperature anomalies, and interactions with regional climate systems (Lakshmi et al., 2025).

Understanding the relationship between El Niño and rainfall variability is essential for climate prediction, drought preparedness, water resource management, and climate-smart agriculture. Seasonal forecasting based on ENSO provides valuable information for crop planning, irrigation scheduling, reservoir operation, and disaster risk reduction. Therefore, an improved understanding of El Niño impacts on Tamil Nadu is critical for developing resilient agricultural systems under changing climatic conditions (Lakshmi et al., 2025; IPCC, 2023).

1.2 Definition of El Niño and ENSO

El Niño is a naturally occurring ocean–atmosphere phenomenon characterized by an abnormal warming of sea surface temperatures in the central and eastern equatorial Pacific Ocean. It represents the warm phase of the El Niño–Southern Oscillation (ENSO), which is one of the most influential drivers of interannual climate variability across the globe. The term "El Niño," meaning "The Little Boy" or "Christ Child" in Spanish, was originally used by Peruvian fishermen to describe the appearance of unusually warm ocean waters along the coast of Peru around Christmas. Scientists later recognized that this warming event influences atmospheric circulation patterns over vast regions of the world, affecting rainfall, temperature, storms, and droughts.

ENSO consists of three phases: El Niño, Neutral, and La Niña. During El Niño events, weakened trade winds allow warm surface waters to shift eastward across the Pacific Ocean, reducing the upwelling of cold nutrient-rich waters near South America. This redistribution of ocean heat alters the Walker Circulation, a large-scale atmospheric circulation system over the tropical Pacific, leading to changes in cloud formation and rainfall patterns across different continents. In contrast, La Niña represents the cool phase of ENSO, during which stronger trade winds enhance cold-water upwelling and generally produce climatic conditions opposite to those observed during El Niño. Neutral conditions occur when sea surface temperatures remain close to their long-term average.

El Niño events usually develop every two to seven years and persist for approximately nine to twelve months, although some events may last longer. Their intensity varies from weak to very strong, with major events recorded during 1982–83, 1997–98, 2015–16, and 2023–24. The climatic impacts of El Niño extend far beyond the Pacific Ocean through atmospheric teleconnections, influencing monsoon rainfall in Asia, droughts in Australia, floods in South America, hurricanes in North America, and temperature anomalies across many regions. In India, El Niño often weakens the Southwest Monsoon and contributes to rainfall deficits, although the response of the Northeast Monsoon over Tamil Nadu is more complex due to interactions with the Indian Ocean and regional circulation systems. Understanding ENSO dynamics is therefore fundamental for seasonal climate forecasting, agricultural planning, and disaster risk reduction.

1.3 Importance of Studying El Niño

El Niño is recognized as one of the most significant climate phenomena because of its widespread influence on weather patterns, water availability, agricultural productivity, ecosystems, and socio-economic development. The impacts of El Niño are not confined to the Pacific Ocean but extend across the globe through atmospheric teleconnections that modify rainfall, temperature, and storm activity. These climatic changes affect millions of people by altering food production, water supplies, energy generation, fisheries, public health, and economic stability. Consequently, studying El Niño has become increasingly important in the context of global climate change and sustainable development.

In India, agriculture remains highly dependent on monsoon rainfall, with a substantial proportion of cultivated land lacking assured irrigation. Deficient rainfall associated with El Niño frequently leads to reduced soil moisture, delayed sowing, poor crop establishment, increased irrigation demand, nutrient deficiencies, and lower crop yields. The phenomenon also influences groundwater recharge, reservoir storage, river flows, and drinking water availability, thereby affecting both rural and urban communities. In Tamil Nadu, where agriculture depends significantly on the Northeast Monsoon, variability in seasonal rainfall can have severe consequences for rice cultivation, pulses, sugarcane, millets, oilseeds, horticultural crops, and livestock production.

Studying El Niño enables scientists to improve seasonal climate prediction models that provide early warnings several months before major climatic anomalies occur. Such forecasts help governments, agricultural

departments, and farmers make informed decisions regarding crop selection, planting dates, irrigation scheduling, fertilizer application, drought preparedness, and water allocation. Furthermore, understanding the interaction between El Niño and climate change contributes to the development of climate-smart agricultural technologies, drought-resilient crop varieties, integrated watershed management, efficient irrigation systems, and sustainable natural resource management. Continued research on El Niño is therefore essential for minimizing climate-related risks, enhancing food security, and strengthening the resilience of farming communities against future climatic uncertainties.

1.4 Objectives of the Review

The present review aims to provide a comprehensive understanding of the influence of El Niño on rainfall variability and agricultural sustainability in Tamil Nadu. Climate variability associated with ENSO has become increasingly important due to its significant impact on rainfall distribution, water resources, crop production, and food security. Although numerous studies have investigated the relationship between El Niño and the Indian monsoon, comparatively fewer reviews focus specifically on the climatic and agricultural implications for Tamil Nadu. This review seeks to bridge that gap by integrating current scientific knowledge and highlighting region-specific responses.

The specific objectives of this review are:

1. To describe the origin, mechanism, characteristics, and phases of the El Niño–Southern Oscillation (ENSO).
2. To examine the influence of El Niño on global atmospheric circulation and rainfall distribution.
3. To review the relationship between El Niño and the Indian monsoon system, including both the Southwest and Northeast Monsoons.
4. To evaluate the effects of El Niño on rainfall variability, temperature, drought occurrence, and water resources in Tamil Nadu.
5. To assess the impact of El Niño-induced climatic variability on agricultural productivity, cropping systems, soil moisture, irrigation, and crop yields in Tamil Nadu.
6. To summarize adaptation and mitigation strategies, including climate-smart agriculture, water conservation, efficient irrigation, improved nutrient management, weather-based advisory services, and resilient crop varieties.
7. To identify research gaps and recommend future directions for improving climate resilience, sustainable agricultural development, and policy planning in Tamil Nadu.

By synthesizing scientific literature and recent research findings, this review provides a valuable resource for researchers, agricultural scientists, policymakers, extension professionals, and students interested in understanding the impacts of El Niño on climate and agriculture. The findings will contribute to the development of effective adaptation strategies that enhance agricultural resilience, optimize water resource management, and support sustainable food production under increasing climate variability. We can develop your review article section by section. Below is the **first complete subsection** written in a journal style.

2.1 Definition and Characteristics of El Niño

El Niño is a naturally occurring ocean–atmosphere phenomenon characterized by the abnormal warming of sea surface temperatures (SSTs) in the central and eastern equatorial Pacific Ocean. It represents the warm phase of the **El Niño–Southern Oscillation (ENSO)**, which is the dominant mode of interannual climate variability affecting weather and climate across the globe. The term *El Niño*, meaning "The Little Boy" or "Christ Child" in Spanish, was originally coined by fishermen along the coasts of Peru and Ecuador during the late nineteenth century to describe the periodic appearance of unusually warm ocean waters around Christmas (McPhaden et al., 2020). Over time, scientists recognized that this oceanic warming was accompanied by large-scale atmospheric changes that influence rainfall, temperature, storms, droughts, and agricultural productivity worldwide.

ENSO is a coupled ocean–atmosphere system consisting of three phases: **El Niño (warm phase)**, **Neutral phase**, and **La Niña (cool phase)**. During El Niño events, sea surface temperatures in the Niño 3.4 region (5°N–5°S, 170°W–120°W) increase by at least **0.5°C above the long-term average** for a sustained period of three consecutive months or more, as defined by the **National Oceanic and Atmospheric Administration (NOAA)** (NOAA, 2024). This warming weakens the easterly trade winds, reduces the upwelling of cold, nutrient-rich water along the western coast of South America, and alters atmospheric circulation patterns known as the Walker

Circulation (Trenberth, 2020). Consequently, regions that normally receive abundant rainfall may experience drought, while normally dry areas may receive excessive rainfall and flooding.

One of the distinguishing characteristics of El Niño is its extensive geographical influence through atmospheric **teleconnections**. Although the warming originates in the tropical Pacific Ocean, changes in atmospheric circulation affect climate patterns across Asia, Australia, Africa, North and South America, and Europe. El Niño typically causes drought conditions in Australia, Indonesia, India, and parts of Southeast Asia, whereas countries along the Pacific coast of South America often experience unusually heavy rainfall and flooding (WMO, 2023). These climatic anomalies influence agriculture, water resources, fisheries, biodiversity, and public health, making El Niño one of the most economically significant climate phenomena in the world.

El Niño events generally occur at irregular intervals of **two to seven years** and usually last between **nine and twelve months**, although some strong events may persist for more than one year (McPhaden et al., 2020). The intensity of El Niño varies considerably and is commonly classified as weak, moderate, strong, or very strong based on sea surface temperature anomalies in the Niño 3.4 region. Among the strongest events recorded during the twentieth and twenty-first centuries are those of **1982–83, 1997–98, 2015–16, and 2023–24**, each producing widespread climatic disruptions and substantial socio-economic losses.

The development of El Niño significantly modifies global atmospheric circulation. Normally, strong easterly trade winds transport warm surface waters toward the western Pacific Ocean near Indonesia and Australia, while colder waters rise near the South American coast through a process known as **upwelling**. During El Niño conditions, weakening of the trade winds allows warm surface waters to migrate eastward, suppressing upwelling and increasing sea surface temperatures in the eastern Pacific. This redistribution of ocean heat alters cloud formation, convection, and precipitation patterns, thereby changing weather systems far beyond the Pacific basin (IPCC, 2023).

El Niño also affects tropical cyclone activity, temperature extremes, marine ecosystems, and global carbon cycling. Elevated sea surface temperatures increase atmospheric moisture and alter the distribution of latent heat, influencing storm tracks and precipitation intensity. Coral bleaching events become more frequent due to prolonged warming of tropical oceans, while reduced nutrient availability decreases marine productivity and fish populations along the Pacific coast of South America (WMO, 2023). Consequently, fisheries, coastal economies, and biodiversity are significantly affected during strong El Niño episodes.

Agriculture is among the sectors most vulnerable to El Niño-induced climate variability. Changes in rainfall distribution, increased temperatures, prolonged dry spells, and reduced soil moisture adversely affect crop establishment, flowering, grain filling, and harvest. In monsoon-dependent countries such as India, El Niño frequently weakens the Southwest Monsoon, reducing agricultural productivity, reservoir storage, and groundwater recharge. However, regional climatic responses differ depending on interactions with other climate oscillations such as the **Indian Ocean Dipole (IOD)** and the **Madden–Julian Oscillation (MJO)** (Roxy et al., 2017). Therefore, understanding the characteristics of El Niño is essential for improving seasonal weather forecasting, climate risk assessment, disaster preparedness, and sustainable agricultural planning.

Advances in satellite observations, ocean buoy networks, climate models, and artificial intelligence have substantially improved the monitoring and prediction of El Niño events during the past two decades. Modern forecasting systems developed by NOAA, the World Meteorological Organization (WMO), and national meteorological agencies enable governments to issue seasonal climate outlooks several months in advance. These forecasts support decision-making in agriculture, water resource management, disaster risk reduction, public health, and energy planning, thereby reducing the socio-economic impacts of extreme climate events.

In conclusion, El Niño is one of the most influential components of the Earth's climate system. Its ability to alter atmospheric circulation and rainfall patterns across continents highlights the importance of continuous monitoring and research. As climate change continues to increase the frequency and intensity of extreme weather events, a better understanding of El Niño characteristics will play a crucial role in strengthening climate resilience and promoting sustainable development worldwide.

3. El Niño in India

3.1 Indian Monsoon System

India experiences a tropical monsoon climate characterized by seasonal reversal of winds and distinct wet and dry seasons. The Indian monsoon is the primary source of freshwater for agriculture, domestic consumption, industries, and hydropower generation. Nearly **75–80% of India's annual rainfall** is received during the **Southwest Monsoon (June–September)**, while the remaining rainfall occurs during the **Northeast Monsoon (October–December)**, particularly over Tamil Nadu and adjoining southeastern regions (Pai et al., 2021).

The Southwest Monsoon originates due to differential heating between the Indian landmass and the Indian Ocean. During summer, low-pressure conditions develop over northwestern India, attracting moisture-laden southwesterly winds from the Arabian Sea and the Bay of Bengal. These winds produce widespread rainfall across most parts of the country. In contrast, during winter, high pressure develops over the Indian subcontinent, and northeasterly winds blow towards the Bay of Bengal. These winds absorb moisture and produce rainfall over Tamil Nadu, Puducherry, and coastal Andhra Pradesh.

The Indian monsoon is influenced by several large-scale climate systems, including the **El Niño–Southern Oscillation (ENSO)**, **Indian Ocean Dipole (IOD)**, **Madden–Julian Oscillation (MJO)**, **Eurasian snow cover**, and **Himalayan topography**. Among these, ENSO is one of the strongest drivers of interannual monsoon variability. Variations in monsoon rainfall directly influence crop production, groundwater recharge, reservoir storage, and food security, making accurate monsoon prediction essential for agricultural planning.

3.2 Relationship between El Niño and the Southwest Monsoon

The relationship between **El Niño and the Indian Southwest Monsoon** has been extensively studied because strong El Niño events are frequently associated with below-normal monsoon rainfall over India. During El Niño years, the warming of the central and eastern Pacific Ocean weakens the Walker Circulation and shifts tropical convection eastward. Consequently, ascending air over the Indian Ocean decreases, resulting in reduced cloud formation and weaker monsoon circulation over the Indian subcontinent (McPhaden et al., 2020).

Historically, nearly **60–70% of severe drought years in India** have coincided with El Niño events. Deficient monsoon rainfall reduces soil moisture, lowers groundwater recharge, decreases reservoir storage, and delays sowing operations. Rainfed agriculture is particularly vulnerable because insufficient rainfall limits seed germination, nutrient uptake, and crop growth.

However, the El Niño–monsoon relationship is not always straightforward. Some El Niño years have experienced near-normal monsoon rainfall due to the positive influence of the **Indian Ocean Dipole (IOD)**, which can partly compensate for ENSO-induced rainfall deficits. Therefore, modern seasonal forecasting considers both ENSO and IOD while predicting Indian monsoon rainfall. For farmers, El Niño years generally require climate-resilient practices such as drought-tolerant crop varieties, contingency crop planning, rainwater harvesting, micro-irrigation, and efficient nutrient management to minimize production losses.

3.3 Historical Drought Years Associated with El Niño

Several major droughts in India have occurred during strong El Niño years. Although not every El Niño event produces drought, many of the country's severe rainfall-deficit years coincide with ENSO warming.

El Niño Year Major Impact in India

1957–58	Moderate rainfall deficit in several regions
1965–66	Severe agricultural drought
1972–73	Nationwide drought and decline in food grain production
1982–83	Weak Southwest Monsoon in many states
1987–88	One of India's worst droughts of the twentieth century
1997–98	Strong El Niño but moderated by a positive Indian Ocean Dipole
2002	Severe monsoon failure and significant crop losses
2009	Rainfall deficit of about 22%; major agricultural drought
2015–16	Strong El Niño causing drought and water shortages
2023–24	Strong El Niño contributed to monsoon variability and regional rainfall anomalies

The economic consequences of these droughts included reduced food grain production, lower agricultural income, drinking water shortages, increased fodder scarcity, and rising food prices. States dependent on rainfed agriculture were particularly affected. Continuous improvements in seasonal forecasting by IMD, NOAA, and WMO have enabled governments to implement contingency planning and drought mitigation measures more effectively.

3.4 Effects on Agriculture, Water Resources, and Food Security

El Niño significantly affects India's agriculture because nearly **half of the cultivated area remains rainfed**. Reduced monsoon rainfall lowers soil moisture availability, delays sowing, shortens the growing period, and decreases crop yields. Major crops such as rice, maize, pulses, soybean, groundnut, cotton, and sugarcane experience moisture stress during critical growth stages, resulting in reduced productivity.

Water resources are equally affected. Deficient rainfall decreases reservoir storage, river discharge, groundwater recharge, and irrigation potential. Hydroelectric power generation may decline due to reduced inflow into reservoirs. Drinking water scarcity becomes severe in drought-prone regions, particularly in central and peninsular India. Livestock production is also affected because drought reduces fodder availability and water supply.

Food security is threatened through lower agricultural production, increased food prices, and reduced rural incomes. Smallholder farmers are the most vulnerable due to limited irrigation facilities and financial resources. Climate-smart agricultural practices—including drought-tolerant crop varieties, precision irrigation, rainwater harvesting, integrated nutrient management, conservation agriculture, crop diversification, and weather-based agro-advisory services—are increasingly promoted to reduce El Niño-related risks.

Government initiatives such as **Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)**, watershed development programmes, contingency crop planning, and improved seasonal climate forecasting have strengthened resilience against drought. Continued investment in climate-resilient agriculture, water conservation, and early warning systems will be essential for ensuring long-term food security under increasing climate variability.

Conclusion

El Niño remains one of the most important climatic drivers affecting rainfall variability and agricultural sustainability in Tamil Nadu. Although the intensity and regional impacts differ among individual El Niño events, the phenomenon consistently increases the risk of rainfall uncertainty, drought, water shortages, and crop yield reductions. Strengthening climate monitoring systems, improving seasonal forecasting, promoting climate-resilient agricultural technologies, enhancing water-use efficiency, and adopting sustainable land and nutrient management practices are essential for minimizing climate-related risks. Greater integration of meteorological information with agricultural planning and policy interventions will improve farmers' adaptive capacity and contribute to long-term food security, environmental sustainability, and resilient agricultural development in Tamil Nadu.

Solutions to Minimize the Impact of El Niño in Thiruvannamalai District

Thiruvannamalai is a **semi-arid district** where agriculture depends on both the Southwest and Northeast monsoons. The district receives an average annual rainfall of about **1,075 mm**, with substantial contributions from both monsoons, making rainfall variability a major concern for farming. Major crops include paddy, groundnut, millets, pulses, sugarcane, banana, mango, tapioca, vegetables, and flowers. ([Thiruvannamalai District](#))

1. Water Resource Management

- Renovate tanks, ponds, ooranis, and check dams through **Kudimaramathu** and watershed programmes.
- Construct farm ponds and recharge pits in every village.
- Promote rainwater harvesting in farms and public buildings.
- Desilt irrigation tanks and supply channels before the Northeast Monsoon.
- Encourage groundwater recharge through percolation ponds and recharge wells. Government programmes such as PMKSY and TNIAMP support many of these interventions. ([Thiruvannamalai District](#))

2. Efficient Irrigation

- Expand **drip and sprinkler irrigation** to improve water-use efficiency.

- Adopt fertigation to reduce fertilizer losses.
- Use irrigation scheduling based on soil moisture and weather forecasts.
- Promote solar-powered micro-irrigation systems.

3. Climate-Resilient Cropping Systems

- Replace long-duration crops with **short-duration and drought-tolerant varieties** during El Niño years.
- Increase cultivation of millets (finger millet, pearl millet), pulses, sesame, horse gram, and sorghum in rainfed areas.
- Introduce intercropping systems such as:
 - Finger millet + black gram
 - Groundnut + red gram
 - Pearl millet + cowpea
- Diversify with drought-tolerant horticultural crops such as amla, ber, tamarind, and custard apple.

4. Soil Health Improvement

- Apply **farmyard manure, compost, biochar, and green manure** to increase soil organic carbon.
- Use mulching to reduce evaporation and moderate soil temperature.
- Apply biofertilizers and integrated nutrient management to improve fertilizer-use efficiency.
- Use hydrogels in drought-prone fields to enhance soil moisture retention.

5. Climate-Smart Agriculture

- Use **weather-based agro-advisories** from IMD and TNAU for sowing and irrigation decisions.
- Adopt precision nutrient management based on soil test results.
- Monitor crop stress using drones and remote sensing where feasible.
- Promote conservation agriculture with minimum tillage and residue retention.

6. Crop Protection

- Monitor pest and disease outbreaks, which often increase during drought and heat stress.
- Adopt Integrated Pest Management (IPM).
- Maintain balanced nutrition, especially potassium and micronutrients, to improve drought tolerance.

7. Livestock Management

- Establish community fodder banks.
- Promote drought-tolerant fodder crops such as COFS-31 and sorghum fodder.
- Improve drinking water availability for livestock during drought periods.

8. Institutional and Government Support

- Increase enrollment in **Pradhan Mantri Fasal Bima Yojana (PMFBY)**.
- Strengthen village-level drought contingency plans.
- Expand watershed development and micro-irrigation subsidies.
- Provide timely credit, crop insurance, and input support to farmers. Existing horticulture and irrigation schemes in Thiruvannamalai already encourage micro-irrigation, dryland horticulture, and water conservation. ([Tiruvannamalai District](#))

9. Community Participation

- Form Water Users' Associations to manage irrigation systems.
- Encourage village-level rainwater harvesting campaigns.
- Train farmers on climate-resilient agriculture through KVK and the Department of Agriculture. Climate resilience initiatives in Thiruvannamalai increasingly emphasize community participation and locally adapted technologies. ([Tamil Nadu Board of Rural Development](#))

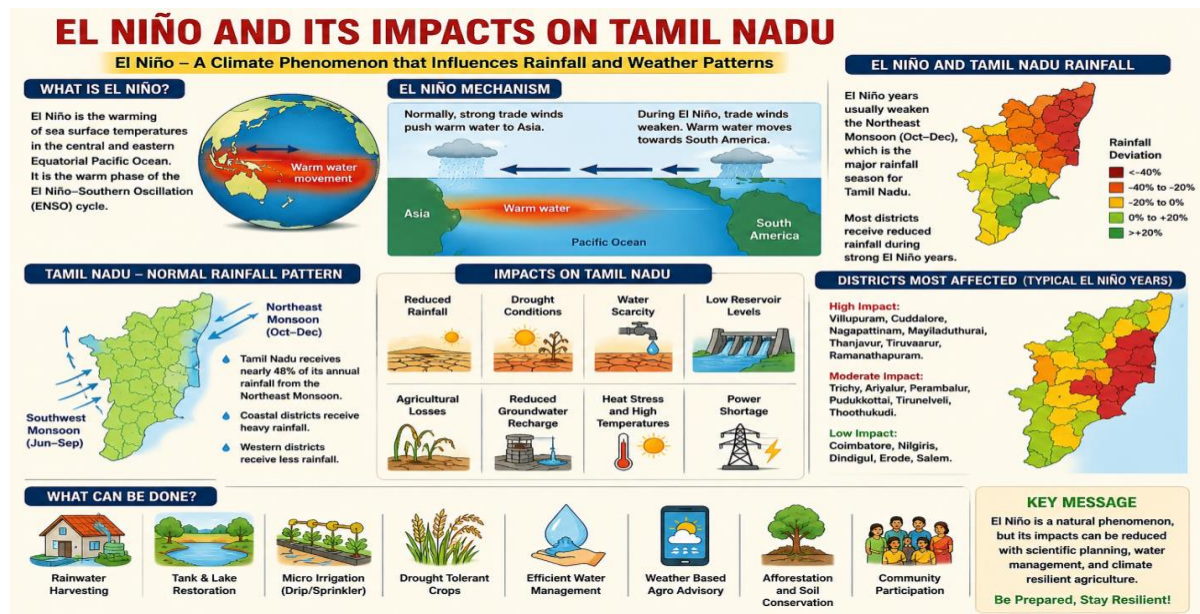
10. Research Priorities for Thiruvannamalai

- Develop drought-resilient rice, millet, and pulse varieties.
- Study the interaction of El Niño with the Northeast Monsoon in northern Tamil Nadu.
- Improve seasonal rainfall forecasting at the district level.
- Evaluate nano-fertilizers, biochar, hydrogels, and AI-based irrigation scheduling under El Niño conditions.
- Strengthen climate information services for farmers.

Conclusion

For Thiruvannamalai District, **water conservation combined with climate-smart agriculture** offers the most effective response to El Niño. The priority should be "**Save Every Drop – Grow Every Crop.**" By integrating

rainwater harvesting, tank restoration, micro-irrigation, drought-tolerant crops, soil health management, weather-based advisories, and strong government support, the district can reduce the adverse effects of El Niño on agriculture, water resources, and rural livelihoods while improving long-term resilience. ([Tiruvannamalai District](#))



References :

- IPCC. (2023). *Climate Change 2023: Synthesis Report*. Intergovernmental Panel on Climate Change.
- Lakshmi, S., Nivethaa, E. A. K., Palanivelu, K., & Ramachandran, A. (2025). Influence of sunspot activity and El Niño Southern Oscillation on Northeast Monsoon rainfall in the coastal districts of Tamil Nadu. *MAUSAM*, 76(2), 577–590.
- Roxy, M. K., Ghosh, S., Pathak, A., et al. (2017). A threefold rise in widespread extreme rain events over central India. *Nature Communications*, 8, 708.
- Mishra, V., Ganguly, A. R., Nijssen, B., & Lettenmaier, D. P. (2020). Changes in observed climate extremes in India and their impacts on agriculture. *Current Climate Change Reports*.

McPhaden, M. J., Santoso, A., & Cai, W. (2020). *El Niño Southern Oscillation in a Changing Climate*. American Geophysical Union.

Pai, D. S., et al. (2021). Monsoon variability over India and its relationship with ENSO and the Indian Ocean Dipole. *India Meteorological Department*.

World Meteorological Organization (WMO). (2023). *State of the Global Climate 2023*.

India Meteorological Department (IMD). (2025). *Long Range Forecast for Southwest Monsoon Rainfall*.

IPCC. (2023). *Climate Change 2023: Synthesis Report*. Intergovernmental Panel on Climate Change.

McPhaden, M. J., Santoso, A., & Cai, W. (2020). *El Niño Southern Oscillation in a Changing Climate*. American Geophysical Union.

NOAA. (2024). *El Niño/Southern Oscillation (ENSO) Diagnostic Discussion*. National Oceanic and Atmospheric Administration.

Roxy, M. K., et al. (2017). A threefold rise in widespread extreme rain events over central India. *Nature Communications*, **8**, 708.

Trenberth, K. E. (2020). The changing character of El Niño. *Nature Reviews Earth & Environment*, **1**, 1–14.

World Meteorological Organization (WMO). (2023). *State of the Global Climate 2023*.

IPCC. (2023). *Climate Change 2023: Synthesis Report*.

WMO. (2023). *State of the Global Climate*.

Roxy, M. K., et al. (2017). *Nature Communications*, **8**, 708.

Mishra, V., et al. (2020). *Current Climate Change Reports*.

IMD. (2025). *Long Range Forecast for Southwest Monsoon Rainfall*.

Pai, D. S., et al. (2021). *India Meteorological Department*.

IPCC. (2023). *Climate Change 2023: Synthesis Report*.

Roxy, M. K., et al. (2017). *Nature Communications*, **8**, 708.



Smart Fertilizer: A Way to Reduce Cost of Cultivation



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Abstract

Food security is the main concern by increasing food grain production. But there are so many challenges that affect the crop growth and available of nutrients. The nutrients supplied to crop in two ways either organic or inorganic. These are prone to loss by leaching, runoff, volatilization, denitrification or it may be fixation, immobilization etc. Smart fertilizers enhance the nutrient use efficiency through slow & controlled release of fertilizers, nanofertilizers and bioformulations. Though the initial investment is high but it would be profitable in long run. The use of such inputs are technically feasible, ecologically sound for improving the profitability. So, the new technology helps in improving crop yield sustainably without affecting the nature.

Keywords: Food grain production, nanofertilizers, profitable & crop yield

Introduction

Smart fertilizers are advanced nutrient delivery systems designed to control the rate, timing, and duration of nutrient release to match a plant's real-time nutritional demands. Different source of the fertilizers increases nutrient use efficiency by minimizing the risks like leaf burning and eutrophication. Among the applied nutrients to the crop prone to various losses which have been estimated to be nitrogen (40-70 %), phosphorus (80-90 %), potassium (50-70 %) and micronutrient (> 95 %) into the atmosphere and results in pollution. The supply of nutrients through nano-fertilizers is precisely available for plant growth and higher use efficiency helps in exploiting immobilized nutrients in the rhizosphere. It can also be delivered to the plant on real time basis by foliar spray. This mostly induced by small size, high specific surface area and reactivity of nano fertilizers increase the solubility and availability of nutrients to plants. Bioformulation contains microbial preparations of specific strain of microorganisms which are capable of fixing or solubilizing or mobilizing plant nutrients for enhancing plant growth and crop yield. So, it can be concluded that it would be better option for the farmers to increase crop production with minimal input in sustainable way without degrading outer environment.

Characteristic of Smart Fertilizer:

- Crop requirements can be mitigated by nutrient release.
- To achieve maximum percentage recovery in minimal cost of the input.
- Negligible effect on the soil, water and air (Umesha *et al.*, 2017).

Types of Smart Fertilizers

- i. **Controlled Release Fertilizers (CRFs):** These utilize specialized coatings made of minerals (bentonite, zeolite), synthetic polymers (polystyrene, poly vinyl alcohol etc.), organic based materials and biodegradable matrices to slow down nutrient dispersion.

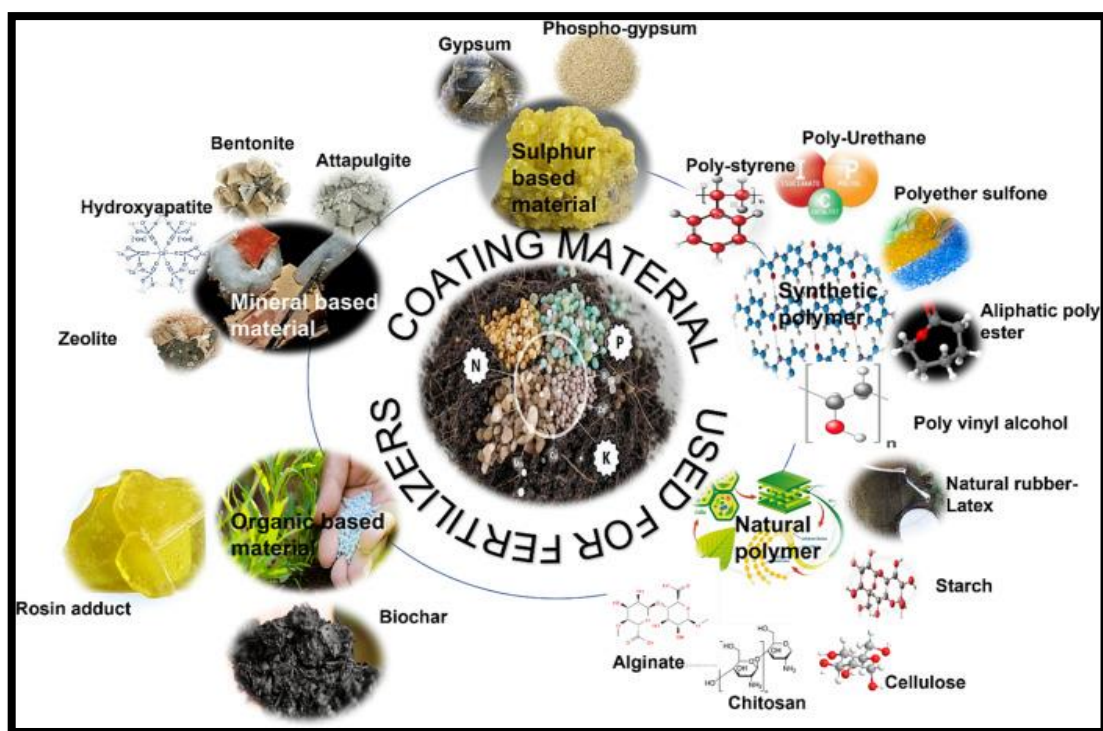


Fig. 1. Coating material used for formulation

- ii. **Nano-fertilizers:** Engineered particles smaller than 100 nanometers that offer a massive surface area, facilitating direct penetration and targeted nutrient delivery into plant tissues.



Fig. 2. Nanofertilizers liquid formulation

- iii. **Bioformulations:** Preparations containing live, beneficial microorganisms (like mycorrhizal fungi) that naturally solubilize soil nutrients and boost stress tolerance.

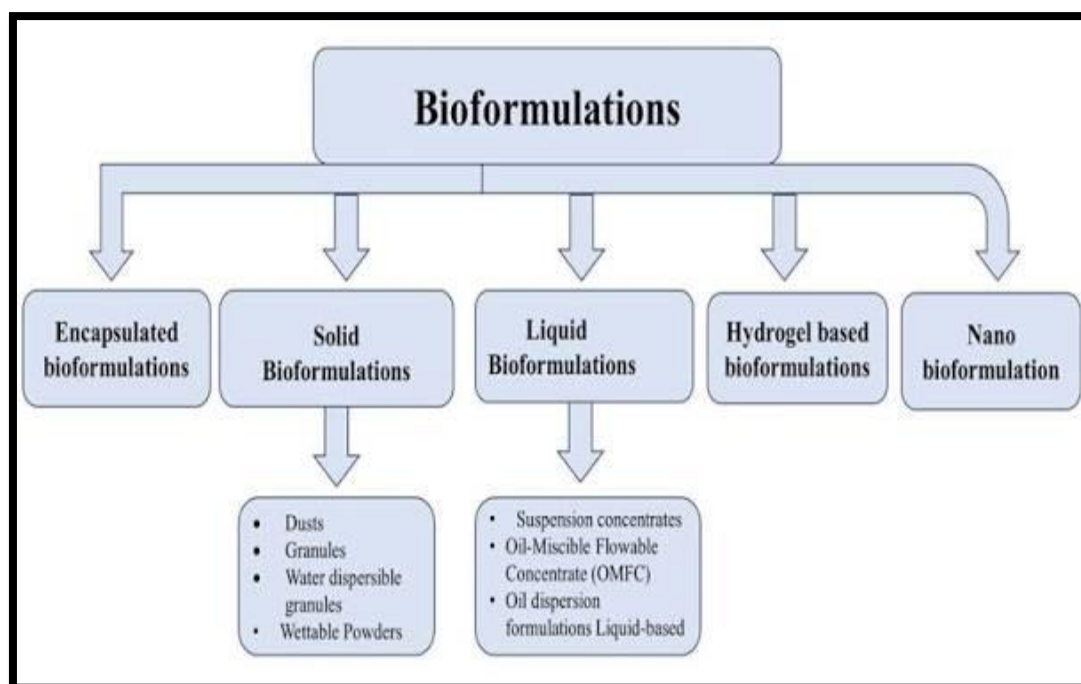


Fig. 3. Bioformulation types and their materials

Benefits of Smart fertilizers

Smart fertilizers having beneficial effect over the conventional fertilizer for increasing quality of crops by reducing the quantity of application.

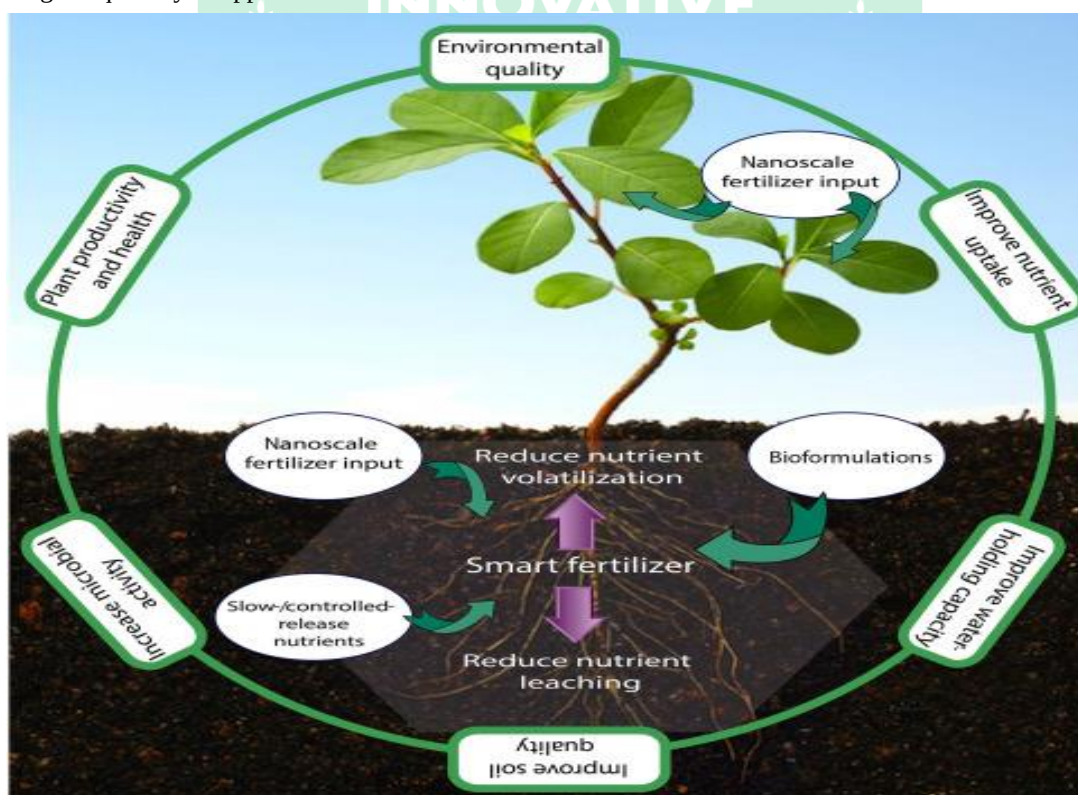


Fig. 4. Benefits of Smart fertilizers

Table 1. Comparison of Conventional Vs. Smart fertilizers

Feature	Conventional Fertilizers	Smart Fertilizers
Nutrient Release	Immediate and not controlled	Controlled, gradual, or easily uptake by plant
Nutrient Use Efficiency	Low (Losses through leaching & volatilization)	High (Enhanced the uptake of plant)
Environmental Impact	High runoff, toxicity to soil, and water pollution	Low runoff and minimal soil degradation
Application Frequency	Multiple applications required per cycle	Less applications required, saving labour

Economic Perspective of Smart Fertilizers

Smart fertilizers are not only technological advancement but also economically viable strategy for sustainability in agricultural production. By using smart fertilizers, farmers can achieve higher yields with fewer fertilizer applications which results overall production costs and also improve the profitability (Karthik and Maheswari, 2021). Higher nutrient recovery and reduction in expenditure on fertilizer, labour, machinery and irrigation; subsequently increasing farmers benefit is the major economic advantage of smart fertilizers (Chen *et al.*, 2018). The initial investment may appear to be relatively high but long-term savings produced through efficient nutrient utilisation and reduced application frequency often outweigh the additional cost (Dimkpa and Bindraban, 2018). Beyond farm level inputs, it also contributes towards environmental improvements by reducing the hidden costs associated with land degradation and water pollution. Efficient use of fertiliser can also help in reducing financial burden of fertiliser subsidies and promote more judicious utilisation of government funds in other societal development (Kah *et al.*, 2018). The successful adoption of smart fertiliser mainly depends on farmers' awareness, affordability, input availability, access to institutional credit and supportive government policies. Overall, the investment in smart fertilizers is economically efficient and provide a pathway for sustainable agricultural development in place of conventional fertilizers.

Table 2. Economic Indicators Associated with Conventional and Smart Fertilizer Application

Indicator	Conventional Fertilizer	Smart Fertilizer
Fertilizer use (kg/ha)	Higher	Lower
Number of applications	3–5	1–2
Labour requirement	High	Low
Cost of application	High	Low
Yield	Moderate	Higher
Net return	Lower	Higher
Benefit-Cost Ratio	Lower	Higher

Conclusion:

The way by which nutrients applied by farmers in traditional farming incur more cost of cultivation and it degrades the soil quality. It badly affects the crop production and marketability of produce. So, to increase the quality of crop and reduce the quantity of fertilizer application, use of smart fertilizer plays an important role in long run. It offers a practical pathway to achieve economic viability, environmental sustainability and climate resilient agriculture through efficient use of inputs, reduction in production cost, conservation of natural resources, improvement of farm profitability and minimization of environmental externalities.

Reference:

- Chen, J., Lü, S., Zhang, Z., Zhao, X., Li, X., Ning, P., & Liu, M. (2018). Environmentally friendly fertilizers: A review of materials used and their effects on the environment. *Science of the Total Environment*, 613–614, 829–839.
- Dimkpa, C. O., & Bindraban, P. S. (2018). Nanofertilizers: New products for the industry? *Journal of Agricultural and Food Chemistry*, 66(26), 6462–6473.

Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*, 13(8), 677–684.

Karthik, A. and Maheswari, M.U. (2021). Smart Fertilizer Strategy for Better Crop Production. *Agricultural Reviews*. 42(1): 12-21. DOI: 10.18805/ag.R-1877

Umesha, C., Sridhara, C.J. and Kumarnaik, A.H. (2017). Recent forms of fertilizers and their use to improve nutrient use efficiency and to minimize environmental impacts. *Int. J. Pure App. Biosci.* 5(2): 858-863.



Invisible Alliances: How Insect Pests and Plant-Parasitic Nematodes Collaborate to Damage Crops



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Abstract

Insect pests and plant-parasitic nematodes are among the most destructive biotic constraints affecting agricultural productivity worldwide. Although traditionally studied and managed separately, growing evidence indicates that these organisms often interact indirectly through their shared host plant, leading to greater crop damage than individual infestations. Plant-parasitic nematodes weaken root systems by impairing water and nutrient uptake, while insect feeding further compromises plant growth and defence mechanisms. These plant-mediated interactions alter physiological and biochemical processes, increasing crop susceptibility to multiple pests and reducing yield and quality. This article highlights the ecological relationship between insect pests and nematodes, explains the mechanisms underlying their interactions, and presents examples from economically important crops such as tomato, cotton, rice, banana, and vegetables. It also emphasizes the importance of integrated pest management (IPM), including crop rotation, resistant varieties, biological control, soil health management, and precision agriculture, for sustainable management of these hidden enemies. Understanding these invisible alliances is essential for developing resilient cropping systems and minimizing economic losses while reducing dependence on chemical pesticides.

Keywords: Agricultural entomology; Plant-parasitic nematodes; Insect pests; Plant-mediated interactions; Root-knot nematodes; Integrated Pest Management (IPM); Crop protection; Soil health; Sustainable agriculture; Plant defence mechanisms.

Introduction

Agriculture faces constant challenges from a wide range of pests that threaten crop productivity and food security. Among these, insect pests and plant-parasitic nematodes (PPNs) are responsible for substantial yield losses across cereals, vegetables, fruit crops, and plantation crops worldwide. While insect damage is usually visible on leaves, stems, flowers, or fruits, nematode infestation often remains hidden beneath the soil, making it difficult to detect until plants begin to show symptoms such as wilting, stunted growth, or nutrient deficiency (Jones et al., 2013).

For decades, these two groups of pests have been studied and managed independently. However, recent research has revealed that they are more closely connected than previously thought. Although insects and nematodes rarely interact directly, they influence one another through the host plant. Changes caused by one pest can modify the plant's physiology, defence responses, and nutritional status, creating favourable conditions for the other. This phenomenon, known as plant-mediated interaction, forms the basis of an "invisible alliance" that often results in greater crop damage than either pest acting alone (Biere & Goverse, 2016).

Insect pests such as aphids, whiteflies, stem borers, and caterpillars feed on aerial plant parts, reducing photosynthesis and weakening plant health. In contrast, plant-parasitic nematodes—including root-knot (*Meloidogyne spp.*), cyst (*Heterodera spp.*), and lesion nematodes (*Pratylenchus spp.*)—attack the roots, disrupting water and nutrient uptake and impairing overall plant growth (Coyne et al., 2018). Although they occupy different habitats, both groups exploit the same host and often intensify each other's effects.

Understanding this hidden relationship has important implications for sustainable crop protection. Instead of viewing insect pests and nematodes as separate problems, researchers now advocate an integrated approach

that considers their ecological interactions. Such an understanding not only improves pest management but also helps reduce crop losses while minimizing dependence on chemical pesticides. As agriculture moves toward more sustainable practices, recognizing these invisible alliances is becoming increasingly important for protecting crop productivity and ensuring long-term food security.

How Insect Pests and Plant-Parasitic Nematodes Intensify Crop Damage

The relationship between insect pests and plant-parasitic nematodes is largely indirect but highly significant. Rather than interacting physically, they influence one another through changes in the host plant. When one pest attacks, it alters the plant's physiology, nutrient allocation, and defence mechanisms, often making the plant more susceptible to the other. This plant-mediated interaction can result in greater crop damage than individual infestations (Biere & Govere, 2016).

Plants defend themselves against herbivores and pathogens through complex signalling pathways regulated mainly by jasmonic acid (JA) and salicylic acid (SA). Root-knot nematodes manipulate these defence pathways to establish feeding sites within roots, suppressing the plant's natural resistance. At the same time, feeding by insects such as aphids, whiteflies, and caterpillars can modify plant metabolism and root chemistry, indirectly influencing nematode infection and reproduction (Pieterse et al., 2012).

Nematode damage to the root system reduces water and nutrient uptake, resulting in poor plant vigour, chlorosis, and stunted growth. Such stressed plants become more vulnerable to insect attack because they have fewer resources to support defence and recovery. Likewise, severe insect feeding further weakens the plant, increasing the adverse effects of nematode infestation. The combined impact often leads to greater yield losses and poorer crop quality than either pest alone (Jones et al., 2013).

Tomato is a classic example of this hidden alliance. Root-knot nematodes (*Meloidogyne incognita*) cause gall formation and weaken root function. When these plants are simultaneously attacked by whiteflies (*Bemisia tabaci*) or aphids (*Myzus persicae*), growth and fruit yield decline sharply. Whiteflies also transmit Tomato Yellow Leaf Curl Virus (TYLCV), while nematode-damaged plants are less capable of tolerating viral infection, making the pest complex particularly destructive (Hauri & Szendrei, 2022). These findings emphasize that successful crop protection depends not only on controlling individual pests but also on understanding the hidden interactions that shape pest outbreaks in agricultural ecosystems.

Crop-Wise Examples and Integrated Management Strategies

The hidden interaction between insect pests and plant-parasitic nematodes has been reported in many economically important crops. Although the nature of these interactions varies with the crop, pest species, and environmental conditions, the outcome is often the same—greater plant stress, reduced yield, and increased management costs.

Cotton is a good example of this interaction. Root-knot (*Meloidogyne incognita*) and reniform (*Rotylenchulus reniformis*) nematodes damage the root system, reducing water and nutrient uptake. The weakened plants become more susceptible to sap-feeding insects such as aphids, whiteflies, and jassids, leading to poor plant growth, reduced boll formation, and lower fibre quality (Jones et al., 2013).

In rice, root nematodes (*Hirschmanniella spp.*) impair root development and nutrient absorption. When combined with insect pests such as the brown planthopper (*Nilaparvata lugens*) and stem borers, plants show poor tillering, reduced grain filling, and lower productivity. Healthy root systems are therefore essential for improving the crop's tolerance to insect attack.

Banana presents another well-known pest complex. Burrowing nematodes (*Radopholus similis*) destroy feeder roots, while the banana weevil (*Cosmopolites sordidus*) tunnels into the corm. Together, these pests weaken the plant, reduce nutrient uptake, and increase the risk of lodging, ultimately lowering bunch weight and fruit quality (Coyne et al., 2018).

In vegetable crops such as tomato, brinjal, chilli, okra, and cucurbits, root-knot nematodes reduce plant vigour and make crops more vulnerable to insect pests, including aphids, whiteflies, thrips, and the shoot and fruit borer. Such combined infestations often result in poor growth, lower marketable yield, and increased pesticide use.

Integrated Management: A Sustainable Solution

Since insects and nematodes influence one another through the host plant, managing them separately is often ineffective. Integrated Pest Management (IPM) offers a sustainable approach by combining multiple compatible practices.

Crop rotation with non-host crops helps reduce nematode populations while interrupting insect life cycles. Resistant or tolerant varieties provide long-term protection against major pests without increasing production costs.

Biological control is another important component of IPM. Natural enemies such as *Trichogramma spp.*, *Chrysoperla spp.*, and entomopathogenic fungi help suppress insect pests, whereas *Purpureocillium lilacinum*, *Pochonia chlamydosporia*, and *Pasteuria penetrans* effectively reduce nematode populations.

Maintaining healthy soils through the application of farmyard manure, compost, neem cake, and biofertilizers enhances beneficial microorganisms and improves plant resilience against multiple pests. Regular field scouting, root examination, and soil sampling enable early detection of infestations, allowing timely intervention before serious damage occurs.

Chemical pesticides and nematicides should be used judiciously and only when necessary. Their integration with cultural and biological practices not only improves pest control but also conserves natural enemies, delays resistance development, and reduces environmental risks.

Ultimately, recognizing the hidden relationship between insect pests and plant-parasitic nematodes allows farmers to adopt more holistic and sustainable crop protection strategies, leading to healthier crops and improved productivity.

Future Perspectives

Advances in agricultural research are transforming the way insect pests and plant-parasitic nematodes are managed. Modern approaches increasingly emphasize integrated and eco-friendly pest management rather than relying solely on chemical control. Technologies such as remote sensing, artificial intelligence (AI), molecular diagnostics, and RNA interference (RNAi) are improving early pest detection and enabling more precise management decisions. In addition, beneficial soil microorganisms and conservation of natural enemies are gaining importance as sustainable tools for suppressing both insect pests and nematodes (Pieterse et al., 2014). Climate change is expected to further influence the distribution and severity of these pests, making continuous monitoring and adaptive management essential for future crop protection (Bebber et al., 2013).

Conclusion

Although insect pests and plant-parasitic nematodes attack different parts of a plant, their interactions often intensify crop damage through changes in plant physiology and defence mechanisms. This hidden alliance highlights the need to move beyond single-pest management and adopt Integrated Pest Management (IPM) strategies that combine crop rotation, resistant varieties, biological control, healthy soil management, regular monitoring, and judicious pesticide use.

A better understanding of these invisible interactions will help researchers, extension workers, and farmers develop more resilient cropping systems, reduce yield losses, and promote environmentally sustainable agriculture.

References

- Bebber, D. P., Ramotowski, M. A., & Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature climate change*, 3(11), 985-988.
- Biere, A., & Goverse, A. (2016). Plant-mediated systemic interactions between pathogens, parasitic nematodes, and herbivores above-and belowground. *Annual Review of Phytopathology*, 54, 499-527.
- Coyne, D. L., Cortada, L., Dalzell, J. J., Claudius-Cole, A. O., Haukeland, S., Luambano, N., & Talwana, H. (2018). Plant-parasitic nematodes and food security in Sub-Saharan Africa. *Annual review of phytopathology*, 56(1), 381-403.
- Hauri, A., & Szendrei, Z. (2022). Plant-mediated interactions between belowground plant-parasitic nematodes and aboveground insect herbivores. *Annual Review of Entomology*, 67, 261-279.

- Jones, J. T., Haegeman, A., Danchin, E. G. J., Gaur, H. S., Helder, J., Jones, M. G. K., Kikuchi, T., Manzanilla-López, R., Palomares-Rius, J. E., Wesemael, W. M. L., & Perry, R. N. (2013). Top 10 plant-parasitic nematodes in molecular plant pathology. *Molecular Plant Pathology*, 14(9), 946–961.
- Karssen, G., Wesemael, W., & Moens, M. (2013). Root-knot nematodes. In *Plant nematology* (pp. 73-108). Wallingford UK: Cabi.
- Pieterse, C. M., Van der Does, D., Zamioudis, C., Leon-Reyes, A., & Van Wees, S. C. (2012). Hormonal modulation of plant immunity. *Annual review of cell and developmental biology*, 28, 489-521.
- Pieterse, C. M., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C., & Bakker, P. A. (2014). Induced systemic resistance by beneficial microbes. *Annual review of phytopathology*, 52(1), 347-375.
- Siddique, S., Coomer, A., Baum, T., & Williamson, V. M. (2022). Recognition and response in plant–nematode interactions. *Annual Review of Phytopathology*, 60, 143-162.
- Sikora, R. A., Coyne, D., Hallmann, J., & Timper, P. (Eds.). (2018). *Plant parasitic nematodes in subtropical and tropical agriculture*. Cabi.



Sundargarada: A Growing Hub of Sustainable Tasar Sericulture in Odisha



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Abstract

Tropical Tasar sericulture is an important forest-based enterprise that supports the livelihoods of tribal and rural communities while promoting the sustainable utilization of natural resources. Sundargarh district of Odisha has emerged as one of the state's major Tasar-producing regions owing to its favourable agro-climatic conditions, abundant availability of *Terminalia tomentosa* (Asan) and *Terminalia arjuna* (Arjun), and a well-established cooperative production system. This study assesses the current status, production potential, institutional framework, and developmental interventions associated with Tasar sericulture in Sundargarh district. The analysis is based on departmental records, annual action plans, cooperative statistics, and other secondary sources for the period 2025–26.

The study highlights the role of host plant development under the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), scientific production and distribution of Disease-Free Layings (DFLs), commercial cocoon procurement through Primary Tasar Marketing Cooperative Societies (PTMCS), and extension support in strengthening the district's Tasar production system. It also examines the major constraints affecting sectoral growth, including Pebrine disease, gall-forming psyllid infestation, seasonal fluctuations in cocoon prices, inadequate post-cocoon infrastructure, declining participation of rural youth, and the continued non-operational status of the Khuntgaon Tasar Silk Park.

The findings indicate that Sundargarh possesses strong ecological and institutional advantages for the sustainable expansion of Tasar sericulture. However, long-term growth will depend on strengthening scientific extension services, improving host plant management, ensuring timely availability of quality DFLs, operationalizing post-cocoon processing infrastructure, promoting value addition, and encouraging greater participation of women and youth in the Tasar value chain. The study concludes that coordinated policy support, cooperative strengthening, and research-based technological interventions can transform Sundargarh into a model district for sustainable Tasar sericulture, contributing to livelihood security, rural employment, and inclusive economic development in Odisha.

Keywords: Tropical Tasar sericulture; *Antheraea mylitta*; Sundargarh; Odisha; Disease-Free Layings (DFLs); Primary Tasar Marketing Cooperative Societies; MGNREGS; tribal livelihoods; sustainable rural development.

1. Introduction

Sericulture represents one of the few agro-based rural enterprises that simultaneously contributes to income generation, employment creation, biodiversity conservation, and sustainable utilization of natural resources. Among the different silk-producing systems practiced in India, tropical Tasar sericulture occupies a distinctive position because it is closely associated with forest ecosystems and is largely dependent on naturally occurring host plant species. Unlike mulberry sericulture, Tasar silkworm rearing is undertaken on perennial forest trees such as *Terminalia tomentosa* (Asan) and *Terminalia arjuna* (Arjun), thereby integrating livelihood generation with ecological conservation and sustainable management of forest resources.

India remains the world's largest producer of tropical Tasar silk, with major production concentrated in Jharkhand, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, and West Bengal. Government interventions implemented through the Central Silk Board, the Ministry of Textiles, and various State Departments have significantly strengthened the sector by promoting scientific seed production, expansion of host plant plantations, farmer capacity building, disease management, and organized marketing systems. These initiatives have enhanced

the economic viability of Tasar sericulture while creating additional livelihood opportunities for tribal and economically disadvantaged communities.

Within Odisha, Sundargarh district occupies an important position in the Tasar production landscape because of its extensive forest resources, favourable climatic conditions, and long-standing tradition of forest-based livelihoods among tribal communities. The widespread occurrence of Asan and Arjun plantations, together with sustained institutional support from the Department of Sericulture, Government of Odisha, the Central Silk Board, and Primary Tasar Marketing Cooperative Societies (PTMCS), has facilitated the steady expansion of Tasar cultivation across the district. Cooperative-based production, organized cocoon procurement, and continuous investment in host plant development have further strengthened the district's production system.

Despite notable achievements, Tasar sericulture in Sundargarh continues to face several technical, biological, economic, and institutional challenges. Diseases affecting silkworm health, insect pests damaging host plants, inadequate post-cocoon infrastructure, seasonal market fluctuations, and declining participation of younger generations collectively limit productivity and long-term sustainability.

Addressing these constraints requires a balanced strategy that integrates scientific production technologies, infrastructure development, market support, and livelihood diversification.

Against this background, the present study documents the current status of Tasar sericulture in Sundargarh district by examining institutional development, plantation expansion, Disease-Free Laying production, commercial cocoon marketing, and recent government interventions. The paper also identifies key constraints affecting sectoral growth and proposes measures that may contribute to the sustainable development of Tasar sericulture in Odisha.

2. Sericulture Potential of Sundargarh District.

Sundargarh district represents one of the most promising regions for tropical Tasar sericulture in Odisha because of its favourable natural environment, abundant forest resources, and long-standing association of tribal communities with forest-based livelihoods. The widespread occurrence of the primary host plants, *Terminalia tomentosa* (Asan) and *Terminalia arjuna* (Arjun), provides a strong ecological foundation for the sustainable rearing of *Antheraea mylitta* Drury. These favourable conditions, together with continuous institutional support, have enabled the district to emerge as an important centre for Tasar silk production in eastern India.

The development of Tasar sericulture in Sundargarh has been facilitated through coordinated efforts of the Directorate of Sericulture, Government of Odisha, the Central Silk Board (CSB), and local cooperative institutions. At present, Tasar cultivation extends across 166 villages located in 42 Gram Panchayats within six development blocks, namely Bonai, Lahunipada, Koida, Sundargarh, Bargaon, and Bisra. Approximately 3,315 active Tasar rearers are engaged in commercial silkworm rearing, collectively producing nearly 3,000 kahans of commercial cocoons annually. These figures demonstrate the significant contribution of Tasar sericulture to livelihood generation and the rural economy of the district.

A distinguishing feature of Sundargarh's Tasar sector is its cooperative-based production and marketing system. Organized cooperative activities began with the registration of the Bargaon Tasar Marketing Cooperative Society in 1965, laying the foundation for institutional support to Tasar farmers. Over time, similar societies were established in other production clusters, creating an effective network for the distribution of Disease-Free Layings (DFLs), technical guidance, organized cocoon procurement, and implementation of government development programmes. This institutional framework has played an important role in improving production efficiency, strengthening market access, and enhancing farmers' participation in scientific Tasar cultivation.

The cooperative network has become the backbone of Tasar development in the district by ensuring timely input supply, facilitating scientific extension services, and providing organized marketing support to rearers. Besides promoting collective action among farmers, these societies have significantly contributed to strengthening the institutional framework required for sustainable Tasar production.

In recent years, considerable emphasis has also been placed on expanding host plant resources through plantation programmes implemented under the convergence of the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) and other government initiatives. Simultaneously, improvements in seed production at the Primary Production Centres (PPCs) located at Medinipur and K. Bolang have enhanced the availability of quality

Disease-Free Layings. Although the Khuntgaon Tasar Silk Park has not yet become fully operational, its establishment reflects the district's long-term vision of developing an integrated Tasar value chain encompassing seed production, cocoon marketing, silk processing, value addition, and entrepreneurship development. Collectively, these initiatives reinforce the strategic importance of Sundargarh as a potential model district for sustainable Tasar sericulture in Odisha.

Table 1. Represents the registered Primary Tasar Marketing Cooperative Societies functioning in Sundargarh district.

Sl. No.	Cooperative Society	Year of Registration	Major Activity
1	Bargaon TMCS	23 March 1965	Tasar production and cocoon collection
2	Bimlagarh TMCS	14 March 1975	Tasar production and cocoon collection
3	Bisra TMCS	20 March 1965	Tasar production and cocoon collection
4	Dalki TMCS	14 March 1981	Tasar production and cocoon collection
5	Jamdihi TMCS	19 January 1974	Tasar production and cocoon collection
6	K. Bolang TMCS	26 September 1979	Tasar production and cocoon collection
7	Khuntgaon TMCS	15 March 1978	Tasar production and cocoon collection
8	Lahunipada TMCS	24 March 1981	Tasar production and cocoon collection
9	Sarasra TMCS	15 March 1978	Tasar production and cocoon collection

Sources: Office of the Assistant director of Sericulture, Sundargarh.

3. Present Status of Tasar Sericulture

Sundargarh district has emerged as one of the leading Tasar sericulture regions in Odisha owing to its favourable ecological conditions, extensive host plant resources, and active involvement of tribal farming communities. Continuous technical support from the Directorate of Sericulture, Government of Odisha, in collaboration with the Central Silk Board (CSB) and the Primary Tasar Marketing Cooperative Societies (PTMCS), has strengthened the district's production system and expanded Tasar cultivation over the past several years.

Currently, Tasar sericulture is practiced in 166 villages distributed across 42 Gram Panchayats within six development blocks. Approximately 3,315 active rearers are engaged in commercial Tasar silkworm rearing, contributing an annual production of nearly 3,000 kahans of commercial cocoons. The widespread adoption of scientific rearing practices, timely availability of quality Disease-Free Layings (DFLs), organized cocoon procurement, and regular extension activities have contributed significantly to maintaining production levels and improving rural livelihoods.

Table 2. Present Status of Tasar Sericulture in Sundargarh District

Particular	Status
Active Tasar Rearers	3,315
Primary Tasar Marketing' Cooperative Societies (PTMCS)	9
Development Blocks Covered	6
Gram Panchayats Covered	42
Villages Covered	166
Annual Commercial Cocoon Production	Approximately 3,000 Kahans

The available statistics indicate that Tasar sericulture has become an important component of the rural economy in the district. Besides generating seasonal employment, the sector provides supplementary income to a large number of tribal households and supports sustainable utilization of forest resources. The cooperative-based production and marketing system has further enhanced farmers' access to quality inputs, technical guidance, and organized marketing channels.

3.1 Block-wise Distribution of Active Tasar Rearers

The spatial distribution of Tasar rearers is uneven across the district, reflecting differences in forest cover, host plant availability, and the historical development of sericulture activities. Bonai and Lahunipada blocks constitute

the principal Tasar production belt, whereas Koida, Sundargarh, Bargaon, and Bisra account for comparatively smaller numbers of rearers.

Table 3. Block-wise Distribution of Active Tasar Rearers in Sundargarh District

Development Block	Number of Tasar Rearers (approx.)
Bonai	2,224
Lahunipada	845
Koida	131
Sundargarh	85
Bargaon	15
Bisra	15
Total	3,315

Among the six development blocks, **Bonai** accounts for the largest concentration of Tasar rearers, representing nearly two-thirds of the district's total beneficiary population. **Lahunipada** occupies the second position, while the remaining four blocks together contribute a relatively smaller share. This distribution reflects the availability of suitable host plants, accessibility to extension services, and the long-established presence of cooperative societies in the major Tasar-growing clusters.

The concentration of rearers within Bonai and Lahunipada offers opportunities for implementing cluster-based development programmes, including improved extension delivery, scientific disease management, mechanized post-cocoon operations, and value-addition enterprises. Such an approach can improve production efficiency, reduce operational costs, and enhance farmers' income while ensuring sustainable expansion of Tasar sericulture in the district.

3.2. Plantation Development Programme (2025–26)

The long-term sustainability of Tasar sericulture largely depends on the availability of healthy and adequately managed host plant resources. Recognizing this requirement, extensive plantation and maintenance activities were undertaken during 2025–26 under the convergence of the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) and the Promotion of Sericulture in Odisha (POSI) programme.

The programme included establishment of new Asan and Arjun plantations, maintenance of plantations of different age groups, and upkeep of plantations maintained by the Primary Production Centres (PPCs) at Medinipur and K. Bolang.

Table 4. Plantation Programme in Sundargarh District (2025–26)

Activity	Area (ha)
New Asan/Arjun Plantation (MGNREGS)	80
First Year Maintenance (MGNREGS)	10
Second Year Maintenance (MGNREGS)	100
Third Year Maintenance (MGNREGS)	100
PPC Medinipur Maintenance (POSI)	5
PPC K. Bolang Maintenance (POSI)	10
Total Area Covered	305

Sources: Office of the ADS, Sundargarh.

The expansion and maintenance of host plant plantations are essential for sustaining future DFL distribution and commercial cocoon production. Besides increasing leaf availability, these plantation activities contribute to ecological restoration, soil conservation, and employment generation under MGNREGS, thereby strengthening both environmental sustainability and rural livelihoods.

3.3. Cocoon Collection

Commercial cocoon collection represents one of the most important indicators for evaluating the performance of Tasar sericulture, as it reflects both production efficiency and the effectiveness of cooperative marketing systems. In Sundargarh district, commercial cocoons are procured primarily through the Primary Tasar Marketing Cooperative Societies, which facilitate organized procurement and ensure transparent marketing mechanisms for Tasar rearers.

Table 5. Society-wise Cocoon Collection in Sundargarh District (2025–26)

Sl. No.	Primary Tasar Rearers' Cooperative Society (PTRCS/TMCS)	Cocoon Collection (Nos.)	Approx. Value (₹)
1	Bargaon	4,84,856	1,72,594
2	Bimlagarh	38,500	1,47,435
3	Bisra	0	0
4	Dalki	1,62,828	7,53,180
5	Jamdihi	28,360	1,09,165
6	K. Bolang	82,560	1,86,710
7	Khuntgaon	14,02,924	49,18,490
8	Lahunipada	89,080	3,19,950
9	Sarasra	12,49,316	47,35,030
Total	Sundargarh District	35,38,424	₹1,13,42,554

Source: Office of the Assistant Director of Sericulture, Sundargarh.

Table 5 presents the society-wise commercial cocoon collection in Sundargarh district during 2025–26, together with the approximate procurement value. A total of **35,38,424 commercial cocoons**, valued at approximately **₹1,13,42,554**, were procured through the cooperative network, demonstrating the significant economic contribution of Tasar sericulture to the livelihoods of rural and tribal communities in the district.

Among the cooperative societies, **Khuntgaon** recorded the highest cocoon collection (**14,02,924 cocoons**) with an approximate procurement value of **₹49,18,490**, contributing nearly **40%** of the district's total collection. **Sarasra** ranked second with **12,49,316 cocoons**, valued at approximately **₹47,35,030**, while **Bargaon** occupied the third position with **4,84,856 cocoons** valued at **₹1,72,594**. Collectively, these three societies accounted for nearly **89%** of the district's commercial cocoon procurement, highlighting their dominant role in Tasar production and cooperative marketing.

Moderate levels of cocoon collection were reported from **Dalki** (**1,62,828 cocoons; ₹7,53,180**), **Lahunipada** (**89,080 cocoons; ₹3,19,950**), and **K. Bolang** (**82,560 cocoons; ₹1,86,710**), whereas **Bimlagarh** (**38,500 cocoons; ₹1,47,435**) and **Jamdihi** (**28,360 cocoons; ₹1,09,165**) contributed comparatively smaller quantities. **Bisra** reported no commercial cocoon collection during the year, indicating the need for a detailed assessment of the factors affecting production and cooperative procurement in the area.

The variation in cocoon collection and procurement value among the cooperative societies reflects differences in the availability of host plant resources, concentration of active rearers, access to quality Disease-Free Layings (DFLs), and the effectiveness of technical and marketing support. Strengthening the performance of lower-producing societies through improved extension services, timely input supply, scientific crop management, and capacity-building programmes will help achieve more balanced growth across the district. Continued modernization of procurement infrastructure, transparent pricing mechanisms, and efficient cooperative marketing systems will further enhance farmers' income, improve market confidence, and support the sustainable development of Tasar sericulture in Sundargarh.

4. Non-operational Status of the Khuntgaon Tasar Silk Park: Implications for Value Addition and Rural Livelihoods.

The establishment of the Khuntgaon Tasar Silk Park was envisioned as a strategic initiative to strengthen the post-cocoon segment of the Tasar value chain in Sundargarh district. The proposed facility was intended to support a range of activities, including cocoon processing, silk reeling, spinning, yarn production, weaving, product

diversification, skill development, and organized marketing. By integrating these activities within a single institutional framework, the Silk Park was expected to create a comprehensive ecosystem for value addition and rural enterprise development.

Despite this vision, the Silk Park has remained non-operational, limiting its contribution to the district's sericulture sector. Consequently, the majority of Tasar rearers continue to market raw cocoons without access to local processing facilities. This dependence on the sale of unprocessed produce restricts opportunities for value addition and reduces the economic returns that could otherwise be realized through the production of silk yarn, fabrics, and finished products.

The absence of functional post-cocoon infrastructure also constrains employment generation, particularly for rural youth and women, who could benefit from decentralized silk processing, weaving, and cottage-based enterprises. Furthermore, the lack of an integrated processing system prevents the district from developing a complete Tasar value chain linking seed production, cocoon procurement, processing, product manufacturing, and market promotion. As a result, much of the economic value generated from Tasar cultivation is transferred outside the district rather than being retained within local communities.

Operationalization of the Khuntgaon Tasar Silk Park would significantly enhance the competitiveness of Sundargarh's Tasar industry. Establishing modern facilities for reeling, spinning, weaving, quality testing, product development, packaging, and marketing would encourage local entrepreneurship, improve farmers' income, create additional employment opportunities, and promote value-added silk products. Such interventions would also strengthen market linkages and reduce dependence on external processing centres.

To realize these benefits, priority should be given to making the Silk Park fully functional through appropriate institutional arrangements, adequate financial support, and professional management. Collaboration among the Directorate of Sericulture, the Central Silk Board, cooperative societies, private entrepreneurs, and self-help groups could accelerate its operationalization and improve long-term sustainability. Once operational, the Khuntgaon Tasar Silk Park has the potential to transform Sundargarh from a major cocoon-producing district into a centre for integrated Tasar silk processing and value-added production, thereby contributing substantially to rural employment, tribal livelihood enhancement, and sustainable economic development.

5. Other Challenges

Despite the encouraging progress of Tasar sericulture in Sundargarh district, several biological and infrastructural constraints continue to limit its full potential. One of the most serious challenges is the occurrence of Pebrine disease, caused by the microsporidian parasite *Nosema bombycis*. The disease affects the health and survival of Tasar silkworms, resulting in poor larval performance, reduced cocoon yield, and economic losses to rearers. Regular disease surveillance, strict seed testing, and the supply of quality Disease-Free Layings (DFLs) are therefore essential to minimize the incidence of Pebrine.

Another significant constraint is the infestation of gall-forming psyllid (*Trioza fletcheri minor* Crawf.) on Tasar host plants, particularly Asan (*Terminalia tomentosa*). Gall formation on young leaves reduces the availability and quality of foliage, adversely affecting silkworm nutrition and subsequent cocoon productivity. Effective pest monitoring, timely pruning, and integrated pest management (IPM) practices are required to maintain healthy host plant plantations. The district also requires continuous expansion and scientific maintenance of host plant plantations to meet the increasing demand for Tasar rearing. Strengthening extension services, ensuring timely availability of quality DFLs, promoting scientific pest and disease management, and operationalizing post-cocoon infrastructure will be crucial for the sustainable development of Tasar sericulture in Sundargarh district.

Field observations in Sundargarh indicate that most active Tasar rearers belong to the older generation, while youth participation remains limited. Informal interactions with farmers suggest that concerns over unstable annual income, production risks, inadequate insurance coverage, and comparatively lower social recognition discourage younger individuals from pursuing Tasar sericulture as a full-time occupation. This emerging generational gap poses a significant challenge to the long-term sustainability of the Tasar sector and highlights the need for policies that improve profitability, social security, and the public perception of sericulture as a viable rural enterprise.

Another important constraint affecting Tasar sericulture in Sundargarh is the variation in cocoon prices, which directly influences farmers' rearing decisions. The market price of commercial cocoons varies considerably between crop seasons. In general, cocoons produced during the first crop (June–July) fetch only about ₹2–3 per cocoon, whereas the second crop (September–November) often receives ₹5–6 per cocoon, depending on cocoon quality and market demand. This substantial price difference reduces the profitability of the first crop, discouraging many rearers from undertaking first-season rearing despite the availability of suitable host plants. Consequently, a significant proportion of farmers prefer to rear only the second crop, where higher market prices offer better economic returns. This imbalance results in underutilization of available host plant resources and limits the overall annual production potential of the district. Introducing a minimum support price (MSP), price stabilization mechanisms, value-addition initiatives, and assured procurement during the first crop could encourage farmers to undertake both rearing seasons and improve annual household income.

6. Future Prospects

Despite these challenges, Sundargarh possesses substantial opportunities for further expansion of Tasar sericulture. The district's favourable ecological conditions, extensive host plant resources, well-established cooperative network, and sustained government support provide a strong foundation for future growth. Greater investment in scientific seed production, host plant improvement, digital extension services, mechanized post-cocoon processing, and market-oriented value addition can significantly enhance productivity and profitability. Operationalization of the Khuntgaon Tasar Silk Park, combined with strengthened research–extension linkages, farmer capacity building, and promotion of women- and youth-led enterprises, would facilitate the development of a more integrated Tasar value chain. Such measures would not only increase rural employment and household income but also reinforce the role of Tasar sericulture as a sustainable, environmentally compatible, and economically viable livelihood system in Odisha.

7. Conclusion

The present study demonstrates that Sundargarh district has developed into one of the most important centres of tropical Tasar sericulture in Odisha, supported by favourable agro-climatic conditions, extensive host plant resources, and a well-established cooperative network. The coordinated efforts of the Directorate of Sericulture, Government of Odisha, the Central Silk Board, and Primary Tasar Marketing Cooperative Societies have significantly strengthened the district's production system through scientific Disease-Free Laying (DFL) production, organized cocoon procurement, plantation expansion, and extension services. These interventions have generated sustainable livelihood opportunities for tribal and rural households while promoting the conservation and productive utilization of forest resources.

The analysis indicates that Tasar sericulture in Sundargarh has progressed beyond a traditional forest-based activity to become an important component of the district's rural economy. Expansion of Asan and Arjun plantations under MGNREGS convergence programmes, coupled with improved seed production and cooperative-based marketing, has enhanced production capacity and strengthened institutional support for Tasar rearers. These achievements demonstrate the potential of Tasar sericulture to contribute simultaneously to rural employment, income generation, ecological sustainability, and inclusive development.

However, several constraints continue to influence the long-term growth of the sector. Biological challenges such as Pebrine disease and gall-forming psyllid infestation, inadequate post-cocoon infrastructure, seasonal fluctuations in cocoon prices, and limited participation of rural youth remain significant concerns. In particular, the continued non-operational status of the Khuntgaon Tasar Silk Park restricts local value addition and limits opportunities for employment generation, entrepreneurship, and higher economic returns from silk processing. Addressing these issues will require coordinated efforts to strengthen scientific extension services, improve pest and disease management, enhance host plant productivity, ensure timely availability of quality DFLs, and establish efficient post-cocoon processing facilities.

Future development of Tasar sericulture in Sundargarh should focus on building an integrated and resilient value chain that extends beyond cocoon production to include processing, product diversification, branding, and market development. Greater participation of rural youth and women can be encouraged through entrepreneurship promotion, skill development programmes, digital extension platforms, and improved access to institutional

finance. Operationalization of the Khuntgaon Tasar Silk Park, modernization of cooperative marketing systems, and adoption of innovative production technologies would further strengthen the competitiveness of the district's Tasar industry.

Overall, Sundargarh possesses the ecological resources, institutional framework, and community participation necessary to emerge as a national model for sustainable tropical Tasar sericulture. Continued investment in scientific research, infrastructure development, capacity building, and evidence-based policy interventions will be essential for ensuring the long-term economic viability of the sector while improving the livelihoods of tribal communities and contributing to the broader objectives of sustainable rural development.

References

- Central Silk Board. (2024). *Annual Report 2023–24*. Ministry of Textiles, Government of India.
- Central Silk Board. (2024). *Tasar Silk: Production Technology and Development Programmes*. Bengaluru, India.
- Datta, R. K. (2007). Sericulture and rural development in India. *Indian Silk*, 46(3), 5–12.
- Directorate of Sericulture, Government of Odisha. (2026). *Annual Action Plan 2026–27*. Bhubaneswar.
- Directorate of Sericulture, Government of Odisha. (2025). *Plantation Programme under MGNREGS Convergence 2025–26*. Bhubaneswar.
- Ministry of Textiles, Government of India. (2024). *Annual Report 2023–24*. New Delhi.
- Central Tasar Research and Training Institute (CTR&TI). (2023). *Package of Practices for Tropical Tasar Sericulture*. Ranchi.
- District Statistical Handbook, Sundargarh. (Latest available edition). Directorate of Economics and Statistics, Government of Odisha.
- Office of the Assistant Director of Sericulture official data 2025-26.



Can Drones Deliver Biopesticides? The Next Step in Eco-Friendly Pest Management



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Introduction

Modern agriculture faces the difficult challenge of protecting crops from insect pests and diseases while reducing environmental risks and maintaining farm profitability. Chemical pesticides continue to play an important role in crop protection, but their repeated and inappropriate use can contribute to pesticide resistance, environmental contamination and adverse effects on non-target organisms. These concerns have increased interest in biological and other environmentally compatible approaches to crop protection.

Biopesticides derived from microorganisms, plants and naturally occurring materials are increasingly recognized as important components of sustainable pest management. Microbial agents include bacteria, fungi and viruses capable of suppressing particular insect pests or plant pathogens. Their use can complement cultural, mechanical and chemical approaches within Integrated Pest Management (IPM) programmes (Marrone, 2019). However, the effectiveness of a biopesticide depends not only on the biological agent but also on formulation quality, application timing, environmental conditions and successful delivery to the target.

This is where agricultural drones could provide an important technological advantage. UAV-based spraying systems can apply crop protection products without requiring workers to move through standing crops. They can also operate with relatively low spray volumes and follow predetermined flight paths. However, successful UAV application depends strongly on flight height, speed, nozzle characteristics, droplet spectrum, spray volume and rotor-generated airflow (Chen *et al.*, 2021). The important question, therefore, is not simply whether a drone can spray a biopesticide. The more relevant question is whether a particular biopesticide formulation can be delivered through a particular UAV system while maintaining adequate biological activity and achieving effective deposition on the intended target.

Why Are Biopesticides Gaining Importance?

Biopesticides are receiving increasing attention because they can contribute to pest suppression while fitting into environmentally responsible IPM programmes. Their diverse modes of action and, in many cases, greater target specificity can help reduce dependence on broad-spectrum chemical insecticides.

Important microbial biopesticide groups include entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae*, bacterial agents such as *Bacillus thuringiensis* and baculoviruses used against specific insect pests. However, these organisms are biological entities and their performance can be strongly influenced by environmental conditions.

For example, fungal spores require suitable conditions for germination and infection, while ultraviolet radiation, temperature, humidity and rainfall can influence their persistence in the field. Similarly, bacterial and viral products require appropriate formulation and application conditions to achieve effective exposure of the target pest.

Consequently, the benefits of biopesticides can be realized only when the product is used according to its approved label, formulation requirements and recommended application conditions. Biopesticides should not be considered universally interchangeable with conventional insecticides in a drone spray tank.

Drones: A New Platform for Biopesticide Delivery

Conventional spraying can become difficult when crops are tall, fields are wet, terrain is uneven or sufficient labour is unavailable at the required time. Agricultural drones can overcome some of these operational limitations because they can fly over standing crops without physically entering the field.

UAVs can also provide precise control over flight paths and spray parameters. Their potential for precision pest management is particularly valuable because insect pest populations are often unevenly distributed within fields. Early detection followed by targeted intervention can improve the efficiency of pest management (Iost Filho *et al.*, 2020). However, drones should not automatically be assumed to reduce pesticide use in every situation. Their environmental and economic benefits depend on appropriate calibration, spray management and correct targeting. Chen *et al.* (2021) emphasized the importance of downwash airflow, atomization, operating parameters and drift management in UAV-based spraying.

How Does Drone-Based Biopesticide Application Work?

Successful drone application begins with pest monitoring. The farmer or field scout should first identify the pest and determine whether intervention is required. The appropriate registered biopesticide formulation is then selected for the specific crop and target pest.

Before spraying, the UAV should be calibrated for:

- Tank capacity,
- Nozzle discharge,
- Flight speed,
- Flight height,
- Swath width,
- Spray volume and
- Spray pattern.

The spray system must also be checked for compatibility with the selected formulation. During operation, the UAV moves over the crop while rotor-generated downwash interacts with the spray droplets and plant canopy. This airflow can influence droplet movement and deposition. Therefore, changes in flight height, speed and nozzle configuration can alter spray coverage (Chen *et al.*, 2021). Post-application monitoring is equally important. Pest mortality, disease suppression and crop response should be evaluated to determine whether the application was successful.

Which Biopesticides Can Be Used Through Drones?

This is an area where caution is particularly important.

Several microbial biopesticide groups have potential for UAV application, but potential does not mean that every commercial formulation is automatically suitable for drone spraying.

Bacillus thuringiensis

Bt-based products are widely used against susceptible insect larvae. Because the toxin generally needs to be ingested by susceptible larvae, adequate deposition on the plant surfaces where larvae feed is important.

Beauveria bassiana

B. bassiana is an entomopathogenic fungus that infects insects through their cuticle. Its successful field performance depends on spore viability, formulation, humidity, temperature, ultraviolet exposure and adequate contact with the target insect.

Metarhizium anisopliae

M. anisopliae is another important entomopathogenic fungus with potential against several insect pests. However, drone-based use should be based on validated formulations and application protocols rather than assuming that all available products are suitable.

Baculoviruses

Baculoviruses can provide highly specific control of certain caterpillar pests. Their use through UAVs requires particular attention to formulation stability, droplet deposition, environmental exposure and the susceptibility of the target pest stage.

Botanical Biopesticides

Botanical products and oil-based formulations may also have potential for UAV application. Their suitability depends on formulation properties, droplet behaviour, crop safety and approved application recommendations.

Thus, the correct principle is:

Biopesticide + compatible formulation + calibrated UAV + suitable weather + correct target = successful drone application.

India Moves Towards Drone-Based Biopesticide Application

India is beginning to generate practical experience in this field. ICAR-National Bureau of Agricultural Insect Resources (ICAR-NBAIR), Bengaluru, has been working on precise delivery mechanisms for biopesticides through agricultural drones and on developing Standard Operating Procedures for their application.

In 2024, ICAR-NBAIR reported approximately 15 biopesticide-spraying demonstrations using oil-based formulations in crops including coconut, brinjal, mango, sugarcane, arecanut and rice in Karnataka and Tamil Nadu. The programme also emphasized the development of SOPs involving dosage, efficacy, drift effects and particle size. Further ICAR-NBAIR demonstrations involving oil-based formulations were conducted in crops including turmeric, tomato, banana, cabbage, sugarcane, avocado, coconut, potato and maize across Karnataka.

The demonstrations were intended to generate farmer awareness and promote agricultural drone technology for crop protection. These initiatives are particularly important because UAV application cannot simply be copied from one crop to another. Crop canopy, target pest location, formulation, weather and UAV characteristics can vary considerably.

The Critical Role of Formulation

Formulation may be the most important link between the biological agent and the drone. A microbial biopesticide may contain viable spores, bacterial cells or viral particles. These biological components must remain sufficiently viable during storage, preparation and application. Unsuitable water quality, excessive heat, incompatible tank mixtures or inappropriate handling can reduce biological performance.

The formulation must also be compatible with the UAV spray system. Problems such as nozzle clogging, inadequate agitation or poor atomization can result in uneven application. Therefore, a product should be considered for drone application only after its formulation and application method have been appropriately evaluated.

Getting the Droplets Right

Spray droplets determine how much of the applied product reaches the crop. Very large droplets may provide inadequate coverage, whereas excessively fine droplets may be more susceptible to drift. The appropriate droplet spectrum depends on the crop, target pest, canopy structure, formulation and environmental conditions.

UAV rotor downwash adds another dimension because airflow generated by the rotors can influence droplet trajectories and canopy penetration. Research on UAV spraying has emphasized the importance of understanding the interaction between downwash airflow and spray droplets (Chen *et al.*, 2021). Therefore, increasing spray volume alone does not necessarily guarantee better pest control. The objective should be sufficient deposition on the target with minimum drift and off-target movement.

Weather Matters

Environmental conditions are especially important for biological products. Temperature, relative humidity, sunlight, rainfall and wind can influence the survival and effectiveness of microbial agents. Entomopathogenic fungi, for example, require suitable environmental conditions for successful infection, while intense sunlight can reduce persistence of some biological agents.

Consequently, drone-based biopesticide spraying should be scheduled according to the biological requirements of the product and local weather conditions rather than following a fixed calendar.

Advantages for Farmers

When properly standardized, drone-based biopesticide application can provide several advantages:

- Rapid treatment of large areas,
- Reduced need for workers to enter standing crops,
- Access to wet, uneven or difficult terrain,
- Controlled flight paths,
- Reduced water requirements in suitable low-volume applications,
- Timely treatment during critical pest stages, and
- Potential integration with digital pest monitoring.

ICAR-NBAIR has highlighted the potential of drone spraying to improve application efficiency and provide more convenient crop protection, particularly in tall crops and difficult-to-access production systems.

But Drones Are Not a Magic Solution

The adoption of UAVs should not create the impression that every drone application will automatically be more effective than conventional spraying. Poor calibration, unsuitable nozzle selection, excessive wind, inappropriate flight height or insufficient spray coverage can result in inadequate pest control. In the case of bio pesticides, poor formulation compatibility or loss of biological viability can further reduce performance.

Dense crop canopies can also limit deposition on target plant parts. Therefore, crop-specific testing is essential. Economic considerations are also important. Purchasing and maintaining a drone may not be feasible for every farmer. Custom hiring centres, Farmer Producer Organizations, cooperatives and trained service providers could make the technology more accessible. Operator training is equally important. A trained operator must understand UAV flight operations as well as spray calibration, formulation handling, weather conditions, drift management and relevant regulatory requirements.

From Drone Spraying to Smart Biological Pest Management

The greatest opportunity may arise when drone spraying is integrated with pest surveillance. Imagine a field where a monitoring drone identifies areas with high pest pressure using cameras or other sensors. Instead of treating the entire field uniformly, pest hotspots could be identified and management decisions made according to the observed pest distribution.

Digital agriculture can support IPM through improved monitoring, early detection and more targeted interventions (Iost Filho *et al.*, 2022). The future could therefore follow a simple sequence:

Monitor → Identify → Decide → Precisely Treat → Evaluate

Such an approach could shift crop protection from routine calendar-based spraying towards need-based and precision pest management.

What Farmers Should Remember

Before using a biopesticide through a drone, farmers and service providers should ask five questions:

1. Is the product registered and recommended for the particular crop and target pest?
2. Is the specific formulation validated for UAV application?
3. Has the UAV been properly calibrated for the required spray volume and nozzle output?
4. Are weather conditions suitable for the biological product and spraying operation?
5. Is the application being conducted according to approved recommendations and SOPs?

If the answer to these questions is yes, drone application can become a valuable component of an integrated pest management programme.

Future Prospects

The future of drone-based biological pest management will depend on the integration of several technologies. UAVs could increasingly be combined with remote sensing, artificial intelligence, pest forecasting and digital decision-support systems.

Instead of spraying an entire field simply because a pest is present, future systems may identify where the pest is concentrated and recommend when and where treatment is necessary. The drone could then deliver a validated biological formulation precisely to the required area.

Such integration could reduce unnecessary pesticide applications while improving the efficiency of biological control. However, these systems will require field validation, reliable sensors, crop-specific algorithms and scientifically established application protocols.

Conclusion

Drones and biopesticides represent two promising components of sustainable agriculture. Their combination could provide farmers with a more precise and environmentally responsible approach to crop protection. However, successful drone-based biopesticide application requires much more than putting a biological product into a UAV spray tank. The specific formulation, biological viability, nozzle, droplet characteristics, spray volume, flight height, flight speed, crop canopy and weather conditions must all be considered.

Most importantly, not every formulation of *Beauveria bassiana*, *Metarhizium anisopliae*, *Bacillus thuringiensis* or baculovirus should be assumed to be suitable for UAV application. Only products and formulations that are appropriately registered, compatible with the spray system and supported by application validation should be used through drones.

India's work through ICAR-NBAIR demonstrates that this field is moving from concept towards practical application, particularly through demonstrations using oil-based biopesticide formulations and efforts to develop crop-specific SOPs. The future of crop protection may therefore not be a choice between biology and technology. It may be the intelligent combination of both—using the biological potential of validated biopesticides and the precision of UAVs to deliver the right product, at the right place and at the right time.

References

- Chen, H., Lan, Y., Fritz, B.K., Hoffmann, W.C. and Liu, S. (2021). Review of agricultural spraying technologies for plant protection using unmanned aerial vehicle (UAV). *International Journal of Agricultural and Biological Engineering*, 14(1): 38–49.
- ICAR-NBAIR (2024). ICAR-NBAIR demonstrates utility of agri-drone in crop protection. ICAR-National Bureau of Agricultural Insect Resources, Bengaluru, India.
- Iost Filho, F.H., Heldens, W.B., Kong, Z. and de Lange, E.S. (2020). Drones: Innovative technology for use in precision pest management. *Journal of Economic Entomology*, 113(1): 1–10.
- Iost Filho, F.H., Pazini, J.B., Alves, T.M., Koch, R.L. and Yamamoto, P.T. (2022). How does the digital transformation of agriculture affect the implementation of Integrated Pest Management? *Frontiers in Sustainable Food Systems*, 6: 972213.
- Marrone P. G. (2019). Pesticidal natural products—status and future potential. *Pest Management Science*, 75(9): 2325–2340.

Cybersecurity in Agricultural Drones: Protecting Smart Farming Technologies



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Abstract

Agricultural drones, also known as Unmanned Aerial Vehicles (UAVs), are transforming modern farming by enabling precision pesticide application, crop health monitoring, nutrient management, irrigation assessment, and field surveillance. Their ability to improve operational efficiency, reduce input costs, and support precision agriculture has led to rapid adoption worldwide. However, increasing reliance on digital technologies has exposed agricultural drones to various cybersecurity threats, including GPS spoofing, signal interference, unauthorized access, malware attacks, data theft, and communication hijacking. These cyber threats can compromise flight safety, disrupt farming operations, damage crops, and expose sensitive farm data. As smart farming becomes increasingly dependent on connected devices, ensuring the security of UAV systems has become essential. Effective cybersecurity measures such as encrypted communication, secure authentication, regular software updates, geofencing, operator training, and adherence to regulatory guidelines can significantly reduce these risks. Integrating cybersecurity into agricultural drone operations will safeguard digital farming technologies, enhance farmer confidence, and promote sustainable adoption of precision agriculture. This article discusses the importance of cybersecurity in agricultural drones, common cyber threats, preventive strategies, and future directions for secure and resilient smart farming.

Keywords: Agricultural drones, Cybersecurity, Precision agriculture, UAV, GPS spoofing, Data security, Smart farming, Digital agriculture

Introduction

Agriculture is undergoing a digital transformation through the adoption of precision farming technologies. Agricultural drones (Unmanned Aerial Vehicles or UAVs) have become valuable tools for crop monitoring, pesticide spraying, fertilizer application, irrigation assessment, and field mapping. These technologies help farmers make informed decisions, improve crop productivity, reduce labour requirements, and optimize the use of agricultural inputs.

Modern agricultural drones are equipped with advanced technologies such as Global Positioning System (GPS), Geographic Information System (GIS), cameras, multispectral sensors, artificial intelligence (AI), cloud computing, and wireless communication systems. While these innovations greatly enhance farming efficiency, they also expose drone operations to cyber risks. Cybersecurity has therefore emerged as an important aspect of digital agriculture, ensuring that drones operate safely, securely, and reliably.

Why Cybersecurity Matters in Agricultural Drones

Agricultural drones continuously collect and transmit valuable information, including:

- Crop health data
- Soil moisture information
- GPS coordinates
- Farm boundaries
- Yield estimates

- Pest and disease occurrence
- Spray operation records

This information is valuable for farm management but can become vulnerable if proper cybersecurity measures are not implemented. Unauthorized access or cyberattacks can interrupt drone operations, compromise sensitive farm data, and cause financial losses.

Major Cybersecurity Threats

1. GPS Spoofing

GPS spoofing occurs when attackers transmit false GPS signals, causing the drone to misidentify its location. As a result, the drone may deviate from its planned flight path, spray the wrong field, or even crash.

Possible impacts:

- Incorrect pesticide application
- Crop damage
- Flight accidents
- Reduced operational efficiency

2. Signal Jamming

Signal jamming blocks communication between the drone and its remote controller.

Effects include:

- Loss of drone control
- Mission interruption
- Emergency landing
- Damage to equipment

3. Unauthorized Access

Hackers may gain access to drone control systems through weak passwords or unsecured wireless networks.

Unauthorized access can allow attackers to:

- Control drone movements
- Change flight plans
- Disable safety features
- Access confidential farm information

4. Malware Attacks

Malicious software may infect drone operating systems or ground control stations.

Malware can:

- Corrupt flight software
- Slow drone performance
- Steal operational data
- Cause unexpected system failures

5. Data Theft

Agricultural drones generate large amounts of digital information that are often stored in cloud platforms.

Stolen data may include:

- Farm production records
- Crop health maps
- Land ownership information
- Precision agriculture recommendations

Loss of such information may affect farm competitiveness and privacy.

6. Communication Hijacking

Wireless communication links between drones and controllers can be intercepted if not properly encrypted.

Consequences include:

- Altered flight commands
- Mission failure

- Unauthorized surveillance
- Loss of operational control

Consequences of Cyber Attacks

Cyberattacks on agricultural drones may result in:

- Crop losses
- Incorrect pesticide spraying
- Reduced crop productivity
- Financial losses
- Equipment damage
- Exposure of confidential farm information
- Reduced confidence in digital farming technologies

For commercial farms and service providers, repeated cyber incidents may also damage reputation and disrupt agricultural operations.

Best Practices for Protecting Agricultural Drones

Use Strong Authentication

Protect drone software and mobile applications with strong passwords and multi-factor authentication whenever available.

Regular Software Updates

Install firmware and software updates released by manufacturers to fix security vulnerabilities and improve system performance.

Encrypted Communication

Use secure communication protocols to protect data transmitted between drones, controllers, and cloud platforms from unauthorized interception.

Secure GPS Systems

Use drones equipped with advanced navigation systems capable of detecting abnormal GPS signals and switching to backup positioning methods when necessary.

Geofencing

Enable geofencing features to prevent drones from entering restricted or unsafe areas and reduce risks associated with navigation errors.

Protect Ground Control Stations

Computers, tablets, and smartphones used to operate drones should be protected with antivirus software, firewalls, and secure operating systems.

Farmer and Operator Training

Drone operators should receive training on:

- Cybersecurity awareness
- Safe password management
- Identifying suspicious activities
- Secure data handling
- Emergency response procedures

Data Backup

Important flight records and farm data should be backed up regularly using secure storage systems to minimize losses in the event of cyber incidents.

Role of Artificial Intelligence

Artificial Intelligence (AI) is playing an increasing role in improving drone cybersecurity by:

- Detecting abnormal flight behaviour
- Identifying attempted cyber intrusions
- Monitoring communication networks
- Supporting automated threat detection

- Improving real-time decision-making

AI-based cybersecurity systems can rapidly recognize unusual drone activities and help prevent unauthorized access before damage occurs.

Government Initiatives

Governments worldwide are promoting secure drone operations through:

- Drone registration systems
- Aviation safety regulations
- Digital identity verification
- Standard Operating Procedures (SOPs)
- Pilot certification
- Data protection guidelines

In India, the **Drone Rules, 2021** and the **Standard Operating Procedures for Agricultural Drones** issued by the Ministry of Agriculture and Farmers Welfare encourage the safe and responsible use of drones in agriculture.

Future Prospects

Future agricultural drones are expected to incorporate:

- Blockchain-based data security
- Artificial intelligence-driven threat detection
- Secure cloud computing
- Quantum-resistant encryption
- Autonomous cybersecurity monitoring
- Advanced anti-spoofing navigation systems

These innovations will improve the reliability and resilience of smart farming technologies.

Benefits of Secure Drone Operations

Implementing cybersecurity measures provides several advantages:

- Safe drone operations
- Protection of valuable farm data
- Improved farmer confidence
- Reliable precision agriculture
- Reduced operational risks
- Enhanced crop productivity
- Better regulatory compliance
- Long-term sustainability of digital farming

Conclusion

Agricultural drones have become indispensable tools in precision farming, offering significant improvements in crop monitoring, pesticide application, and resource management. However, their increasing dependence on digital communication, GPS navigation, cloud platforms, and artificial intelligence has introduced new cybersecurity challenges. Threats such as GPS spoofing, signal jamming, unauthorized access, malware, and data theft can compromise both drone operations and farm productivity. By adopting robust cybersecurity practices—including encrypted communication, strong authentication, regular software updates, secure data management, and operator training—farmers and service providers can substantially reduce cyber risks. As agriculture continues to embrace digital transformation, integrating cybersecurity into drone operations will be essential for ensuring safe, resilient, and sustainable smart farming systems.

References

FAO. 2022. *The State of Food and Agriculture 2022: Leveraging Automation in Agriculture for Transforming Agrifood Systems*. Food and Agriculture Organization of the United Nations, Rome.

Ministry of Agriculture and Farmers Welfare. 2022. *Standard Operating Procedures (SOPs) for Use of Agricultural Drones*. Government of India, New Delhi.

Ministry of Civil Aviation. 2021. *Drone Rules, 2021*. Government of India, New Delhi.

NIST. 2024. *Cybersecurity Framework (CSF) 2.0*. National Institute of Standards and Technology, USA.

Sharma, A., Singh, V. and Kumar, R. 2023. Cybersecurity challenges and emerging solutions in agricultural drone systems. *Computers and Electronics in Agriculture*, 208: 107789.

Wolfert, S., Ge, L., Verdouw, C. and Bogaardt, M.J. 2017. Big data in smart farming: A review. *Agricultural Systems*, 153: 69–80.



Natural Enemies in Agriculture: Conserving Biodiversity for Sustainable Pest Control



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Abstract

Modern agriculture has significantly increased crop production, but excessive dependence on chemical pesticides has led to environmental pollution, pesticide resistance, pest resurgence, and the decline of beneficial organisms. Natural enemies, including predators, parasitoids, and entomopathogenic microorganisms, play a vital role in suppressing insect pest populations and maintaining ecological balance in agricultural ecosystems. These beneficial organisms provide an eco-friendly, cost-effective, and sustainable alternative to indiscriminate pesticide use by naturally regulating pest populations. Conservation of natural enemies through habitat management, reduced pesticide application, flowering refuges, and adoption of Integrated Pest Management (IPM) practices can substantially enhance biological pest control while preserving biodiversity. Farmers can improve crop productivity and reduce production costs by promoting the activity of beneficial insects such as ladybird beetles, lacewings, spiders, dragonflies, praying mantids, hoverflies, and parasitoid wasps. Recent advances in precision agriculture, including drone-assisted pesticide application, selective insecticides, and decision-support technologies, further contribute to the conservation of natural enemies by minimizing non-target impacts. Promoting biodiversity in agricultural landscapes not only strengthens ecosystem resilience but also ensures long-term food security and environmental sustainability. This article highlights the importance of natural enemies, their role in sustainable pest management, conservation strategies, and their contribution to climate-smart agriculture.

Keywords: Natural enemies, Biological control, Biodiversity, Integrated Pest Management, Predators, Parasitoids

Introduction

Agriculture is the backbone of food production, but crops are constantly threatened by a wide range of insect pests that reduce yield and quality. Traditionally, farmers have relied heavily on chemical pesticides for pest control. Although pesticides provide rapid control, their indiscriminate and repeated use has created several problems, including pesticide resistance, resurgence of secondary pests, destruction of beneficial organisms, contamination of soil and water, and risks to human and animal health. Therefore, sustainable crop protection strategies that reduce dependence on synthetic pesticides have become increasingly important.

Nature itself provides an effective pest management system through natural enemies. These beneficial organisms help maintain ecological balance by feeding on or parasitizing insect pests. Conserving these organisms is one of the most economical and environmentally friendly approaches to sustainable agriculture.

Who are Natural Enemies?

Natural enemies are beneficial organisms that naturally suppress pest populations without causing harm to crops. They are broadly classified into three major groups:

1. Predators

Predators consume several prey individuals during their lifetime. Both immature and adult stages of many predators actively feed on insect pests.

Common agricultural predators include:

- Ladybird beetles (*Coccinellidae*)

- Green lacewings (*Chrysoperla* spp.)
- Spiders
- Dragonflies
- Damselflies
- Predatory bugs
- Ground beetles
- Praying mantids
- Hoverfly larvae

These predators effectively control aphids, whiteflies, thrips, mealybugs, caterpillars, mites, and other soft-bodied insects.

2. Parasitoids

Parasitoids are insects that lay eggs inside or on the bodies of insect pests. The developing larvae feed on the host internally, eventually killing it.

Important parasitoids include:

- *Trichogramma* spp.
- *Telenomus* spp.
- *Bracon* spp.
- *Chelonus* spp.
- *Cotesia* spp.

Parasitoids are widely used in biological control programmes against stem borers, fruit borers, and lepidopteran pests.

3. Entomopathogenic Microorganisms

Certain microorganisms naturally infect and kill insect pests.

Examples include:

- *Beauveria bassiana*
- *Metarhizium anisopliae*
- *Bacillus thuringiensis* (Bt)
- Nuclear Polyhedrosis Virus (NPV)

These microbial agents are environmentally safe and compatible with Integrated Pest Management (IPM).

Importance of Natural Enemies

Natural enemies provide numerous ecological and economic benefits.

Natural Pest Suppression

Beneficial organisms continuously regulate pest populations, reducing the chances of severe outbreaks.

Reduced Pesticide Use

Effective biological control minimizes the need for repeated insecticide applications, lowering production costs.

Delay in Resistance Development

Unlike chemical pesticides, biological control agents reduce the risk of pests developing resistance.

Environmental Protection

Conservation of beneficial organisms reduces pesticide contamination of soil, water, and air while protecting biodiversity.

Improved Crop Productivity

Healthy populations of natural enemies contribute to better crop health and stable yields through long-term pest regulation.

Major Beneficial Insects in Different Crops

Crop	Major Pest	Important Natural Enemy
Maize	Fall armyworm	<i>Telenomus remus</i> , <i>Trichogramma</i> spp., spiders
Rice	Stem borer	<i>Trichogramma japonicum</i>
Cotton	Aphids	Ladybird beetles, lacewings
Cotton	Whitefly	Predatory bugs, spiders
Groundnut	Leaf miner	Parasitoid wasps
Vegetables	Fruit borer	<i>Trichogramma</i> spp., <i>Bracon</i> spp.

Threats to Natural Enemies

Despite their importance, beneficial organisms face several threats:

- Excessive use of broad-spectrum insecticides
- Indiscriminate pesticide mixtures
- Habitat destruction
- Monocropping
- Removal of flowering plants
- Climate change
- Environmental pollution

These factors reduce biodiversity and weaken natural pest regulation.

Strategies for Conserving Natural Enemies

Use Selective Insecticides

Prefer insecticides that are less harmful to beneficial insects and apply them only when pest populations exceed economic threshold levels.

Adopt Integrated Pest Management (IPM)

Combine cultural, mechanical, biological, and chemical methods to achieve sustainable pest management.

Maintain Flowering Plants

Growing flowering species such as marigold, sunflower, sesame, coriander, fennel, and buckwheat along field borders provides nectar and pollen for parasitoids and predators.

Reduce Unnecessary Spraying

Avoid routine pesticide applications. Spray only when pest monitoring indicates a need.

Use Biological Control Agents

Release parasitoids such as *Trichogramma* and apply microbial biopesticides when appropriate.

Maintain Field Biodiversity

Preserve hedgerows, grassy strips, and refuge areas to provide shelter and alternative food sources for beneficial organisms.

Role of Precision Agriculture

Modern technologies are improving the conservation of natural enemies.

- Drone-based pesticide application enables precise and uniform spraying.
- GPS-guided application reduces off-target drift.
- Selective spraying minimizes exposure of beneficial organisms.
- Digital pest monitoring helps avoid unnecessary pesticide applications.
- Artificial intelligence and remote sensing assist in early pest detection and decision-making.

These innovations support environmentally responsible crop protection.

Benefits to Farmers

Conserving natural enemies offers several advantages:

- Lower pesticide expenditure
- Reduced labour requirements
- Sustainable pest management
- Improved crop yield and quality
- Enhanced biodiversity
- Better soil and environmental health
- Safer food production
- Increased farm profitability

Future Perspectives

Sustainable agriculture will increasingly depend on biodiversity-based pest management. Future research should focus on developing natural enemy-friendly pesticides, expanding biological control programmes, integrating

precision agriculture technologies, and promoting farmer awareness about biodiversity conservation. Government support, extension services, and farmer participation will be essential for large-scale adoption of these practices.

Conclusion

Natural enemies are invaluable allies in agriculture, providing effective and environmentally friendly control of insect pests while reducing dependence on chemical pesticides. Their conservation through habitat management, selective pesticide use, biological control, and integrated pest management enhances biodiversity, safeguards ecosystem health, and supports sustainable crop production. By protecting these beneficial organisms and embracing modern precision agriculture technologies, farmers can achieve higher productivity, lower production costs, and long-term agricultural sustainability. Conserving biodiversity is therefore not only an ecological necessity but also a practical strategy for ensuring food security and resilient farming systems.

References

FAO. 2022. *The State of Food and Agriculture 2022: Leveraging Automation in Agriculture for Transforming Agrifood Systems*. Food and Agriculture Organization of the United Nations, Rome.

ICAR-National Bureau of Agricultural Insect Resources (NBAIR). 2023. *Biological Control of Crop Pests*. Bengaluru, India.

Ministry of Agriculture and Farmers Welfare. 2022. *Standard Operating Procedures (SOPs) for Use of Agricultural Drones*. Government of India, New Delhi.

Pedigo, L.P. and Rice, M.E. 2014. *Entomology and Pest Management*. 6th Edition. Waveland Press, Illinois.

Van Lenteren, J. C. (2012). The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake. *BioControl*, 57(1): 1-20.



Soil-Health Products and Services as Business Opportunities



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“The future of agriculture depends not only on what we grow, but on how wisely we invest in the soil that grows it.”

Soil is often considered simply the medium in which crops grow. In reality, it is one of agriculture’s most valuable productive assets. It supplies nutrients, stores water, supports microorganisms and determines how efficiently crops use fertilizers and other inputs.

Today, declining soil organic matter, nutrient imbalance, salinity, acidity, compaction and inefficient fertilizer use are emerging challenges for agriculture. But every challenge also creates a demand for solutions. This opens an emerging field of opportunity: **the soil-health economy**.

The opportunity is not simply to sell another agricultural input. It is to **identify a soil problem, provide a scientifically sound solution and demonstrate its economic value to the farmer.**

Soil-Health Products & Services as Business Opportunities

Healthy Soil • Healthy Crops • Profitable Farming



From Soil Problems to Business Opportunities

Consider a farmer whose crop yield is declining despite regular fertilizer application. The problem may not necessarily be a lack of fertilizer. It could be poor soil organic matter, nutrient imbalance, salinity, micronutrient deficiency or poor physical condition.

This creates the first opportunity: **soil diagnosis**.

A modern soil-health enterprise can provide soil sampling, laboratory testing, interpretation of results and crop-specific recommendations. The value lies not merely in producing a soil-test report, but in converting that report into a **practical farm decision**.

The business model can therefore evolve from:

Soil testing → Diagnosis → Recommendation → Follow-up monitoring

Such services can be offered to individual farmers, Farmer Producer Organisations (FPOs), plantations, nurseries and commercial farms.

Turning Agricultural Waste into Soil Wealth

Agricultural waste is another promising business opportunity. Crop residues, animal manure, poultry litter and other organic wastes can be converted into **compost, vermicompost, biochar and other soil amendments**.

The business model is simple:

Waste → Processing → Quality product → Soil application → Agricultural value

Instead of treating agricultural residues as waste, entrepreneurs can turn them into standardized agricultural inputs. However, quality is critical. A successful soil amendment business should focus on **consistent composition, nutrient content, maturity, safety and demonstrated field performance**, rather than relying only on labels such as “organic” or “natural.”

Thus, the opportunity is not merely to sell compost; it is to **convert waste into a reliable and value-added soil product**.

Biological Products: Working with the Living Soil

Soil is a living ecosystem. Its microorganisms play important roles in nutrient cycling and plant growth. This creates opportunities for **biofertilizers and microbial products**, including nitrogen-fixing organisms, phosphate-solubilizing microorganisms, potassium-solubilizing microorganisms and mycorrhizal inoculants.

The future opportunity lies in developing products with:

- Good formulation stability
- Adequate shelf life
- Effective application methods
- Compatibility with farm inputs
- Consistent field performance

The market should gradually move from simply selling a “microbial product” to providing a **reliable biological solution with measurable benefits**.

Precision Soil Management: Selling Knowledge and Data

Agriculture is becoming increasingly data-driven, and soil management is no exception.

GPS-based soil sampling, GIS mapping, remote sensing, drones and digital platforms can identify differences in soil fertility within the same farm. This creates opportunities for:

- Soil fertility mapping
- Precision soil sampling
- Variable-rate fertilizer recommendations
- Digital soil-health records
- Farm-specific nutrient-management plans

Here, the entrepreneur may not need to manufacture a physical product. **Data, interpretation and decision support themselves become the product**.

A service provider could, for example, work with an FPO to collect soil samples from member farms, prepare fertility maps and provide customized nutrient recommendations.

Specialized Products for Specific Soil Problems

A strong soil-health business should begin with a clearly defined problem (Stephen *et al.*, 2024).

Soil challenge	Potential business opportunity
Low organic carbon	Compost, biochar and organic amendments
Soil acidity	Liming materials and reclamation services
Sodicity	Gypsum and reclamation management
Micronutrient deficiency	Customized micronutrient products
Nutrient losses	Enhanced-efficiency fertilizers
Salinity	Soil diagnosis and reclamation services
Poor soil physical condition	Soil assessment and management services

The business question therefore changes from:

“What product can I sell?”

to:

“What soil problem can I solve?”

That shift is important for building a sustainable agricultural enterprise.

Soil Health as a Service

One of the most promising models is to move from **one-time product sales to continuous soil-health services**.

For example, an entrepreneur could offer an annual package:

Soil testing + fertilizer recommendation + amendment recommendation + seasonal monitoring

This creates recurring value for both the farmer and the service provider.

A farmer may not need another product every season, but the farmer will always need to make decisions about **nutrients, soil condition, crop requirements and input costs**.

This makes knowledge-based soil services a potentially strong business model.

Soil Carbon: An Emerging Opportunity

Soil organic carbon is important for soil quality and is also receiving increasing attention in climate-smart agriculture (Gurau *et al.*, 2025).

Practices such as residue retention, cover crops, reduced tillage, organic matter addition and agroforestry can contribute to carbon storage in agricultural systems.

This creates emerging opportunities in:

- Soil-carbon assessment
- Carbon monitoring
- Carbon-project development
- Verification and reporting
- Carbon-farming advisory services

However, carbon-related income should not be presented as guaranteed. Credible measurement, verification and appropriate carbon accounting are essential for a trustworthy business.

The Farmer's Profit Must Come First

A soil-health enterprise will ultimately succeed only when it creates **economic value for the farmer**.

Suppose a farmer spends ₹5,000 on a soil-health intervention. The important question is not simply whether the product contains advanced ingredients.

The real question is:

“What did the farmer gain from spending ₹5,000?”

The benefit may come through:

- Reduced fertilizer expenditure
- Better nutrient-use efficiency
- Improved water-use efficiency
- Higher yield or quality
- Reduced crop losses
- Lower long-term soil-reclamation costs

Therefore, **return on investment (ROI)** should become an important part of soil-health businesses.

A product that costs ₹1,000 but saves ₹2,000 through improved input efficiency may provide greater value than a cheaper product with no measurable benefit.

From Selling Products to Solving Problems

The future soil-health business model can be represented simply:

Problem → Diagnosis → Solution → Monitoring → Measurable benefit

For example:

Low organic carbon → Soil testing → Organic amendment → Follow-up assessment

or

Nutrient imbalance → Soil diagnosis → Customized fertilizer recommendation → Improved nutrient-use efficiency

This approach creates a stronger relationship between the farmer and the service provider while encouraging evidence-based agricultural practices.

Opportunities for Young Entrepreneurs

Soil-health entrepreneurship does not always require a large manufacturing facility. Young agricultural graduates and entrepreneurs can explore relatively low-investment service models such as:

- Soil sampling and testing
- Soil-health consultancy
- Compost and vermicompost production
- Agricultural-waste processing
- Bio-input services
- Precision soil mapping
- Digital nutrient advisory
- Soil-health monitoring

A particularly promising model is to combine **soil science, digital technology and local agricultural knowledge**. For example, an entrepreneur could partner with an FPO, provide soil testing for its members, develop field-specific nutrient recommendations and offer seasonal monitoring as a paid service.

The Road Ahead

The soil-health market is likely to become increasingly connected with **precision agriculture, biological inputs, circular economy, climate-smart agriculture and digital advisory services**.

But one principle should remain central:

A soil-health business should not create a new problem while claiming to solve an old one.

Unscientific claims, poor-quality products and exaggerated yield promises may generate short-term sales, but they cannot create a sustainable business.

The strongest enterprises will combine three elements:

Scientific credibility + Farmer affordability + Measurable benefit

The future entrepreneur should therefore ask not merely:

“What can I sell to farmers?”

but:

“What soil problem can I solve, how much value can I create, and can I prove it?”

That is where **soil science meets entrepreneurship**.

Conclusion

Soil is more than the ground beneath our feet. It is a **productive asset, a biological resource and the economic foundation of agriculture**.

As soil-related challenges increase, the demand for reliable diagnosis, efficient inputs, customized management and measurable soil-health improvement will also grow.

The opportunity is clear:

“Don’t just look at soil as something beneath your feet. Look at it as an opportunity beneath your business.”

References

Stephen, G. S., Shitindi, M. J., Bura, M. D., Kahangwa, C. A., & Nassary, E. K. (2024). Harnessing the potential of sugarcane-based liquid byproducts—molasses and spentwash (vinasse) for enhanced soil health and environmental quality. A systematic review. *Frontiers in Agronomy*, 6, 1358076.

Gurau, S., Imran, M., & Ray, R. L. (2025). Algae: A cutting-edge solution for enhancing soil health and accelerating carbon sequestration—A review. *Environmental Technology & Innovation*, 37, 103980.

“Paper Wasps: Nature’s Tiny Warriors for Sustainable Agriculture”



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Abstract

Paper wasps (*Polistes spp.*) are among nature’s most efficient yet underappreciated allies in sustainable agriculture. Beyond their reputation as stinging insects, these social wasps play dual ecological roles as natural pest managers and incidental pollinators. They actively prey on crop-damaging insects such as caterpillars, aphids and leaf miners, thereby reducing the need for chemical pesticides and supporting Integrated Pest Management (IPM) strategies. In addition, as they visit flowers in search of nectar, paper wasps aid in pollination, contributing to improved crop productivity and biodiversity. Their presence enhances ecological balance and reduces environmental impact, aligning with the goals of low-input, eco-friendly farming. Encouraging paper wasp populations through habitat conservation and reduced pesticide use can help transform farmlands into more resilient, self-sustaining ecosystems. This article highlights the ecological importance, behavioral traits and agricultural benefits of paper wasps, showcasing how these tiny warriors exemplify nature’s own model of sustainable pest control.

Key words: Paper wasps, Sustainable, Pollination, Integrated Pest Management (IPM)

Introduction

In the vast expanse of agricultural landscapes, paper wasps (*Polistes spp.*) are among nature's most efficient yet often overlooked allies. Commonly mistaken as stinging nuisances, these social wasps provide valuable ecosystem services through their dual role as natural predators and incidental pollinators. Belonging to one of the most widespread genera of social wasps, *Polistes* comprises over 300 species distributed predominantly across tropical and subtropical regions. Paper wasps actively prey on caterpillars, aphids and other crop-damaging insects, helping to regulate pest populations and strengthening biological control and Integrated Pest Management (IPM) strategies (Prezoto *et al.*, 2019). While foraging for nectar, they also contribute to pollination, supporting crop productivity and biodiversity within agroecosystems (Santos *et al.*, 2020). By reducing dependence on chemical pesticides and maintaining ecological balance, paper wasps exemplify nature's own sustainable solution for resilient and environmentally friendly agriculture.

Taxonomy and Diversity of Paper Wasps

Paper wasps belong to the order Hymenoptera, family Vespidae and subfamily Polistinae. The genus *Polistes* is the largest and most widely distributed group within the subfamily, comprising over 300 described species found across tropical and temperate regions of the world. These wasps are easily recognized by their slender bodies, long legs and narrow waist. They derive their common name from their characteristic paper-like nests, which are built by chewing plant fibres mixed with saliva.

Unlike yellowjackets and hornets, *Polistes* species construct open, umbrella-shaped nests without an outer covering. In India, more than 25 species have been recorded, with *Polistes olivaceus*, *P. stigma* and *P. hebraeus* being the most common. These species frequently nest on tree branches, buildings and farm structures, thriving in both natural and agricultural habitats. Their wide distribution, adaptive nesting behaviour and ecological

versatility make paper wasps important beneficial insects in sustainable agriculture, particularly as natural pest regulators and incidental pollinators (Piekarski *et al.*, 2018).



Behaviour and Ecological Role

Paper wasps (*Polistes* spp.) are highly social insects that live in small to medium-sized colonies with a well-organized division of labour, cooperative brood care and overlapping generations. Colonies are founded by one or a few mated females that build a small nest and rear the first brood. Once adult workers emerge, they assume responsibilities such as nest maintenance, foraging and brood care, while the queen primarily lays eggs.

Their characteristic open-combed, paper-like nests are constructed from chewed plant fibres mixed with saliva and are commonly found beneath eaves, tree branches and farm structures. Adult wasps feed mainly on nectar, whereas the larvae are nourished with caterpillars, aphids and other soft-bodied insects collected by the workers. This predatory behaviour makes paper wasps effective natural enemies of several economically important crop pests, including armyworms, leaf miners and other defoliators.

While foraging for nectar, paper wasps also act as incidental pollinators, contributing to the pollination of many cultivated and wild plants (da Silva *et al.*, 2020). Their combined roles as biological control agents and pollinators strengthen ecosystem services, enhance biodiversity and support sustainable agriculture. Conserving nesting habitats and minimizing indiscriminate pesticide use can encourage paper wasp populations, improving natural pest regulation and ecological stability in agroecosystems.

Role of Paper Wasps in Sustainable Agriculture and Pest Management

Paper wasps (*Polistes* spp.) are important natural allies in sustainable agriculture, serving as effective biological control agents in Integrated Pest Management (IPM) systems. They prey on caterpillars, aphids, leaf miners and other soft-bodied pests, including *Spodoptera litura*, *Helicoverpa armigera* and *Aphis craccivora*, thereby reducing crop damage and dependence on chemical pesticides.

While foraging for nectar, paper wasps also act as incidental pollinators, contributing to crop pollination and biodiversity conservation. Conserving nesting habitats, maintaining flowering field margins and minimizing indiscriminate pesticide use can enhance their populations and improve natural pest regulation (Clemente *et al.*, 2018). By combining biological pest control with pollination services, paper wasps support resilient, low-input and environmentally sustainable farming systems.

Pollination and Ecological Services of Paper Wasps

Beyond their role as natural pest controllers, paper wasps (*Polistes* spp.) also provide valuable pollination and other ecological services in agricultural ecosystems. Adult wasps feed on nectar and frequently visit flowering plants, transferring pollen between flowers and contributing to the pollination of several cultivated and wild species. Although they are less specialized than bees, their regular flower visits complement bee activity and help maintain pollination, particularly where bee populations are declining (Rader *et al.*, 2016).

In addition to pollination, paper wasps regulate herbivorous insect populations, support biodiversity and contribute to ecological balance in agroecosystems. Conserving flowering field margins, nesting habitats and reducing indiscriminate pesticide use can enhance these ecosystem services. By serving as both predators and incidental pollinators, paper wasps strengthen resilient, productive and environmentally sustainable farming systems.

Conservation and Management Strategies

The benefits of paper wasps (*Polistes* spp.) can be enhanced through simple conservation practices that protect their nesting and foraging habitats. Maintaining hedgerows, field margins, flowering plants and other semi-natural

habitats provides suitable nesting sites and reliable food sources, helping sustain healthy wasp populations. Since adult wasps depend on nectar, planting nectar-rich flowering species around fields further supports their survival and pollination activity.

Reducing the indiscriminate use of broad-spectrum insecticides and adopting Integrated Pest Management (IPM) practices help conserve paper wasps while minimizing non-target effects on other beneficial insects. Artificial nesting structures and farmer awareness programmes can also encourage their establishment in agricultural landscapes. By conserving paper wasps, farmers can strengthen natural pest control, support pollination and promote biodiversity, contributing to resilient and environmentally sustainable farming systems.

Conclusion

Paper wasps (*Polistes* spp.) play a vital role in sustainable agriculture by serving as natural predators of crop pests and contributing to pollination. Their presence enhances ecological balance, reduces pesticide dependence, and supports environmentally sound pest management. Promoting paper wasp conservation through habitat protection and reduced chemical use can strengthen Integrated Pest Management (IPM) systems, fostering resilient and sustainable farming ecosystems.

Paper wasps (*Polistes* spp.) are valuable components of sustainable agricultural systems, serving as both effective biological control agents and incidental pollinators. Their natural pest regulation and contribution to pollination enhance crop productivity while maintaining ecological balance. Promoting their conservation through habitat management and reduced pesticide use can strengthen Integrated Pest Management (IPM) strategies, leading to more resilient and environmentally sustainable farming systems.

Reference

- Clemente, M. A., Prezoto, F. and Santos, G. M. M. (2018). Enhancing ecosystem services provided by social wasps in agricultural landscapes through habitat management. *Biological Control*, **126**: 105–113.
- Da Silva, R. J., Clemente, M. A. and Prezoto, F. (2020). Potential of social wasps as pollinators in agroecosystems. *Sociobiology*, **67**(4): 569–576.
- Piekarski, P. K., Carpenter, J. M., Lemmon, A. R., Moriarty Lemmon, E. and Sharanowski, B. J. (2018). Phylogenomic evidence overturns current conceptions of social evolution in wasps (*Vespidae*). *Molecular Biology and Evolution*, **35**(9): 2097–2109.
- Prezoto, F., Clemente, M. A. and Santos, G. M. M. (2019). The role of social wasps in biological control: A review. *Sociobiology*, **66**(3): 461–468.
- Rader, R., Cunningham, S. A., Howlett, B. G. and Inouye, D. W. (2016). Non-bee insects as visitors and pollinators of crops: Biology, ecology, and management. *Annual Review of Entomology*, **61**: 391–408.
- Santos, G. M. M., Bichara Filho, C. C. and Resende, J. J. (2020). Pollination potential of social wasps: a neglected ecological service. *Neotropical Entomology*, **49**(2), 219–231.

Heavy Metal Pollution in Aquatic Ecosystems: An Emerging Challenge for Fish Health and Sustainable Aquaculture



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Abstract

Heavy metal contamination is considered a major environmental concern affecting aquatic ecosystems across the globe. While certain metals naturally occur in the environment and play important roles in biological processes, their elevated levels due to human activities such as industrial development, urban expansion, agricultural practices, mining, and poor waste management have become a serious threat to aquatic health. Persistent heavy metals contaminate water, sediments, and aquatic organisms, disrupting ecological balance and adversely affecting fish health, biodiversity, aquaculture productivity, and food safety. Through bioaccumulation and biomagnification, these contaminants can also reach humans via the consumption of contaminated fish and shellfish. Continuous surveillance through advanced analytical methods, along with effective pollution management strategies, is crucial for the timely identification of contamination and minimizing associated environmental risks. Sustainable management practices, including wastewater treatment, eco-friendly remediation technologies, and responsible environmental management, are crucial for minimizing heavy metal contamination. Safeguarding aquatic ecosystems from heavy metal contamination is essential for preserving biodiversity, maintaining the safety of aquatic food resources, and supporting sustainable fisheries and aquaculture development.

Keywords: Heavy metal contamination, aquatic environment, bioaccumulation, fish health, metal toxicity, sustainable aquaculture

Introduction

Heavy metals are naturally occurring metallic elements characterized by relatively high atomic weight and density. While many of these elements occur naturally in the Earth's crust, their concentration in aquatic environments has increased significantly due to industrialization, urbanization, mining, agricultural activities, and improper waste disposal. Even at very low concentrations, many heavy metals can exhibit toxic effects and create significant threats to aquatic organisms, ecosystem stability, and human health. Environmentally significant heavy metals include arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), manganese (Mn), silver (Ag), copper (Cu), zinc (Zn), and thallium (Tl). Among these elements, copper, zinc, and selenium (Se) are classified as essential trace metals because they contribute to important biological functions, including enzyme activity, growth, immune response, and metabolic regulation. However, their excessive accumulation beyond physiological requirements can lead to toxic effects in aquatic organisms. However, when present above their physiological limits, even these essential elements become toxic and can adversely affect aquatic organisms. Heavy metals enter aquatic ecosystems through both natural processes, such as weathering of rocks and volcanic activities, and anthropogenic sources including industrial effluents, agricultural runoff, domestic sewage, mining operations, and atmospheric deposition. Once released into water bodies, these metals are highly persistent because they cannot be degraded into harmless compounds. Rather than being degraded or eliminated, these metals persist in the environment and accumulate in sediments and living organisms. Their concentrations may increase within individual organisms through bioaccumulation and become further amplified across trophic levels through biomagnification in the food chain. The excessive accumulation of heavy metals disrupts physiological and biochemical processes in fish and other aquatic organisms, leading to impaired growth, reproductive failure, weakened immune responses, tissue damage, behavioral abnormalities, and increased susceptibility to diseases. In extreme cases, exposure to toxic levels of heavy metals can result in large-scale mortality of aquatic organisms.

and lead to considerable economic losses in aquaculture production systems. Furthermore, contaminated fish and shellfish may transfer these toxic metals to humans through consumption, making heavy metal pollution not only an environmental concern but also a significant challenge for food safety, public health, and sustainable aquaculture.

Sources of Heavy Metals in Aquatic Ecosystems

Heavy metals reach aquatic environments through a combination of natural processes and human activities. The relative contribution of each source depends on geographical conditions, industrial development, land use, and environmental management practices. Natural processes contribute to the background levels of metals in aquatic ecosystems. Weathering of rocks and soil erosion gradually release naturally occurring metals such as iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn), which are transported into rivers, lakes, and groundwater. Volcanic activity can also release metals such as mercury (Hg), arsenic (As), and lead (Pb) into surrounding environments. Similarly, forest fires and natural mineral leaching can increase the movement of trace metals into soil and water systems. However, the rapid increase in heavy metal contamination is mainly associated with anthropogenic activities. Industrial activities such as mining, electroplating, battery production, textile processing, and chemical manufacturing contribute significantly to aquatic metal contamination by releasing hazardous elements, including lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg), into the environment. Agricultural practices also contribute through the use of fertilizers, pesticides, and animal waste, which may introduce metals like cadmium, copper, and zinc into aquatic ecosystems through surface runoff. Furthermore, untreated urban wastewater, poor management of electronic waste, maritime activities, and coastal expansion add to heavy metal inputs in both freshwater and marine ecosystems. The combined influence of these sources increases metal accumulation in aquatic environments, highlighting the need for regular assessment of water, sediments, and aquatic organisms to protect fisheries resources and support sustainable aquaculture practices.

Impact of Heavy Metals on Aquatic Ecosystems

Heavy metals can disrupt the balance of aquatic ecosystems long before their effects become visible. Once these contaminants enter water bodies, they are absorbed by aquatic plants, plankton, invertebrates, and fish, gradually moving through the food web. Since most heavy metals are not easily broken down, they remain in the environment for extended periods, increasing the risk of long-term ecological damage. The earliest effects are often observed in microscopic organisms and aquatic plants, which form the foundation of the aquatic food chain. Elevated concentrations of metals such as cadmium, mercury, and lead can suppress photosynthesis, reduce enzyme activity, and slow cell growth. As a result, the productivity of the entire ecosystem may decline because less food is available for higher organisms. Aquatic animals are equally vulnerable. Filter-feeding organisms such as mussels readily absorb metals from surrounding water, while crustaceans and shrimp may experience impaired growth and moulting. In fish, heavy metals accumulate mainly in the gills, liver, kidneys, and muscles, where they interfere with normal physiological functions. Prolonged exposure can damage tissues, weaken the immune system, reduce growth and reproductive performance, and increase susceptibility to diseases. Mercury, for example, is well known for causing damage to the gills and liver of fish. Heavy metal pollution can also alter the structure of aquatic communities. Sensitive species gradually disappear, while only pollution-tolerant species survive, leading to reduced biodiversity. Because fish respond quickly to changes in water quality, they are widely used as biological indicators to assess the health of aquatic ecosystems. The consequences extend beyond the aquatic environment. The accumulation of heavy metals in fish and shellfish can compromise their safety for human consumption and may increase the risk of neurological, developmental, and other long-term health disorders. Therefore, effective control of heavy metal contamination is essential to conserve aquatic biodiversity, ensure food safety, and promote the sustainable development of fisheries and aquaculture.

Monitoring Heavy Metal Pollution

Regular monitoring is essential to detect heavy metal contamination before it poses a serious threat to aquatic ecosystems and public health. Scientists assess heavy metal pollution by collecting samples of water, sediments, fish, shellfish, and aquatic plants from different locations. The collected samples are analysed under laboratory conditions to quantify the levels of heavy metals such as mercury, lead, cadmium, arsenic, and chromium. Sensitive analytical techniques, including Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled

Plasma–Optical Emission Spectrometry (ICP–OES), are commonly employed because they provide precise and reliable detection of metals, even at trace concentrations. Simpler methods, such as UV–Visible spectrophotometry, are also used for preliminary screening of certain metals. Routine monitoring of heavy metals helps identify contamination hotspots, assess the environmental status of aquatic ecosystems, and verify that fish and shellfish are safe for human consumption. Such monitoring also supports regulatory agencies and aquaculture farmers in adopting timely management measures to protect aquatic ecosystems and maintain food safety.

Managing Heavy Metal Pollution in Water

Preventing heavy metal contamination is always more effective than removing it after it enters aquatic ecosystems. Proper treatment of industrial effluents, responsible use of fertilizers and pesticides, scientific disposal of waste, and regular monitoring of water quality are essential to reduce heavy metal inputs into rivers, lakes, and aquaculture systems. When contamination occurs, several treatment technologies can be used to remove heavy metals from water. Adsorption is one of the most widely adopted methods, in which materials such as activated carbon, biochar, natural zeolites, and agricultural by-products trap dissolved metal ions on their surface. This technique is cost-effective and suitable for removing metals such as lead, cadmium, and chromium. Advanced treatment methods, including reverse osmosis (RO), nanofiltration (NF), and ion exchange, are highly efficient in removing dissolved heavy metals and are commonly used in drinking water treatment and industrial wastewater management. Chemical treatment methods, including precipitation and coagulation, transform dissolved heavy metals into insoluble particles, allowing them to be efficiently removed from water. An environmentally friendly alternative is bioremediation, where microorganisms, algae, or aquatic plants naturally absorb, transform, or immobilize heavy metals. This sustainable approach is gaining attention because it is eco-friendly, economical, and suitable for long-term restoration of contaminated aquatic environments. An integrated approach combining pollution prevention, regular monitoring, and appropriate treatment technologies is essential to safeguard aquatic ecosystems, support sustainable aquaculture, and ensure the safety of aquatic food resources.

Conclusion

Healthy aquatic ecosystems are the foundation of sustainable fisheries, aquaculture, and food security. Despite their natural occurrence, the rising levels of heavy metal contamination have become a major concern for aquatic biodiversity, fish health, and the safety of aquatic food resources. Anthropogenic activities are the principal contributors to this problem, emphasizing the importance of environmentally responsible industrial operations, sustainable agricultural practices, and efficient waste management systems. Continuous monitoring of water, sediments, and aquatic organisms, coupled with modern treatment technologies and eco-friendly remediation approaches, can significantly reduce the risks associated with heavy metals. Protecting our water resources requires the combined efforts of researchers, policymakers, industries, farmers, and the public. By adopting science-based management practices today, we can preserve aquatic ecosystems for future generations while ensuring healthy fish, safe seafood, and a sustainable aquaculture sector.

Reference

- Singh, S., et al. (2011). “Toxic effects of cadmium and lead on growth and biochemical parameters of algae.” *Environmental Toxicology and Chemistry*, 30(9), 2124–2130.
- Authman, M. M. N., et al. (2015). “Heavy metals pollution and their effects on gills and liver of Nile tilapia (*Oreochromis niloticus*).” *Environmental Monitoring and Assessment*, 187(1), 556.
- APHA (2017). *Standard Methods for the Examination of Water and Wastewater*, Method 3500-Cr B.
- Van der Bruggen, B. & Vandecasteele, C. (2021). Removal of pollutants from surface water and groundwater by nanofiltration: Overview of possible applications. *Environmental Pollution*, 292, 118385.
- Heavy Metal Pollution in Coastal Environments: Ecological Implications and Management Strategies: A Review (Chen et al., 2022)
- Heavy Metal Contamination in Marine Fish from the Andaman Sea: Influence of Habitat and Health Risk Assessment (2023)
- Heavy Metals and Their Ecological Risk Assessment in Surface Sediments of the Changjiang River Estuary and Contiguous East China Sea (2023)

A Review of Heavy Metals Pollution in Riverine Sediment from Various Asian and European Countries: Distribution, Sources, and Environmental Risk (Zeb et al., 2024)

Toxic Metal Pollution in Freshwater Ecosystems: A Systematic Review of Assessment Methods Using Environmental and Statistical Indices (2025)



Present Status of Dairying in India Vis – a – Vis Global Scenario, Production Dynamics and Recent Policy Initiatives in Dairy Development



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Introduction

Dairying plays a crucial role in the Indian agricultural economy and contributes significantly to rural livelihoods, nutrition, and employment generation. India is currently the largest producer of milk in the world. The rapid growth of the dairy sector can be attributed to improved breeding technologies, better veterinary care, enhanced feed and fodder management, cooperative marketing systems, and supportive government policies. India holds the **1st position in global milk production** for several years now, and contributes nearly a **quarter** of the world's supply. The dairy sector has grown into one of the strongest pillars of the rural economy and has become central to food and nutritional security. **Currently, dairy is the largest agricultural product in India, contributing 5 percent to the national economy and directly employing more than 8 crore farmers** (as per National Accounts Statistics). The contribution of livestock in total agriculture and allied sector to Gross Value Added (GVA) has increased from 24.38% in 2014-15 to **30.87% in 2023-24 (at Current Prices)**. Livestock sector contributed **5.49% of total GVA in 2023-24 (at Current Prices)**.

Population Dynamics

- ✦ The total Livestock population is 535.78 million in the country showing an increase of 4.6% over Livestock Census 2012
- ✦ Total Bovine population (Cattle, Buffalo, Mithun and Yak) is 302.79 Million in 2019 which shows an increase of 1.0% over the previous census.
- ✦ The total number of cattle in the country is 192.49 million in 2019 showing an increase of 0.8 % over previous Census.
- ✦ The Female Cattle (Cows population) is 145.12 million, increased by 18.0% over the previous census (2012).
- ✦ The Exotic/Crossbred and Indigenous/Non-descript Cattle population in the country is 50.42 million and 142.11 million respectively.
- ✦ The population of the total Exotic/Crossbred Cattle has increased by 26.9 % in 2019 as compared to previous census.
- ✦ There is a decline of 6 % in the total Indigenous (both descript and non-descript) Cattle population over the previous census. However, the pace of decline of Indigenous Cattle population during 2012-2019 is much lesser as compared to 2007-12 which was about 9%.
- ✦ The total buffaloes in the country is 109.85 Million showing an increase of about 1.0% over previous Census.

Key Production Dynamics and Trends:

- ✦ **Global Leadership and Growth:** India has been the top global milk producer since 1998, with production increasing from 146.30 million tonnes in 2014–15 to 247.87 million tonnes in 2024-25.
- ✦ **Contribution and Consumption:** The dairy sector, with 18 million farmers and 80 million people employed, is a vital rural economic driver. Daily per capita availability has increased to over 485 grams in 2024-25.
- ✦ **Production Composition:** Production is nearly evenly split, with buffalo milk contributing approximately 49% and cow milk 48%, with goats accounting for the remainder.

- ✚ **Regional Concentration:** Production is heavily concentrated in the northern and western regions, with top states including Uttar Pradesh, Rajasthan, Madhya Pradesh, Andhra Pradesh, and Gujarat.
- ✚ **Low Productivity Per Animal:** Despite being the top producer, India's per-animal productivity is lower (3.86 litres) compared to global leaders like Israel (33 litres) and the US (25 litres). Growth is driven by the sheer number of animals rather than high yields.
- ✚ **Challenges and Future Outlook:** Key challenges include low productivity, feed shortages, and regional disparities, with Northeastern states (e.g., Mizoram, Nagaland) experiencing significant deficits. Future growth requires enhancing genetic potential and increasing nutrient supply to livestock.

Species-Wise Milk Contribution

The contribution of milk production by Cattle, Buffalo and Goat. The analysis shows nearly 31.18% of the total milk production is contributed by Indigenous Buffaloes followed by 30.80 % by crossbred cattle. The Indigenous cattle contribute 11.20% of the total milk production in the country whereas non-descript cattle contribute 9.64% and non-descript buffaloes contribute 11.97% of the total milk production in the country. Goat milk shares a contribution of 3.32% in the total milk production across the country. Exotic cow has share (1.89%) to the total milk production.

Annual Growth Rate of Milk Production

The decline in the annual growth rate of milk production from 3.78% in 2023-24 to 3.58% in 2024-25 could be attributed to several factors:

- ✚ **Reduction in Fodder Crop Area:** The area under fodder crops in India has significantly declined by approximately 23% from 2018-19 to 2023-24. This reduction in fodder availability could have impacted milk production, as livestock rely heavily on fodder for nutrition.
- ✚ **Climate Variability:** Adverse weather conditions, such as droughts, floods, or unseasonal rainfall, can affect the availability of feed and water for livestock, leading to reduced milk production.
- ✚ **Disease Outbreaks:** Livestock diseases, such as Foot and Mouth Disease (FMD) and Lumpy Skin Disease (LSD), can negatively impact milk yield and overall productivity. The report highlights several outbreaks of such diseases in 2024, which may have contributed to the decline.
- ✚ **Regional Disparities:** While some states have shown growth in milk production, others may have experienced stagnation or decline due to local challenges such as inadequate veterinary infrastructure, poor disease management, or limited access to quality feed.
- ✚ **Economic Factors:** Rising costs of animal feed and fodder, coupled with inflation, may have affected farmers' ability to maintain optimal livestock health and productivity.
- ✚ **Natural Production Limits:** As milk production continues to grow, the rate of growth may naturally slow down due to biological and resource constraints.

Average Yield Rate of Cattle

The milk yield of Exotic/Crossbred cows reported 9.05 Kgs per cow per day during 2024-25 and Indigenous/Non-descript cows reported yield of 3.86 Kgs per cow per day during the year 2024-25.

State-wise annual growth of milk production during 2024-25

It was observed that 8 states have registered growth of more than the National Average Growth Rate (NAGR) i.e. 3.58%. These 8 states are Punjab, Madhya Pradesh, Tamilnadu, Rajasthan, Gujarat, Bihar, West Bengal & Maharashtra.

State-wise share of milk production during 2024-25

The largest producer of milk is Uttar Pradesh with 15.66% of the total milk production in the country followed by Rajasthan that produces 14.82% of the total milk production. Madhya Pradesh, Gujarat and Maharashtra stand as the third, fourth and fifth largest milk producing states that produce 9.12%, 7.78% and 6.71% of the total milk produced in the country respectively.

Future Vision: White Revolution 2.0

The White Revolution 2.0 initiative will be implemented for five years during 2024-25 to 2028-29. By 2028-29, milk procurement by dairy cooperatives is expected to reach **1007 lakh kg per day** from current levels. The plan includes: -

- I. Expanding the coverage by dairy cooperatives by the formation of **75,000 new Dairy Cooperative Societies**. Women farmers will be drawn into the organized dairy sector by setting up cooperatives in every uncovered village.
- II. Strengthening of **46,422 existing Dairy Cooperative Societies**.
- III. Embedding sustainability and circularity in the dairy sector by formation of three exclusive **Multi-State Cooperative Societies (MSCS)** to undertake the following activities:
 - a. To supply cattle feed, mineral mixtures and other technical inputs.
 - b. To promote organic manure production and sustainable waste utilization through cooperative efforts, contributing to natural farming and a circular economy by utilization of cow dung and agricultural waste for conversion into organic fertilizers and biogas, in response to rising demand for eco-friendly soil inputs and national sustainability goals.
 - c. For Management of hides, bones and horns of fallen animals.

Recent Policy Initiatives

The Department of Animal Husbandry and Dairying has been allocated ₹4,521.24 crore in the 2024-25 union budget, a rise from ₹3,913.93 crore in the previous fiscal.

- ✚ **National Livestock Mission (NLM):** ₹324 crore allocated to increase per-animal productivity, focusing on meat, goat milk, egg, and wool production.
- ✚ **Animal Husbandry Infrastructure Development Fund (AHIDF):** The revised outlay for the fund, which supports infrastructure for dairy and meat processing, is ₹29,610 crore.
- ✚ **National Animal Disease Control Programme (NADCP):** Continued funding to target eradication of Foot and Mouth Disease (FMD) and Brucellosis by 2030.
- ✚ **Rashtriya Gokul Mission (RGM):** Further supported to improve genetic merit of livestock, including heifer rearing centers.
- ✚ **Digital Agriculture Mission:** A 2024 initiative focusing on digital services, traceability, and tele-veterinary care.

Conclusion

India's dairy sector is the backbone of rural livelihoods and a symbol of inclusive growth. As the largest milk producer in the world, the country has combined farmer-led cooperatives, women's participation and scientific practices to achieve remarkable progress. With the momentum of White Revolution 2.0, the sector is poised to boost productivity, expand opportunities and continue transforming rural prosperity.

References

Basic Animal Husbandry Statistics, 2025, Dept. of Animal Husbandry and Dairying, Govt. of India.

<https://dahd.gov.in/schemes/programmes/didf>

<https://www.pib.gov.in/PressReleasePage.aspx?PRID=2172546®=3&lang=2>

20th Livestock Census, Dept. of Animal Husbandry and Dairying,
<https://dahd.gov.in/schemes/programmes/animal-husbandry-statistics>

Role of Functional Foods in Health Promotion and Disease Prevention



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Abstract

Functional foods are foods that offer health benefits beyond their basic nutritional contributions, largely due to the presence of biologically active compounds such as dietary fibre, probiotics, polyphenols, carotenoids, phytosterols, omega-3 fatty acids, vitamins, minerals, and bioactive peptides. Increasing scientific evidence suggests that diets rich in minimally processed plant-based foods, including whole grains, fruits, vegetables, legumes, nuts, seeds, and certain fermented foods, may play an important role in promoting health and reducing the risk of chronic diseases.

Functional foods may support health through various physiological mechanisms, including the regulation of gut microbiota, reduction of oxidative stress and inflammation, improvement of lipid and glucose metabolism, maintenance of healthy blood pressure, and enhancement of immune responses. Nevertheless, the health effects of these foods can vary according to the food matrix, type and concentration of bioactive compounds, consumed dose, individual characteristics, and the overall dietary pattern. Therefore, functional foods should be considered as part of a balanced and varied diet rather than as substitutes for healthy eating practices or appropriate medical treatment. This article examines the potential contributions of functional foods to health promotion and their role in the prevention and management of chronic conditions, including cardiovascular disease, type 2 diabetes, obesity, gastrointestinal disorders, and certain types of cancer.

Keywords: Functional foods, health promotion, disease prevention, dietary fibre, probiotics, polyphenols, omega-3 fatty acids, whole grains, nutraceuticals.

1. Introduction

Nutrition is a fundamental component of maintaining overall health and preventing the development of chronic diseases. According to the World Health Organization (WHO), unhealthy dietary habits are a major contributing factor to noncommunicable diseases (NCDs), such as cardiovascular disease, diabetes, and cancer.

A healthy and well-balanced diet should provide adequate nutrients while emphasizing variety, moderation, and dietary balance. It should primarily consist of minimally processed and nutrient-dense foods to support optimal health and reduce disease risk. (*Healthy Diet*, 2026)

The concept of functional foods emerged from the understanding that certain foods contain bioactive components capable of affecting physiological functions beyond their basic role in providing energy and essential nutrients. These foods may naturally contain beneficial compounds, such as the β -glucan found in oats, or they may be enhanced, fortified, or otherwise modified to deliver specific health benefits. The Academy of Nutrition and Dietetics emphasizes that the health claims associated with functional foods should be assessed based on the strength and reliability of available scientific evidence. (Hasler & Brown, 2009)

Functional foods have consequently attracted considerable attention in nutrition science because they may provide a practical dietary approach to health promotion and chronic disease prevention.

2. Definition and Characteristics of Functional Food

Functional foods are generally defined as foods that offer health and physiological benefits beyond their fundamental nutritional value, potentially supporting overall well-being and helping to lower the risk of certain diseases.

Examples include:

S. No	Functional food/component	Key bioactive compounds	Potential health benefits
1	Oats and barley	β -glucan	May help regulate blood cholesterol and blood glucose levels
2	Fruits and vegetables	Polyphenols, carotenoids, vitamins	May provide antioxidant and anti-inflammatory benefits
3	Legumes	Dietary fibre, resistant starch, phytochemicals	May support blood glucose regulation and cardiovascular health
4	Yogurt and fermented foods	Probiotic microorganisms	May promote gastrointestinal health and support immune function
5	Fatty fish	EPA and DHA	May contribute to cardiovascular and brain health
6	Nuts and seeds	Unsaturated fatty acids, fibre, phytochemicals	May improve cardiometabolic health
7	Soy-based foods	Soy protein, isoflavones	May support cardiovascular and overall nutritional health
8	Green tea	Catechins and polyphenols	May provide antioxidant and beneficial metabolic effects
9	Tomatoes	Lycopene and other carotenoids	May contribute to antioxidant protection and cardiovascular health
10	Whole grains	Dietary fibre, minerals, phenolic compounds	May support cardiovascular and metabolic health

Importantly, functional foods should not be regarded as substitutes for medicines or medical treatment. Their potential health benefits may differ depending on the amount consumed, methods of preparation, an individual's health condition, and the overall composition of the diet.

3. Role of Functional Foods in Health Promotion

3.1 Cardiovascular health

Functional foods may support cardiovascular health by influencing several important risk factors, including blood lipid levels, blood pressure, inflammation, endothelial function, and body weight.

Whole grains, especially oats and barley, are notable examples of functional foods with potential cardiovascular benefits. Their high content of dietary fibre and other bioactive compounds may help improve various cardiovascular risk markers. Evidence from a systematic review and meta-analysis of randomized controlled trials suggests that replacing refined grains with whole grains may lead to improvements in total cholesterol, LDL cholesterol, HbA1c, and C-reactive protein. However, the available evidence remains

insufficient to establish that consumption of whole grains alone can prevent cardiovascular disease.(Marshall et al., 2020)

Observational research further supports the potential cardiovascular benefits of whole-grain consumption. A dose–response meta-analysis of 45 prospective studies reported that higher intake of whole grains was associated with a reduced risk of coronary heart disease, cardiovascular disease, and overall mortality.(Aune et al., 2016)

Soluble fibre is another key functional component that may contribute to cardiovascular health. The U.S. Food and Drug Administration (FDA) has authorized a health claim indicating that soluble fibre from certain foods may help reduce the risk of coronary heart disease.(*Authorized Health Claims That Meet the Significant Scientific Agreement (SSA) Standard* | FDA, n.d.)

3.2 Prevention and management of type 2 diabetes

Dietary fibre, whole grains, legumes, and other minimally processed carbohydrate-rich foods may support blood glucose regulation by slowing digestion and glucose absorption, promoting satiety, and improving overall metabolic function. Whole grains provide substantial amounts of dietary fibre along with other bioactive compounds that may positively influence insulin sensitivity and glucose metabolism. Evidence from a systematic review and meta-analysis of randomized controlled trials in individuals with diabetes also suggests that incorporating whole grains into the diet may have beneficial effects on glycaemic control.(Xu et al., 2021). An umbrella review of meta-analyses further reported that higher whole-grain intake was associated with a reduced risk of developing type 2 diabetes, although the certainty and quality of the available evidence differed across the included studies.(McRae, 2017)

3.3 Gastrointestinal health and gut microbiota

The gastrointestinal tract harbours a diverse microbial ecosystem that plays an important role in digestion, metabolism, intestinal barrier function and immune regulation. Dietary components, particularly probiotics, prebiotics and dietary fibre, can modify the composition and activity of the gut microbiota. Probiotics may introduce beneficial microorganisms, whereas prebiotics and fermentable dietary fibres provide substrates that promote the growth and metabolic activity of beneficial gut bacteria. Fermentation of dietary fibre by intestinal microorganisms also produces short-chain fatty acids (SCFAs), such as acetate, propionate and butyrate, which contribute to intestinal and metabolic health. Evidence from clinical trials and systematic reviews suggests that dietary fibre interventions can increase beneficial bacterial groups such as *Bifidobacterium* and *Lactobacillus* and may increase faecal butyrate concentrations.(Sanders et al., 2019)

Probiotics are live microorganisms that provide health benefits to the host when consumed in sufficient quantities. Fermented foods, especially yogurt and other fermented dairy products, may contain beneficial microorganisms such as lactic acid bacteria, along with specific probiotic strains from genera including *Lactobacillus* and *Bifidobacterium*. Regular consumption of fermented dairy foods may support gastrointestinal health by improving lactose digestion and potentially influencing the composition and activity of the gut microbiota. However, the presence of live microorganisms in a fermented food does not necessarily qualify it as a probiotic. Probiotic benefits are strain-specific and must be supported by scientific evidence demonstrating a health benefit.(Savaiano & Hutkins, 2020).

Prebiotic and fermentable dietary fibres serve as important substrates that support the growth and metabolic activity of beneficial microorganisms in the gastrointestinal tract. When gut bacteria ferment these fibres, they produce short-chain fatty acids (SCFAs), particularly acetate, propionate, and butyrate. These metabolites play important roles in maintaining the intestinal barrier, regulating immune responses, and supporting metabolic processes. Dietary fibre obtained from whole foods, such as whole grains, legumes, fruits, and vegetables, may promote gastrointestinal health by influencing the composition of the gut microbiota and the production of microbial metabolites. However, the physiological effects of dietary fibre can vary depending on its type, structural characteristics, fermentability, and food source.(Gill et al., 2020)

3.4 Antioxidant and anti-inflammatory effects

Oxidative stress and persistent low-grade inflammation are key biological processes associated with the onset and progression of various chronic diseases. Plant-based foods, including fruits, vegetables, whole grains, and other

plant-derived foods, provide a diverse range of bioactive phytochemicals, such as polyphenols, flavonoids, and carotenoids. These compounds may help regulate oxidative and inflammatory processes through antioxidant effects and by influencing cellular signalling mechanisms. Evidence suggests that phytochemicals can modulate pathways such as Nrf2 and NF- κ B, which play important roles in antioxidant defence and the regulation of inflammation. Consequently, regular consumption of phytochemical-rich plant foods may support cellular health and help protect the body against oxidative damage and chronic inflammatory stress.(Guan et al., 2021)

Plant-based foods, including berries, tomatoes, green tea, citrus fruits, leafy vegetables, cocoa, nuts, and seeds, are rich sources of diverse bioactive compounds such as anthocyanins, lycopene, catechins, flavonoids, carotenoids, folate, flavanols, and vitamin E. These phytochemicals may affect several physiological processes, including oxidative stress, inflammatory signalling, endothelial and vascular function, and cellular metabolism. Human research suggests that certain polyphenol-rich foods, particularly berries and cocoa, may have favourable effects on vascular function and cardiometabolic health markers. However, antioxidant activity observed in in-vitro laboratory assays does not necessarily indicate that the same effects will occur in humans. Factors such as absorption, metabolism, bioavailability, dose, and individual physiological responses can significantly influence the biological effects of dietary phytochemicals.(Rodriguez-Mateos et al., 2014)

3.5 Obesity and weight management

Functional foods may support weight management by promoting satiety, regulating appetite, improving dietary quality, and helping maintain energy balance. Dietary fibre can enhance feelings of fullness and may reduce subsequent food consumption, although these effects depend on the type and physical characteristics of the fibre. Whole-grain foods may also provide greater satiety and fullness compared with refined grains. Similarly, legumes, which are rich in both dietary fibre and protein, may contribute to healthier body weight and favourable changes in body composition. Although nuts are relatively energy-dense, their inclusion in a balanced diet does not necessarily lead to weight gain, potentially due to their effects on satiety, nutrient density, and overall food intake.

The World Health Organization (WHO) emphasizes the importance of consuming a varied, balanced, and diverse diet that primarily consists of minimally processed and unprocessed foods, such as whole grains, legumes, vegetables, fruits, and nuts. At the same time, intake of foods containing excessive amounts of free sugars, unhealthy fats, and sodium should be limited. Such dietary patterns can support healthy energy balance and help reduce the risk of obesity and other noncommunicable diseases. Consequently, foods with potential functional benefits should be viewed as part of an overall healthy dietary pattern, rather than being regarded as individual “superfoods.” The overall quality, variety, and balance of the diet are more important for health than dependence on any single food or nutrient.WHO (2026)

3.6 Immune function

Several micronutrients play essential roles in supporting normal immune system function, including vitamins A, C, D, and E, zinc, selenium, iron, and folate. Insufficient intake or poor nutritional status of these nutrients may impair immune responses and increase vulnerability to infections. Fruits and vegetables are important sources of vitamin C, carotenoids, folate, and various polyphenols, whereas nuts, seeds, legumes, and whole grains provide minerals, dietary fibre, and other beneficial bioactive compounds. Nevertheless, the relationship between individual functional foods and immune health is complex, and consuming a particular food alone does not necessarily enhance immunity. Maintaining adequate overall nutrition, along with regular physical activity and sufficient sleep, is essential for supporting healthy immune function.(Hatch-McChesney & Smith, 2023)

3.7 Cancer prevention

Dietary patterns that emphasize whole grains, fruits, vegetables, and legumes have been linked to a lower risk of various chronic diseases and certain types of cancer. Findings from systematic reviews and meta-analyses suggest that greater consumption of whole grains may be associated with a reduced risk of overall cancer, particularly colorectal cancer. Several mechanisms may explain these potential benefits, including the fermentation of dietary fibre by gut microorganisms and the resulting production of short-chain fatty acids, improved insulin sensitivity, regulation of inflammatory processes, modification of gut microbiota, and the biological activity of phytochemicals found in plant-based foods. Nevertheless, no single functional food should be regarded as a

guaranteed means of preventing or treating cancer. Cancer development is influenced by numerous interacting factors, including overall dietary patterns, physical activity, body weight, tobacco and alcohol consumption, genetic susceptibility, and environmental exposures. WHO (2023)

4. Important Functional Components

Dietary fibre

Dietary fibre is naturally found in whole grains, pulses, vegetables, fruits, nuts, and seeds and plays an important role in supporting overall health. Adequate fibre intake can promote healthy bowel function, enhance feelings of fullness, and may help regulate blood glucose and improve blood lipid levels. However, the effects of dietary fibre depend on factors such as its type, fermentability, viscosity, and dietary source. The World Health Organization (WHO) recommends that adults consume at least 25 g of naturally occurring dietary fibre daily, with carbohydrates obtained mainly from whole grains, vegetables, fruits, and pulses. For children and adolescents, fibre intake should be adjusted according to age, with a recommended intake of at least 25 g per day for individuals aged 10 years and above. WHO (2023)

Omega-3 fatty acids

Omega-3 fatty acids, especially the long-chain forms eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are primarily obtained from oily fish and play important roles in cardiovascular, neurological, and cellular functions. However, findings from randomized controlled trials suggest that the cardiovascular benefits of omega-3 supplementation are not consistently demonstrated. A large Cochrane systematic review reported that increasing EPA and DHA intake had little or no effect on overall mortality, total cardiovascular events, stroke, or arrhythmias, although modest reductions in coronary heart disease events and coronary mortality were observed. These findings highlight the importance of distinguishing between isolated nutrient supplementation and the consumption of whole foods, such as oily fish, which provide omega-3 fatty acids alongside other nutrients, including protein, vitamin D, selenium, iodine, and additional bioactive compounds. (Ghasemi Fard et al., 2019)

Polyphenols

Polyphenols are a broad class of naturally occurring bioactive compounds found mainly in plant-based foods such as fruits, vegetables, tea, coffee, cocoa, legumes, and whole grains. This group includes flavonoids, phenolic acids, stilbenes, and several other compounds that may interact with biological pathways associated with oxidative stress and inflammation. Research suggests that dietary polyphenols may support antioxidant defence, regulate inflammatory processes, and contribute to healthy vascular function. However, their potential effects can vary considerably depending on the specific polyphenol, its food source, the amount consumed, bioavailability, and individual metabolic characteristics. (Rana et al., 2022)

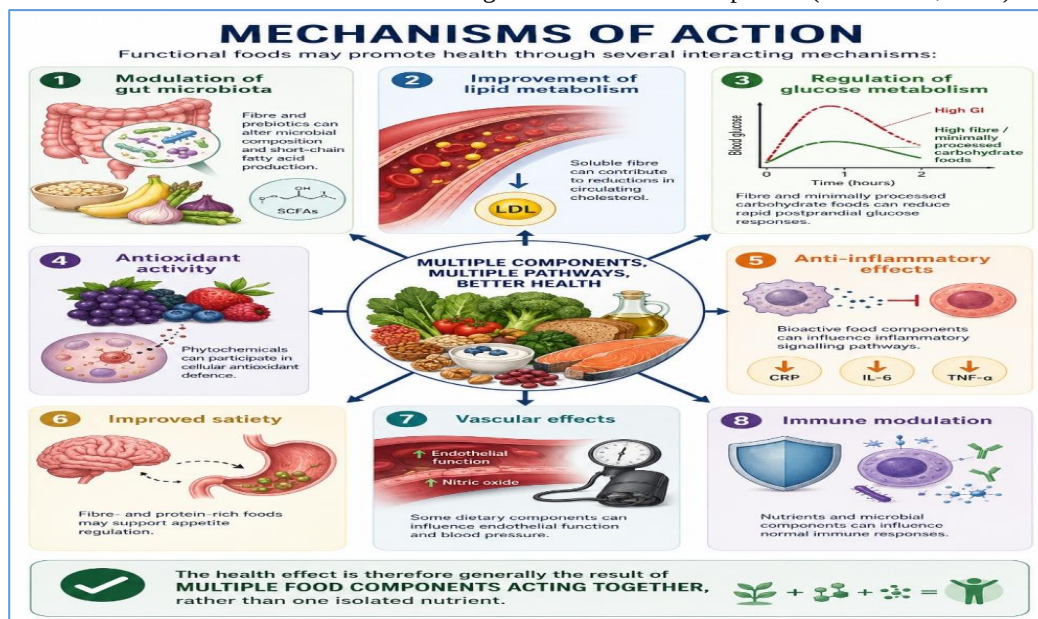
Probiotics and prebiotics

Probiotics are live microorganisms that can provide health benefits to the host when consumed in adequate amounts. They may help maintain or restore aspects of the intestinal microbial ecosystem, while prebiotic fibres are selectively utilized by beneficial microorganisms and can promote their growth or activity in the gut. However, the effects of probiotics can vary considerably depending on the specific strain, dosage, formulation, and health condition being considered. Evidence supporting one probiotic strain or product cannot necessarily be applied to other strains, fermented foods, or commercial probiotic products. Therefore, the presence of probiotics or live microorganisms in a food does not automatically mean that it will provide the same health or clinical benefits as other probiotic products. (Hill et al., 2014)

5. Mechanisms of Action

Functional foods may promote health through several interconnected physiological mechanisms. Dietary fibre and prebiotics can influence the composition and activity of the gut microbiota and enhance the production of beneficial short-chain fatty acids. Soluble fibre may contribute to improved lipid metabolism by helping reduce circulating cholesterol levels, while fibre-rich and minimally processed carbohydrate foods can slow digestion and glucose absorption, thereby supporting better blood glucose regulation. Bioactive phytochemicals may contribute to antioxidant defence and influence cellular pathways involved in oxidative stress and inflammation. In addition, foods rich in fibre and protein can increase satiety and appetite control, which may support healthy body weight. Certain dietary components may also benefit vascular health by influencing endothelial function

and blood pressure. Furthermore, essential nutrients and microbiota-related food components can contribute to the maintenance of normal immune function and regulation of immune responses. (Aune et al., 2016)



6. Functional Foods in the Indian Context

Functional foods are especially relevant in the Indian dietary context, as many traditional foods naturally provide a variety of bioactive compounds and essential nutrients. Millets are rich in dietary fibre, minerals, and phenolic compounds, while pulses and legumes provide substantial amounts of protein, fibre, and phytochemicals. Curd and yogurt supply protein and calcium and may contain beneficial microorganisms. Amla (Indian gooseberry) is a source of vitamin C and polyphenols, whereas turmeric contains bioactive curcuminoids. Flaxseed provides alpha-linolenic acid and lignans, while nuts and seeds contribute unsaturated fatty acids, dietary fibre, and various phytochemicals. Similarly, whole-grain cereals provide fibre and phenolic compounds that may support overall health. These foods can be incorporated into culturally appropriate and balanced dietary patterns rather than being viewed as isolated supplements or “superfoods.” The WHO also emphasizes that healthy dietary recommendations should take into account local food availability, cultural preferences, and traditional dietary practices (Gatkal et al., 2026)



7. Limitations and Considerations

Despite their potential health benefits, several important limitations should be considered when evaluating functional foods. First, functional foods are not medicines and should not be regarded as substitutes for prescribed medical treatments. Second, the strength of evidence supporting individual functional foods varies considerably. Associations observed in observational studies do not necessarily establish a cause-and-effect relationship, and beneficial effects demonstrated in laboratory studies may not always translate into significant clinical outcomes in humans. Third, the health effects of functional foods depend on the amount consumed, food composition, and overall dietary context. Simply adding a functional ingredient to a highly processed or energy-dense food does not necessarily make the product a healthy choice. Finally, dietary supplements should not automatically be considered equivalent to whole foods. For instance, research on omega-3 supplementation has produced mixed findings, highlighting the importance of distinguishing evidence related to whole foods from that concerning isolated nutrients or supplements (Aung et al., 2018)

8. Conclusion

Functional foods provide an important connection between nutrition and disease prevention. Foods rich in dietary fibre, whole grains, fruits, vegetables, legumes, nuts, seeds, fermented foods, and healthier sources of fats may contribute to health promotion by influencing metabolic processes, gut microbiota, inflammation, oxidative stress, cardiovascular risk factors, and immune function.

The most important public-health approach is not to depend on a single “superfood,” but rather to adopt a varied and balanced dietary pattern based primarily on minimally processed foods. Current WHO dietary guidance emphasizes regular consumption of vegetables, fruits, whole grains, pulses, and nuts, while encouraging limitation of excessive sodium, free sugars, and unhealthy fats.

Thus, functional foods should be considered integral components of a healthy and balanced diet, rather than alternatives to medical treatment or prescribed therapies. Further research is needed to determine which specific foods, bioactive compounds, doses, and dietary combinations can produce meaningful health benefits across different populations.

References

- Aune, D., Keum, N., Giovannucci, E., Fadnes, L. T., Boffetta, P., Greenwood, D. C., Tonstad, S., Vatten, L. J., Riboli, E., and Norat, T. (2016). Whole grain consumption and risk of cardiovascular disease, cancer, and all cause and cause specific mortality: systematic review and dose-response meta-analysis of prospective studies. *BMJ (Clinical Research Ed.)*, 353.
- Aung, T., Halsey, J., Kromhout, D., Gerstein, H. C., Marchioli, R., Tavazzi, L., Geleijnse, J. M., Rauch, B., Ness, A., Galan, P., Chew, E. Y., Bosch, J., Collins, R., Lewington, S., Armitage, J., and Clarke, R. (2018). Associations of Omega-3 Fatty Acid Supplement Use With Cardiovascular Disease Risks: Meta-analysis of 10 Trials Involving 77 917 Individuals. *JAMA Cardiology*, 3(3):225–234.
- Authorized Health Claims That Meet the Significant Scientific Agreement (SSA) Standard | FDA*. (n.d.). Retrieved August 11, 2026, from <https://www.fda.gov/food/nutrition-food-labeling-and-critical-foods/authorized-health-claims-meet-significant-scientific-agreement-ssa-standard?utm>
- Gatkal, N. R., Shelke, M. S., Nalawade, S. M., Deshmukh, M. S., Sahni, R. K., Beňová, K., and Liška, J. (2026). Energy potential, health benefits, antinutrient reduction methods, and nutritional properties of Indian millets: a review. *Frontiers in Nutrition*, 13.
- Ghasemi Fard, S., Wang, F., Sinclair, A. J., Elliott, G., and Turchini, G. M. (2019). How does high DHA fish oil affect health? A systematic review of evidence. *Critical Reviews in Food Science and Nutrition*, 59(11):1684–1727.
- Gill, S. K., Rossi, M., Bajka, B., and Whelan, K. (2020). Dietary fibre in gastrointestinal health and disease. *Nature Reviews Gastroenterology & Hepatology* 2020, 18(2): 101–116.
- Guan, R., Van Le, Q., Yang, H., Zhang, D., Gu, H., Yang, Y., Sonne, C., Lam, S. S., Zhong, J., Jianguang, Z., Liu, R., and Peng, W. (2021). A review of dietary phytochemicals and their relation to oxidative stress and human diseases. *Chemosphere*, 271.

- Hasler, C. M., and Brown, A. C. (2009). Position of the American Dietetic Association: functional foods. *Journal of the American Dietetic Association*, **109**(4): 735–746.
- Hatch-McChesney, A., and Smith, T. J. (2023). Nutrition, Immune Function, and Infectious Disease in Military Personnel: A Narrative Review. *Nutrients*, **15**(23).
- Healthy diet. (n.d.). Retrieved August 11, 2026, from https://www.who.int/en/news-room/fact-sheets/detail/healthy-diet?utm_
- Hill, C., Guarner, F., Reid, G., Gibson, G. R., Merenstein, D. J., Pot, B., Morelli, L., Canani, R. B., Flint, H. J., Salminen, S., Calder, P. C., and Sanders, M. E. (2014). Expert consensus document. The International Scientific Association for Probiotics and Prebiotics consensus statement on the scope and appropriate use of the term probiotic. *Nature Reviews. Gastroenterology & Hepatology*, **11**(8): 506–514.
- Marshall, S., Petocz, P., Duve, E., Abbott, K., Cassettari, T., Blumfield, M., and Fayet-Moore, F. (2020). The Effect of Replacing Refined Grains with Whole Grains on Cardiovascular Risk Factors: A Systematic Review and Meta-Analysis of Randomized Controlled Trials with GRADE Clinical Recommendation. *Journal of the Academy of Nutrition and Dietetics*, **120**(11):1859-1883.e31.
- McRae, M. P. (2017). Health Benefits of Dietary Whole Grains: An Umbrella Review of Meta-analyses. *Journal of Chiropractic Medicine*, **16**(1):10–18.
- Rana, A., Samtiya, M., Dhewa, T., Mishra, V., and Aluko, R. E. (2022). Health benefits of polyphenols: A concise review. *Journal of Food Biochemistry*, **46**(10).
- Rodriguez-Mateos, A., Heiss, C., Borges, G., and Crozier, A. (2014). Berry (poly)phenols and cardiovascular health. *Journal of Agricultural and Food Chemistry*, **62**(18): 3842–3851.
- Sanders, M. E., Merenstein, D. J., Reid, G., Gibson, G. R., and Rastall, R. A. (2019). Probiotics and prebiotics in intestinal health and disease: from biology to the clinic. *Nature Reviews Gastroenterology & Hepatology* 2019, **16**(10):605–616.
- Savaiano, D. A., and Hutkins, R. W. (2020). Yogurt, cultured fermented milk, and health: a systematic review. *Nutrition Reviews*, **79**(5): 599.
- Xu, D., Fu, L., Pan, D., Lu, Y., Yang, C., Wang, Y., Wang, S., and Sun, G. (2021). Role of Whole Grain Consumption in Glycaemic Control of Diabetic Patients: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *Nutrients*, **14**(1).

CARBON FARMING: A WIN FOR FARMERS, SOILS AND THE CLIMATE



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Abstract:

Climate change and declining soil organic carbon have emerged as major challenges to sustainable agriculture, threatening soil health, crop productivity, and environmental quality. Carbon farming offers a climate-smart solution by promoting sustainable land management practices that enhance carbon sequestration in agricultural soils. Practices such as conservation tillage, residue retention, cover cropping, agroforestry, and organic amendments increase soil organic carbon while improving soil fertility, water-holding capacity, and ecosystem resilience. Beyond these agronomic benefits, carbon farming has the potential to support carbon markets through scientifically verified carbon credits, providing an additional incentive for sustainable land management. Although challenges related to carbon measurement, verification, and policy support remain, continued scientific and technological advancements position carbon farming as a promising strategy for achieving climate-resilient agriculture, healthy soils, and long-term environmental sustainability.

1. Introduction:

Agriculture is at the forefront of the climate crisis. While it plays a vital role in ensuring global food security, it is also a significant contributor to greenhouse gas emissions. Decades of intensive cultivation, excessive tillage, and residue burning have depleted soil organic carbon, resulting in declining soil fertility, reduced productivity, and increased carbon emissions. At the same time, the growing demand for food places greater pressure on farmers to produce more with limited natural resources. **Can farmers restore soil health while earning an additional income by storing carbon in their fields?** Carbon farming offers a promising solution. By adopting sustainable land management practices that capture atmospheric carbon dioxide (CO₂) and store it as soil organic carbon, farmers can improve soil health, enhance climate resilience, and potentially benefit from emerging carbon credit markets. As the world moves towards climate-smart agriculture and net-zero emissions, carbon farming is gaining recognition as an innovative approach that supports both environmental sustainability and rural livelihoods.

2. What is Carbon Farming?

Carbon farming refers to a set of sustainable agricultural practices aimed at capturing carbon dioxide (CO₂) from the atmosphere and storing it in plants and soil as soil organic carbon (Sharma *et al.*, 2021). Simply put, it is a way of managing farmland so that the soil becomes a carbon sink, locking away carbon that would otherwise remain in the atmosphere and contribute to global warming.

Plants naturally absorb carbon dioxide during photosynthesis and convert it into biomass. A portion of this carbon is transferred below ground through roots, crop residues, and organic amendments. With the help of soil microorganisms, these materials decompose and are transformed into stable organic matter, allowing carbon to be stored in the soil for years or even decades under appropriate management. This natural process, known as soil carbon sequestration, forms the foundation of carbon farming.

Unlike conventional farming practices that often lead to the depletion of soil organic matter, carbon farming emphasizes practices such as residue retention, reduced tillage, cover cropping, crop rotation, organic manure application, agroforestry, and improved grazing management. These practices not only increase the amount of

carbon stored in the soil but also enhance soil fertility, improve water-holding capacity, promote microbial activity, and strengthen the resilience of farming systems to climate change. By restoring soil organic carbon, farmers can simultaneously improve the health of their soils, contribute to climate change mitigation, and create opportunities to participate in emerging carbon markets.

2.1. Carbon Farming Practices

Carbon farming is not based on a single technology but on a combination of sustainable land management practices that increase soil organic carbon over time. These practices enhance the amount of carbon entering the soil while minimizing carbon losses, making agricultural systems more productive and environmentally resilient.

- **Conservation tillage:** Minimizing soil disturbance reduces the oxidation and mineralization of soil organic matter, enhances soil aggregate stability, and promotes the long-term stabilization of soil organic carbon (SOC).
- **Crop residue retention:** Retaining crop residues on the soil surface increases organic carbon inputs, protects the soil against erosion, moderates soil temperature and moisture, and facilitates the gradual formation of stable soil organic matter.
- **Cover cropping:** Cover crops maintain continuous photosynthetic carbon fixation during fallow periods, increase below-ground carbon inputs through root biomass and exudates, reduce soil erosion, and improve nutrient cycling.
- **Crop diversification and rotation:** Diverse cropping systems enhance the quantity and quality of plant-derived carbon inputs, stimulate microbial diversity, and promote greater SOC accumulation through varied rooting patterns and residue characteristics.
- **Organic amendments:** The application of farmyard manure, compost, vermicompost, green manures, and biochar increases soil organic carbon stocks by supplying stable organic substrates, improving microbial activity, nutrient availability, and aggregate formation.
- **Agroforestry:** Integrating trees with crops enhances carbon sequestration by increasing above- and below-ground biomass, while continuous litter deposition and extensive root systems contribute to long-term soil carbon storage.
- **Integrated nutrient management:** The combined use of organic and inorganic nutrient sources enhances biomass production and residue return, improves nutrient use efficiency, and supports greater carbon sequestration through increased soil organic matter accumulation.
- **Improved grazing management:** Controlled grazing practices maintain continuous vegetative cover, increase root biomass and carbon inputs, reduce soil degradation, and enhance long-term soil carbon sequestration in grassland ecosystems.

The effectiveness of carbon farming is greatest when these practices are implemented together as part of an integrated soil management strategy. Building soil carbon is a gradual process, but consistent adoption of these practices can restore degraded soils, improve farm productivity, and strengthen the role of agriculture in addressing climate change.

3. How carbon farming and carbon credit works?

Carbon farming functions by maintaining a positive soil carbon balance, where the amount of carbon entering the soil exceeds the amount lost through decomposition, erosion, and soil disturbance. Carbon captured from the atmosphere through photosynthesis is transferred below ground via plant roots, crop residues, and organic amendments. Soil microorganisms decompose these materials, releasing a portion of the carbon back to the atmosphere while converting the remainder into stable soil organic matter (humus). This stabilized carbon becomes protected within soil aggregates and mineral complexes, enabling long-term storage in agricultural soils. As soil organic carbon accumulates, soils act as effective carbon sinks while simultaneously improving soil fertility, structure, water-holding capacity, microbial activity, and resilience to climate stress.

The carbon stored in agricultural soils can also generate economic value through carbon markets and being converted into carbon credits. A carbon credit is a tradable certificate that represents the removal, reduction, or avoidance of one metric tonne of carbon dioxide equivalent (CO₂e) from the atmosphere. Carbon credits are

designed to encourage activities that mitigate climate change by reducing greenhouse gas emissions or increasing carbon storage (Silva and Vieira 2025).

In carbon farming, farmers can generate carbon credits by adopting sustainable land management practices that increase soil organic carbon. However, carbon credits are not issued simply for implementing these practices. The increase in soil carbon must be measured, reported, and verified (MRV) using scientifically accepted protocols to ensure that the carbon has been genuinely sequestered. Only after independent verification are carbon credits certified and made eligible for trading.

Certified carbon credits are traded through voluntary and compliance carbon markets. In voluntary carbon markets, companies and organizations purchase carbon credits to meet sustainability commitments and achieve net-zero targets. Compliance carbon markets operate under government regulations, where industries are legally required to offset or reduce a portion of their greenhouse gas emissions. In both systems, the sale of carbon credits provides an economic incentive for adopting sustainable agricultural practices.

Carbon credits provide an opportunity to recognize the environmental services delivered by farmers through sustainable soil management. By transforming agricultural soils into effective carbon sinks, carbon farming has the potential to create value beyond food production, linking improved soil health with environmental sustainability and emerging green economic opportunities with the following challenges and some of the future prospects were also discussed.

4. Challenges and Future Prospects

4.1. Challenges

- **Accurate carbon measurement:** Changes in soil organic carbon occur gradually and require standardized sampling, long-term monitoring, and scientific verification.
- **High implementation costs:** Carbon assessment, certification, and verification can be expensive, especially for smallholder farmers.
- **Limited awareness:** Many farmers are unfamiliar with carbon farming practices and carbon market opportunities.
- **Small and fragmented landholdings:** The predominance of small farms makes carbon accounting and market participation more challenging.
- **Policy and institutional gaps:** Clear regulations, incentive mechanisms, and carbon trading frameworks are still evolving in many countries, including India.
- **Capacity building:** Farmers need technical guidance, training, and extension support to successfully adopt carbon farming practices.

4.2. Future Prospects

- **Climate-smart agriculture:** Carbon farming is expected to become an integral component of sustainable and climate-resilient agricultural systems.
- **Advancements in technology:** Remote sensing, GIS, artificial intelligence, and digital soil mapping are improving soil carbon monitoring and verification.
- **Expansion of carbon markets:** Growing global demand for carbon offsets may create new opportunities for farmers to participate in voluntary carbon markets.
- **Supportive government policies:** Incentive-based programmes and policy initiatives can encourage wider adoption of carbon farming.
- **Improved soil health:** Long-term adoption will enhance soil fertility, water retention, biodiversity, and overall farm productivity.
- **Sustainable future:** By integrating scientific innovation with sustainable land management, carbon farming has the potential to simultaneously improve agricultural productivity, strengthen climate resilience, and contribute to global carbon neutrality goals.

5. Conclusion

Carbon farming represents an innovative approach to sustainable agriculture by integrating soil carbon sequestration with climate change mitigation. Enhancing soil organic carbon not only improves soil quality, nutrient cycling, and ecosystem resilience but also contributes to reducing atmospheric carbon dioxide. Although

challenges related to carbon measurement, verification, and market accessibility remain, ongoing scientific advancements and supportive policy initiatives are expected to accelerate its adoption. By recognizing agricultural soils as both productive resources and vital carbon sinks, carbon farming has the potential to play a significant role in achieving sustainable food production and long-term environmental resilience.

References

- Sharma, M., Kaushal, R., Kaushik, P., & Ramakrishna, S. (2021). Carbon farming: Prospects and challenges. *Sustainability*, 13(19), 11122.
- Silva, N. F. S., & Vieira, V. M. (2025). Carbon credit market: a comparative analysis of consolidation in Brazil and the world. *Journal Of Bioengineering, Technologies And Health*, 8(1), 42-49.



Hydroponics: From Water to Harvest – A Guide to Soilless Farming



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Introduction

Agriculture plays a crucial role in ensuring global food security and economic development. Increasing population, shrinking arable land, water scarcity, climate change and rapid urbanization have accelerated the adoption of sustainable and resource efficient cultivation systems. Among these, soilless cultivation has emerged as an effective alternative to conventional agriculture. Soilless cultivation is broadly classified into hydroponics (plant cultivation in nutrient solution), aquaponics (combined cultivation of plants and fish) and aeroponics (plant cultivation with roots suspended in air and supplied with nutrient mist) (Sharma et al., 2023).

Hydroponics is the most widely adopted soilless cultivation technique because of its adaptability and high resource use efficiency. It involves growing plants in a nutrient rich water solution, with or without inert growing media such as expanded clay, coco peat, perlite, vermiculite, peat moss, charcoal or wood fibre, which provide physical support to the root system (Wahome et al., 2011; George et al., 2016). Compared with conventional soil based cultivation, hydroponics can reduce water consumption by up to 90%, utilize only about 10% of the land area, and enable year-round production with higher crop productivity (Dutta and Gupta, 2023).

The term hydroponics is derived from the Greek words hydro (water) and ponos (labour). The term was first introduced by Dr. William F. Gericke in 1929, who transformed laboratory techniques of growing plants in nutrient solutions into a commercially viable production system (Khan, 2018). Although hydroponics gained commercial importance in the twentieth century, cultivation of plants without soil has been practiced for over a century in plant nutrition research and was recognized by the United States Department of Agriculture (USDA) as an established technique for scientific investigations.

Hydroponic systems are broadly classified as liquid systems, where plant roots are directly immersed in nutrient solution without a supporting medium and aggregate systems, where inert substrates support the roots. Based on nutrient management, these systems are further categorized as open systems, in which the nutrient solution is supplied once and discarded, and in closed systems, where excess nutrient solution is collected, replenished and recirculated.

Common hydroponic production systems include the wick system, drip irrigation, Nutrient Film Technique (NFT), Deep Water Culture (DWC) and ebb-and-flow (flood-and-drain) systems (Morite et al., 2023). Deep Water Culture (DWC) is a simple hydroponic system in which plants are suspended in an aerated nutrient solution. It is one of the easiest and most popular methods of hydroponic cultivation, making it a convenient choice for beginners and home growers.

Wick system is also the simplest form of passive hydroponics that do not require any mechanical parts like pumps for functioning and works by a process called capillary action. The wick absorbs the nutrient solution like a sponge and releases it to plants when it comes in contact with the porous growing media.

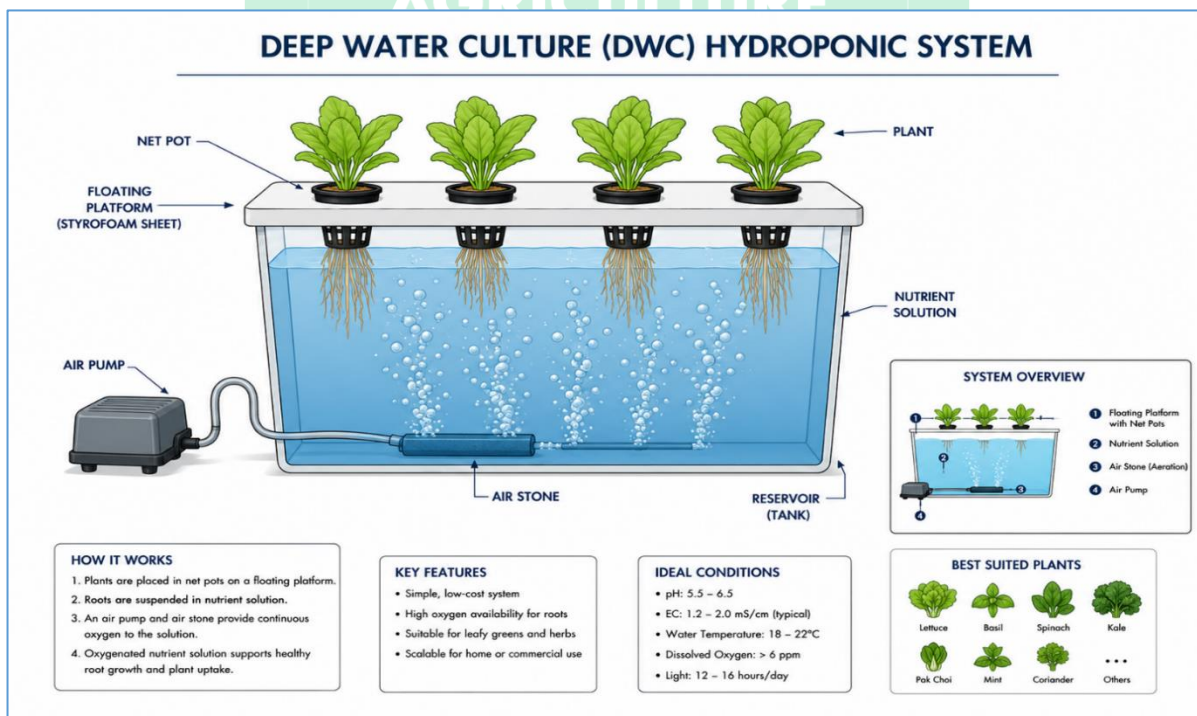
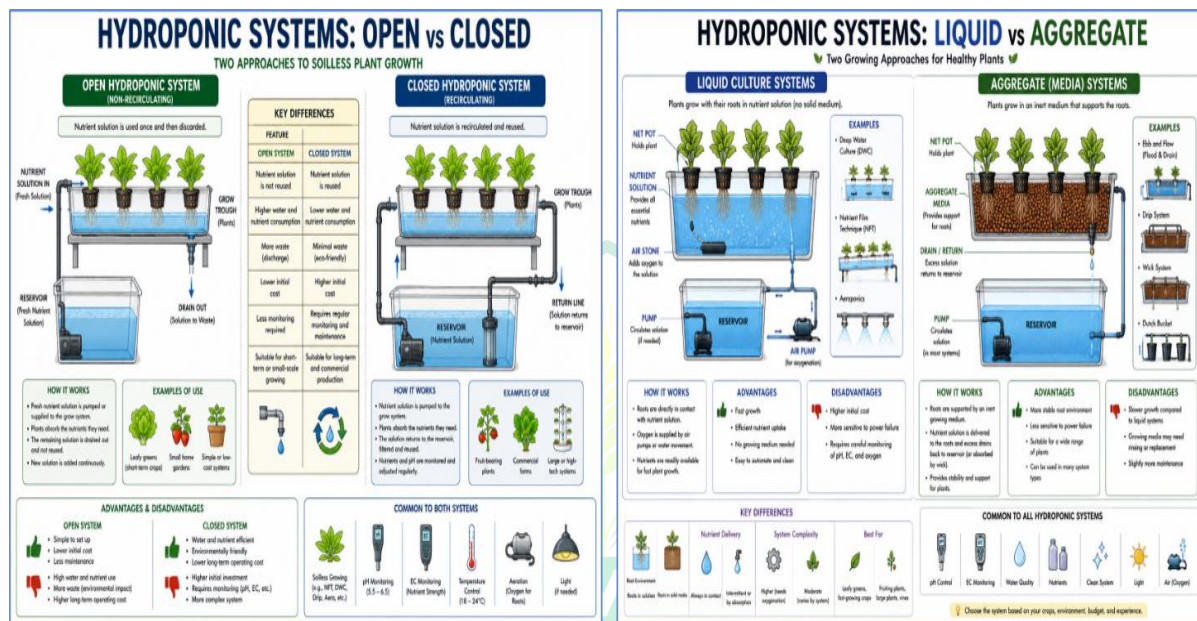
Nutrient Film technique is more appropriate system for light weight plants like kale, spinach, lettuce etc. where plants are suspended above a stream of continuously flowing nutrient solution that washes over the ends of the roots system

Ebb and Flow system also known as Flood and Drain system. Works by flooding a growing bed with the nutrient solution from a reservoir below which is fitted with a timer.

Drip system is popular and widely adopted method for commercial cultivation. The aerated and nutrient rich reservoir, pumps solution through a network of tubes to plants. The solution is getting dripped slowly into the growing media surrounding the root system.

Hydroponics is extensively used for cultivating leafy vegetables (foliage plants), tomatoes, cucumbers, peppers, strawberries, herbs, ornamentals and medicinal plants under greenhouse and controlled environment conditions. The integration of Internet of Things (IoT) technologies, cloud computing, automation, and artificial intelligence (AI) has further enhanced hydroponic production by enabling real-time monitoring of environmental conditions, precise nutrient management, and early detection of crop stress, making hydroponics a key component of smart and sustainable agriculture (Akter et al., 2024).

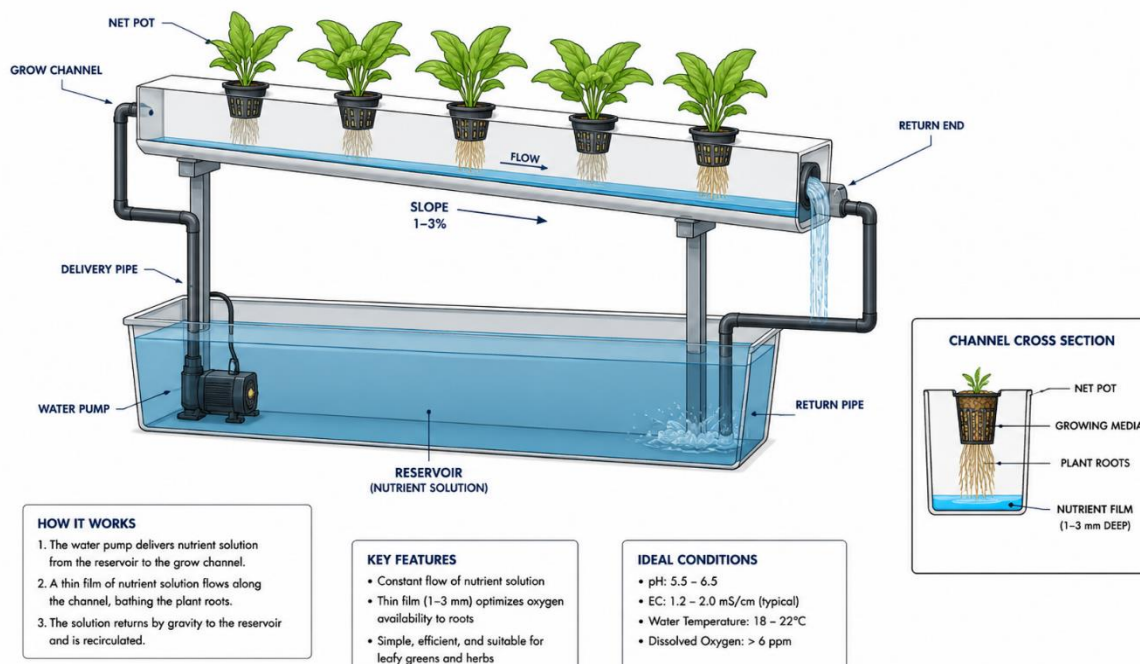
Fig.1 Open and Closed – Liquid and Aggregate method of Hydroponics



(Pictures Courtesy: AI tools)

Fig. 2 &3. DWC and NFT (Pictures Courtesy: AI tools)

NUTRIENT FILM TECHNIQUE (NFT) HYDROPONIC SYSTEM



EBB-AND-FLOW (FLOOD & DRAIN) HYDROPONIC SYSTEM

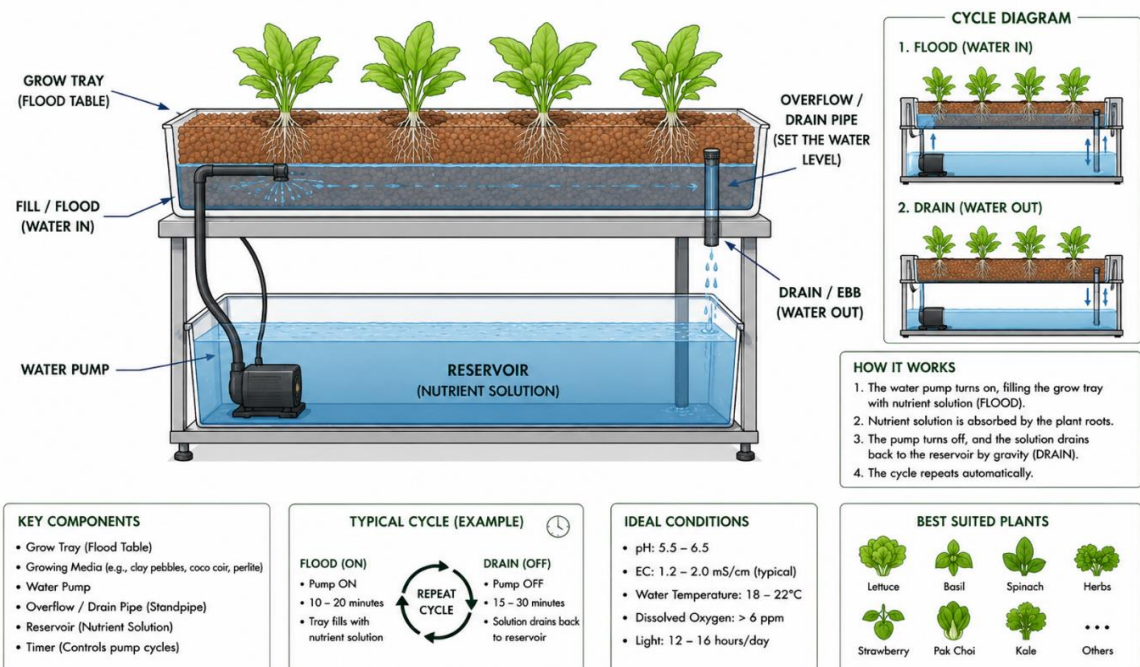
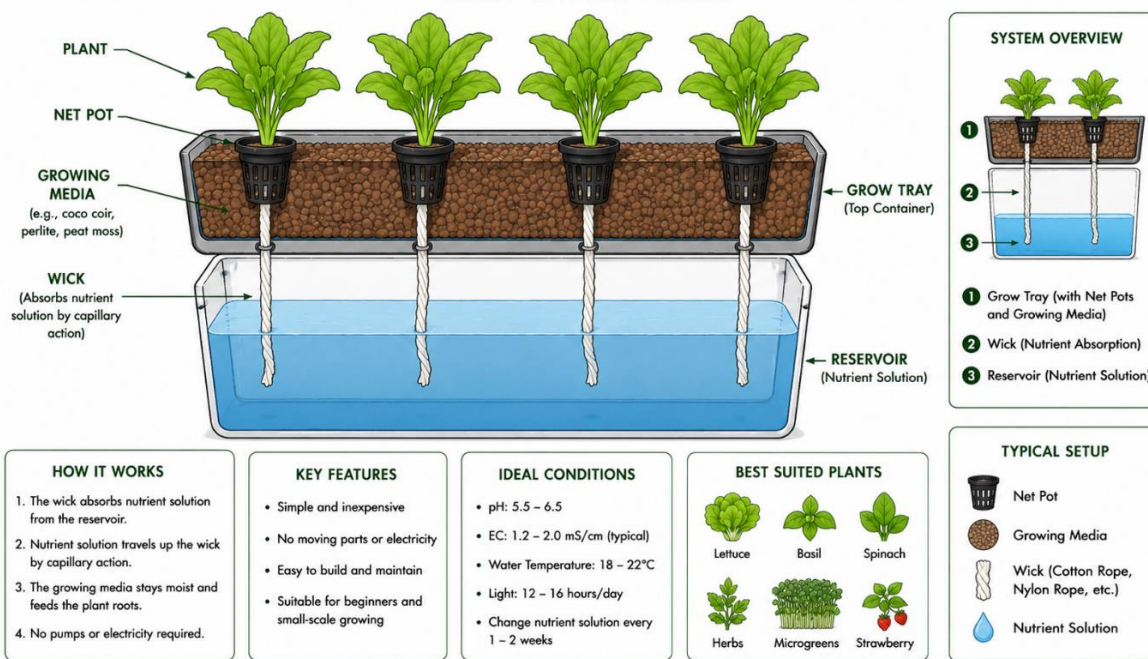


Fig. 4 & 5 EBB and Flow and Wick system (Pictures Courtesy: AI tools)

WICK SYSTEM HYDROPONICS

SIMPLE • LOW COST • PASSIVE



DRIP IRRIGATION HYDROPONIC SYSTEM

PRECISE • EFFICIENT • SCALABLE

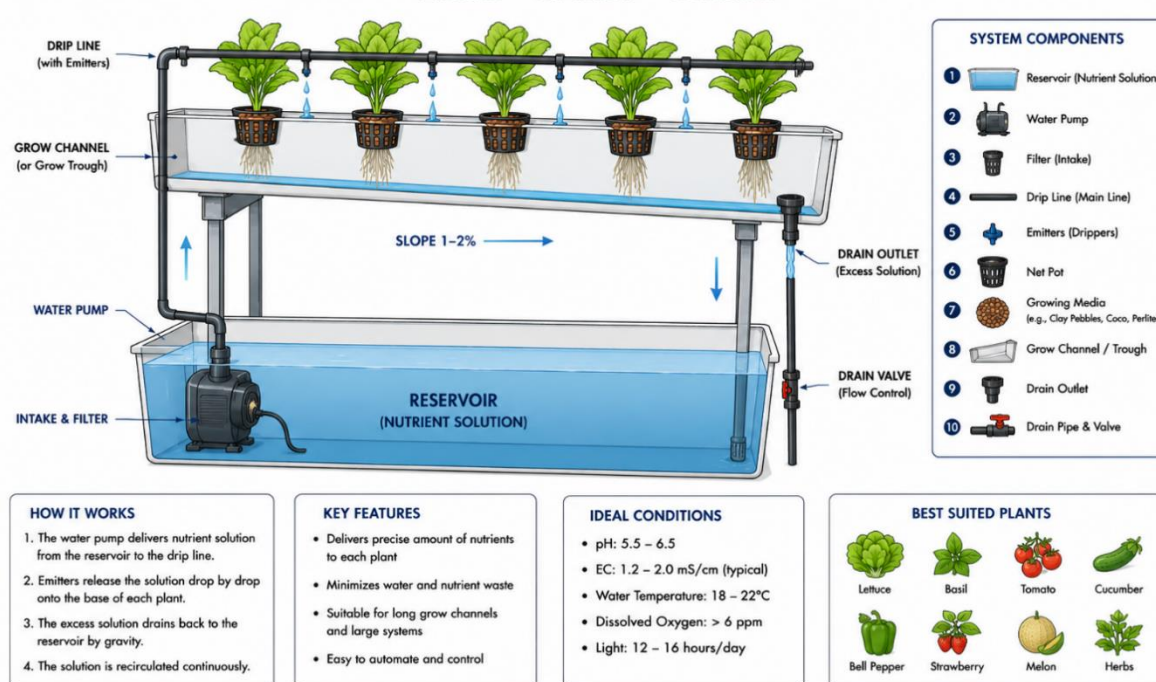
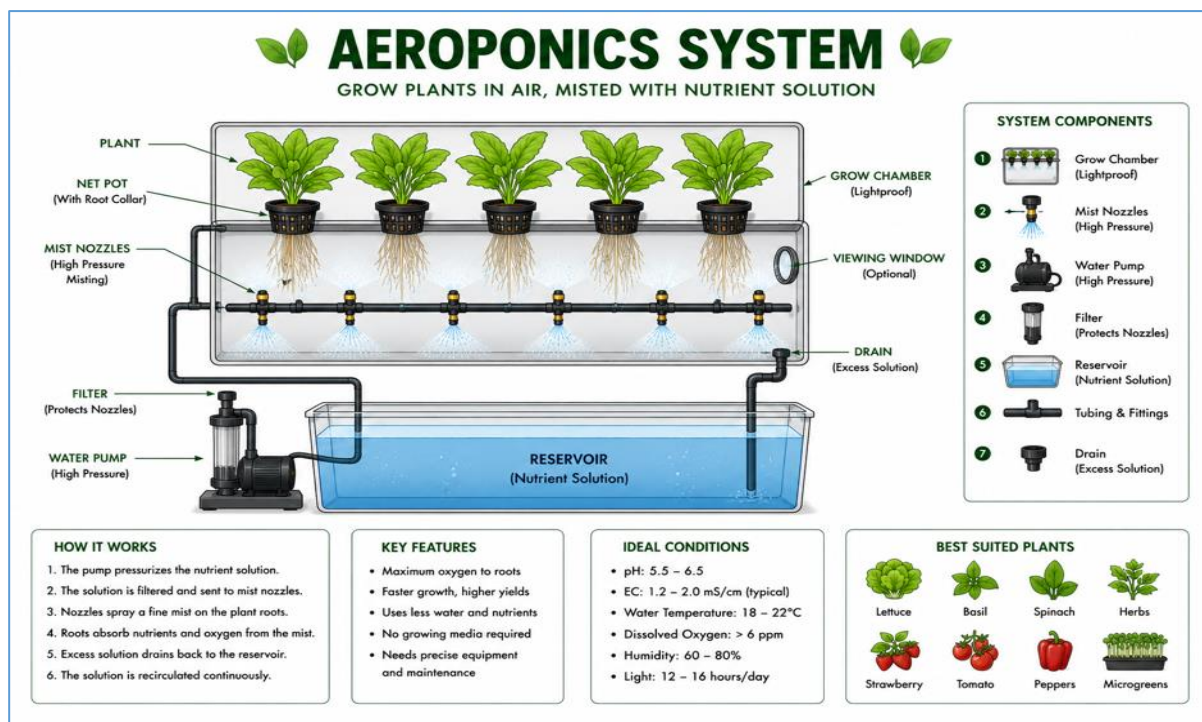
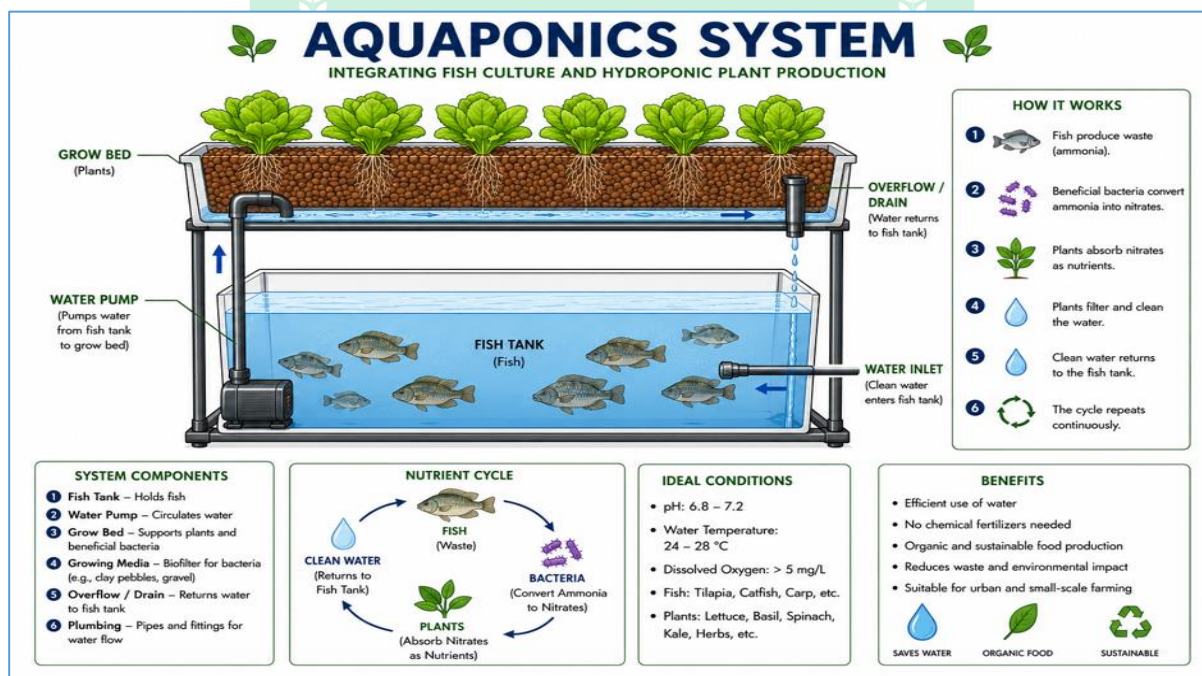


Fig. 6 and Fig. 7 Drip irrigation and Aeroponics (Pictures Courtesy: AI tools)



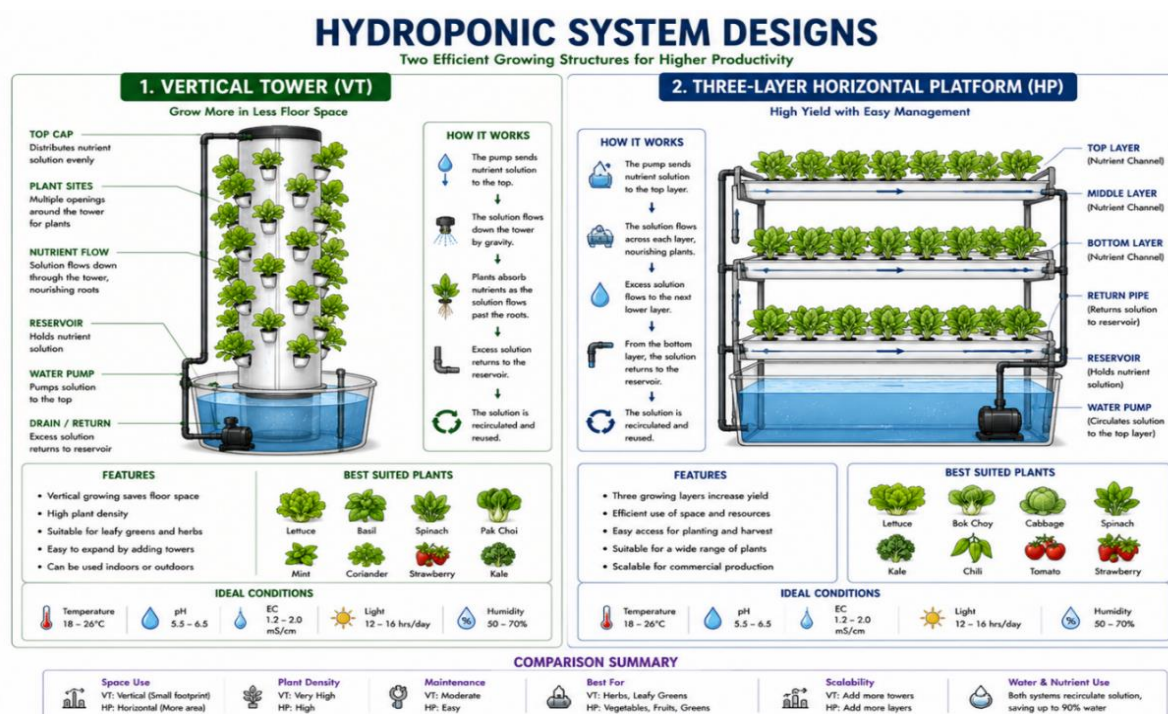
In this system, plants are suspended in the air, with their bare roots exposed to a nutrient rich mist. The roots are continuously supplied with oxygen and nutrients through the mist, promoting healthy growth and allowing plants to grow rapidly.

Fig. 8 Aquaponics (Pictures Courtesy: AI tools)



Aquaponics is a sustainable cultivation system that combines fish farming with plant cultivation. In this system, fish waste provides nutrients for plant growth, while the plants naturally filter and recycle the water, creating a mutually beneficial environment for both fish and plants.

Fig. 9 Hydroponics (Pictures Courtesy: AI tools)



Advantages

- Requires up to 90% less water than conventional soil cultivation.
- Enables year-round production under protected and controlled environments.
- Produces higher yields through precise nutrient and environmental management.
- Efficient utilization of land, making it suitable for urban agriculture and areas with limited cultivable land.
- Allows accurate control of nutrient concentration, pH and irrigation.
- Reduces fertilizer wastage through nutrient recycling in closed systems.
- Minimizes soil-borne diseases, weeds and many insect pests.
- Eliminates the need for crop rotation and intensive land preparation.
- Reduces transplant shock and promotes faster plant growth due to better root aeration.
- Improves labour efficiency by facilitating easier planting, maintenance and harvesting.

Limitations of Hydroponics

- High initial investment and infrastructure costs.
- Requires technical knowledge and continuous monitoring of nutrient solution and environmental conditions.
- Dependence on uninterrupted electricity and water supply in automated systems.
- Rapid spread of water-borne diseases, such as Fusarium and Verticillium, in recirculating systems if not properly managed.
- Equipment failure or nutrient imbalance can quickly affect crop growth and productivity.

Recent research achievements

Rapid population growth, declining natural resources, climate change, and increasing demand for sustainable food production have accelerated research on hydroponic cultivation systems (Tilman et al., 2011; Gonnella and Renna, 2021). Hydroponics has emerged as a climate-resilient production technology that enables precise control over plant nutrition and environmental conditions, resulting in improved productivity and resource-use efficiency (Schooneveldt, 2025).

Recent advances have focused on improving nutrient management, water-use efficiency, automation, and crop quality. Closed-loop hydroponic systems substantially reduce nutrient losses while lowering water consumption by more than 70–90% compared with conventional agriculture (Sharma et al., 2018; Bunyuth and

Mardy, 2024). The integration of sensors, IoT, machine learning, and artificial intelligence enables real-time monitoring of pH, electrical conductivity, dissolved oxygen, temperature, and nutrient status, facilitating automated decision-making and precision crop management.

Vertical hydroponic farming has gained considerable attention due to its efficient use of space, reduced land requirements, year-round production capability, and enhanced resource conservation. Research has also demonstrated improvements in crop yield, nutritional quality, and production efficiency through optimized nutrient formulations, LED lighting, climate control, and intelligent automation. These developments position hydroponics as a promising technology for sustainable urban agriculture, protected cultivation, and future food production systems.

Validated technologies

- Standardized hydroponic production protocols for leafy vegetables (lettuce, spinach, kale, pak choi) under protected cultivation.
- Optimized nutrient solution formulations are available for different crop growth stages, improving nutrient use efficiency.
- Developed low-cost NFT (Nutrient Film Technique), Deep Water Culture (DWC), and cocopeat-based hydroponic systems suitable for small and marginal farmers.
- Standardized water parameters (pH 5.5–6.5 and EC 1.2–2.5 mS cm⁻¹) for enhanced crop productivity.
- Hydroponic system, the nutrient solution was prepared with a pH of 6.0 for ensuring nutrient solubility.
- Established integrated fertigation and automated nutrient monitoring systems for precision hydroponics.

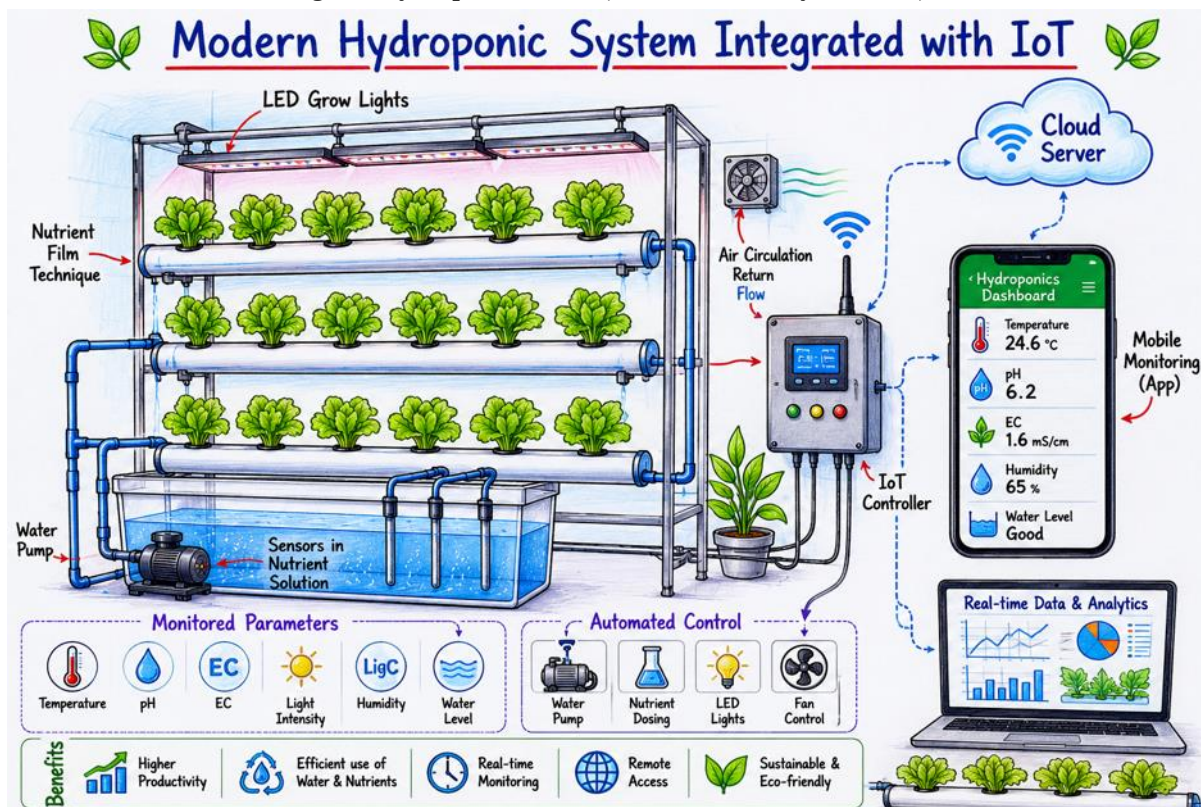
Innovative Practices

The integration of Machine Learning (ML), the Internet of Things (IoT), automation, and vertical farming is transforming hydroponic cultivation into a highly efficient, resource-conserving and climate-resilient production system.

- Machine Learning (ML) for smart hydroponics: ML enables automated analysis of sensor data to optimize nutrient management, irrigation, environmental control, plant growth monitoring, pest and disease detection, and yield prediction, thereby improving system efficiency and reducing manual intervention (Ragaveena et al., 2021; Dutta et al., 2025).
- IoT-enabled real-time monitoring: IoT-based hydroponic systems employ sensors to continuously monitor critical parameters such as pH, electrical conductivity (EC), dissolved oxygen, temperature, relative humidity, nutrient concentration, and water quality. Real-time monitoring and automated control ensure optimal crop growth while minimizing labour, water, and nutrient use (Ragaveena et al., 2021; Ares et al., 2021; Dutta et al., 2025).
- AI-assisted nutrient and irrigation management: Artificial intelligence supports precision nutrient scheduling and irrigation management, reducing fertilizer and water consumption while maintaining optimum crop productivity (Abhishek Rana et al., 2026).
- Solar-powered hydroponic systems: The development of solar-powered hydroponic units enables sustainable, off-grid cultivation, particularly suitable for remote and energy-limited regions.
- Biofertilizers and beneficial microorganisms: The use of beneficial microbes and live microalgae in nutrient solutions is emerging as a sustainable practice. Application of *Chlorella* sp. in hydroponic lettuce increased total yield by 18.3% compared with the control (Memeli et al., 2025). Further research is needed to understand microalgae–plant interactions and evaluate their effectiveness across different crops and hydroponic systems.
- Vertical farming integrated with hydroponics: Combining hydroponics with vertical farming maximizes production per unit area while reducing land and water requirements. Vertical farming offers year-round production of vegetables, herbs, and fruits in climate-controlled environments with minimal pesticide use. However, wider adoption requires improvements in energy efficiency, economic viability, policy support, and consumer acceptance (van Delden et al., 2021).

Overall, these innovations are making hydroponic cultivation more precise, resource-efficient, sustainable, and suitable for urban and climate-resilient agriculture.

Fig. 10. Hydroponics + IoT (Pictures Courtesy: AI tools)



Policy relevant recommendations

- Promote hydroponics under urban agriculture and peri-urban farming initiatives.
- Include hydroponic infrastructure under government subsidy schemes.
- Develop quality standards for hydroponic produce and nutrient formulations.
- Establish skill development programs and certification for hydroponic farming.
- Encourage public-private partnerships for commercial hydroponic production.

Quantitative impact data

- Water savings of 80–95% compared with conventional cultivation.
- Fertilizer use efficiency increased by 30–50%.
- Crop yield increased by 20–50%, depending on crop and production system.
- Reduction in pesticide usage by 70–100% under controlled environments.
- Production cycles shortened by 15–30% for leafy vegetables.
- Land productivity improved by 5–10 times using vertical hydroponic systems.

Success stories with measurable outcomes

- Urban rooftop hydroponic units supplying fresh vegetables to local markets throughout the year.
- Farmer producer organizations successfully adopting commercial lettuce and basil cultivation with higher net returns (Chatterjee et al., 2025).
- Educational institutions establishing hydroponic demonstration units for training students and entrepreneurs.
- Women and youth entrepreneurs generating sustainable income through small-scale hydroponic enterprises.

Field case studies (Table 1)

Recommended Best Practices

- Selection of the hydroponic system should be based on crop requirements, climatic conditions, production objectives, and economic feasibility.
- Maintenance of nutrient solution pH should be within the range of 5.5–6.5 to ensure optimum nutrient availability.

- Maintenance of nutrient solution EC should be within 1.4–1.8 dS m⁻¹, or as recommended for the specific crop.
- Monitoring and adjustment of nutrient composition, pH, and EC should be carried out regularly using calibrated instruments or IoT-based monitoring systems.
- Provision of adequate dissolved oxygen in the nutrient solution should be ensured through continuous aeration to promote healthy root growth.
- Use of clean, pathogen-free water and regular sanitation of nutrient reservoirs, channels, pipes, and other system components should be practiced between production cycles to minimize disease incidence.
- Monitoring of environmental parameters, including temperature, relative humidity, and light intensity, should be conducted using digital sensors or data loggers to maintain optimum growing conditions.
- Positioning of LED lighting systems should ensure uniform light distribution across the crop canopy to maximize photosynthetic efficiency.
- Calibration of pH meters, EC meters, nutrient dosing equipment, and environmental sensors should be performed periodically to ensure accurate measurements and nutrient delivery.
- Implementation of Integrated Pest Management (IPM) practices should include regular crop scouting, sanitation, biological control, and environmental management, even under protected cultivation.
- Maintenance of comprehensive production records should include nutrient schedules, environmental conditions, crop performance, and pest incidence to support continuous system optimization and improved productivity.

Adoption of these best management practices enhances crop productivity, resource-use efficiency, produce quality, and economic returns while ensuring sustainable hydroponic production under both commercial and urban farming conditions.

Relevant national and international publications/references

- Ahmed, M. & Singla, N. (2023). Spatial market integration, price transmission and transaction costs in major onion markets of India. *The Indian Economic Journal*, 71(3), 532–547. <https://doi.org/10.1177/00194662231159851>
- Akter, N., Cammarisano, L. & Ahamed, M. S. (2026). Interactive effects of electrical conductivity and light intensity on growth, yield, and nutrient dynamics of hydroponic lettuce. *Scientific Reports*, 16, 14803. <https://doi.org/10.1038/s41598-026-44508-2>
- Akter, T., Mahmud, T., Chakma, R., Datta, N., Hossain, M. S. & Andersson, K. (2024). Smart monitoring and control of hydroponic systems using IoT solutions. In *Proceedings of the 2024 International Conference on Inventive Computing and Informatics (ICICI)* (pp. 761–767). IEEE. <https://doi.org/10.1109/ICICI62254.2024.00128>
- Anusree, G., Sajitha Rani, T., Shalini Pillai, P., Rajasree, G., Thomas, U. C. & Dhalin, D. (2025). Evaluation of hydroponic systems for optimizing growth and yield of tomato (*Solanum lycopersicum* L.). *International Journal of Environment and Climate Change*, 15(5), 144–151. <https://doi.org/10.9734/ijecc/2025/v15i54841>
- Ares, G., Ha, B. & Jaeger, S. R. (2021). Consumer attitudes to vertical farming (indoor plant factory with artificial lighting) in China, Singapore, UK, and USA: A multi-method study. *Food Research International*, 150, 110811. <https://doi.org/10.1016/j.foodres.2021.110811>
- Biçici, E. & Boyacı, H. F. (2026). Hydroponic design influences morphophysiology and mineral uptake in kale (*Brassica oleracea* var. *acephala*). *Scientific Reports*, 16, 8982. <https://doi.org/10.1038/s41598-026-40756-4>
- Bunyuth, Y. & Mardy, S. (2024). Hydroponic systems: An overview of benefits, challenges, and future prospects. *International Journal of Sustainable Engineering and Applied Practices*, 1(1), 10–18.
- Chatterjee, A., Ghosh, P., Winkler, B., Vijayaragavan, V., Debnath, S., Cichocki, J., Trenkner, M., Vanicela, B., Riethmueller, C., Walz, M., Chandra, S. & Pal, H. (2025). Demystifying the integration of hydroponics cultivation system reinforcing bioeconomy and sustainable agricultural growth. *Scientia Horticulturae*, 341, 113973. <https://doi.org/10.1016/j.scienta.2025.113973>

- Dutta, M. & Gupta, D. (2023). Green IoT for sustainable smart vertical farming: A comprehensive analysis. In Proceedings of the IEEE 2nd International Conference on Industrial Electronics: Developments & Applications (ICIDeA) (pp. 175–180). IEEE. <https://doi.org/10.1109/ICIDeA59866.2023.10295191>
- Dutta, M., Gupta, D., Juneja, S., et al. (2025). Machine learning insights for sustainable hydroponic cultivation and growth monitoring of *Allium cepa* using smart hydro kit. *Scientific Reports*, 15, 10164. <https://doi.org/10.1038/s41598-024-82920-8>
- El-Demerdash, D. I., Morad, M. M., Wasfy, K. I., et al. (2026). Aeroponic and NFT system optimization for lettuce: Effects of flow rate and nutrient source on water use efficiency, growth, and profitability. *Scientific Reports*, 16, 14292. <https://doi.org/10.1038/s41598-026-41347-z>
- En, L. W., Lim, C. L., Kok, C. L., et al. (2026). Sustainable urban farming using a smart hydroponic approach using IoT and real-time monitoring. *Scientific Reports*, 16, 8361. <https://doi.org/10.1038/s41598-026-37971-4>
- Frasetya, B., Harisman, K. & Ramdaniah, N. A. H. (2021). The effect of hydroponics systems on the growth of lettuce. *IOP Conference Series: Materials Science and Engineering*, 1098.
- George, P. & George, N. (2016). Hydroponics (soilless cultivation of plants) for biodiversity conservation. *International Journal of Modern Trends in Engineering and Science*, 3, 97–104.
- Gonnella, M. & Renna, M. (2021). The evolution of soilless systems towards ecological sustainability in the perspective of a circular economy: Is it really the opposite of organic agriculture? *Agronomy*, 11(5), 950.
- Kabir, M. S. N., et al. (2023). Technological trends and engineering issues on vertical farms: A review. *Horticulturae*, 9(11), 1229.
- Khan, F. A. (2018). A review on hydroponic greenhouse cultivation for sustainable agriculture. *International Journal of Agriculture, Environment and Food Sciences*, 2(2), 59–66. <https://doi.org/10.31015/jaefs.18010>
- Memeli, İ., Tüzel, Y., Uysal, Ö., et al. (2025). Microalgae enhanced plant growth and yield, and improved leaf color in soilless lettuce. *Scientific Reports*, 15, 40313. <https://doi.org/10.1038/s41598-025-24004-9>
- Morite, A. S., Bacarro, R. R., Gamboa, G. Z., Angob, V. J. V. D. & Manzo, E. J. M. (2023). Water circulation and control of hydroponics using the Internet of Things. *Science International*, 35(3), 299–305.
- Ragaveena, S., Shirly Edward, A. & Surendran, U. (2021). Smart controlled environment agriculture methods: A holistic review. *Reviews in Environmental Science and Bio/Technology*, 20(4), 887–913.
- Rodríguez-Delfin, A., Gruda, N., Eigenbrod, C., Orsini, F. & Gianquinto, G. (2017). Soil-based and simplified hydroponics rooftop gardens. In F. Orsini, M. Dubbeling, H. de Zeeuw & G. Gianquinto (Eds.), *Rooftop Urban Agriculture* (pp. 61–81). Cham, Switzerland: Springer. <https://doi.org/10.1007/978-3-319-57720-3>
- Schooneveldt, J. (2025). Regenerative farming and greening of food production. In J. A. Matthews & A. Oqubay (Eds.), *The Greening of Economic Development* (pp. 431–455). Oxford University Press.
- Sharkey, A., et al. (2024). Modeling Bibb lettuce nitrogen uptake and biomass productivity in vertical hydroponic agriculture. *Agriculture*, 14(8), 1358.
- Sharma, N., Acharya, S., Kumar, K., Singh, N. & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, 17(4), 364–371.
- Sharma, S., Dhanda, N. & Verma, R. (2023). Urban vertical farming: A review. In Proceedings of the 13th International Conference on Cloud Computing, Data Science and Engineering (Confluence) (pp. 432–437). IEEE. <https://doi.org/10.1109/Confluence56041.2023.10048883>
- Tilman, D., Balzer, C., Hill, J. & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 108(50), 20260–20264.
- van Delden, S. H., SharathKumar, M., Butturini, M., et al. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nature Food*, 2, 944–956. <https://doi.org/10.1038/s43016-021-00402-w>
- Wahome, P. K., Oseni, T. O., Masarirambi, M. T. & Shongwe, V. D. (2011). Effects of different hydroponics systems and growing media on the vegetative growth, yield and cut flower quality of *Gypsophila* (*Gypsophila paniculata* L.). *World Journal of Agricultural Sciences*, 7, 692–698.

Table 1: Recent Research Achievements and Technological Innovations in Hydroponics

Crop	Type of hydroponic system	Technology/Innovation	Applications	Benefits	Reference
Tomato (<i>Solanum lycopersicum</i> L.)	Ebb and Flow (Flood and Drain)	The growing medium is periodically flooded with nutrient solution and then drained, providing alternate nutrient availability and root aeration.	Commercial fruit vegetable production in greenhouses and protected cultivation systems.	• 25–30% increase in fruit yield compared with soil cultivation. • Highest average fruit weight (46.85 g) and fruit yield (2.10 kg plant⁻¹). • Enhanced root development and plant vigour. Improved fruit uniformity and quality with reduced disease incidence under controlled environments.	Anusree <i>et al.</i> (2025)
Onion (<i>Allium cepa</i> L.)	Deep Water Culture (DWC)	Plant roots are continuously suspended in an aerated nutrient solution, ensuring uninterrupted access to water, nutrients, and dissolved oxygen.	Commercial year-round onion production, bulb and shoot cultivation under protected environments, water-limited regions, urban and vertical farming.	• Cost-effective production system. • Comparable or higher yields using only ~10% of cultivable land. • Up to 90% water saving compared with soil cultivation. • Improved bulb and shoot growth with a shorter crop duration, enabling multiple production cycles annually. • Increased biomass by 0.373 t ha⁻¹ and dry yield by 0.097 t ha⁻¹ over soil cultivation.	Torquato-Tavares <i>et al.</i> (2017); Ahmed & Singla (2023); Dutta <i>et al.</i> (2025)
Kale (<i>Brassica oleracea</i> var. <i>acephala</i>)	Nutrient Film Technique (NFT)	IoT-enabled smart household hydroponic system integrated with LED grow lights. The system incorporates sensors to monitor environmental parameters, including light intensity and water temperature, enabling automated control and real-time data acquisition.	Indoor urban farming, household hydroponic production, real-time environmental monitoring, automated nutrient management, remote connectivity, and optimization of crop growth using IoT and LED lighting.	• Provides a well-controlled growing environment for efficient household hydroponics. • LED lighting under ambient room temperature increased leaf	En <i>et al.</i> (2026)

				number and biomass by 15–20% compared with other lighting and temperature conditions. Enhances photosynthetic efficiency and promotes uniform indoor plant growth.	
Kale (<i>Brassica oleracea</i> var. <i>acephala</i>) (Cultivars: Oldenbor F1 and Redbor F1)	Vertical Tower (VT) and Three-layer Horizontal Platform (HP)	Comparative evaluation of Vertical Tower (VT) and Three-layer Horizontal Platform (HP) hydroponic systems to assess their effects on growth performance, physiological traits, and nutrient uptake in curly kale cultivars.	Optimization of hydroponic system design through cultivar–system matching to improve morphophysiological performance, nutrient-use efficiency, and sustainability in vertical farming and climate-resilient soilless production systems.	- The Three-layer Horizontal Platform (HP) consistently outperformed the Vertical Tower (VT) system. - Promoted superior vegetative growth, higher photosynthetic pigment retention, and greater nutrient accumulation. - Improved productivity and resource-use efficiency for commercial hydroponic kale production.	Biçici <i>et al.</i> (2026)
Spinach (<i>Spinacea oleraceae</i>)	Nutrient Film Technique (NFT)	A hydroponic system in which a thin, continuously flowing film of nutrient solution passes over the roots, ensuring efficient nutrient delivery, root aeration, and uniform plant growth under protected cultivation	Commercial production of leafy vegetables, greenhouse cultivation, high-density planting, year-round production, and efficient water- and nutrient-managed farming systems.	- Enhances biomass production and overall yield. - Increases seed germination percentage and reduces mean germination time. - Improves seed vigour index, resulting in better crop establishment. - Promotes uniform plant growth and efficient nutrient uptake. - Improves water and nutrient use efficiency compared with conventional soil cultivation.	Balasubramaniam <i>et al.</i> (2025); Rautela <i>et al.</i> (2025)

Banana (<i>Musa spp.</i>)	Hydroponic hardening using Nutrient Film Technique (NFT)	Continuous recirculation of a thin nutrient film over roots, providing constant water, nutrients, and aeration	Acclimatization (hardening) of tissue culture banana plantlets in commercial nurseries	Approximately 90% reduction in water use • Hardening period reduced from 50–60 to 30–35 days • Hardening cost reduced by ~35% (Rs. 2.00 to Rs. 1.40 per plantlet) • Faster root development and uniform plant growth • Healthy, vigorous plantlets with improved transplant establishment • Suitable for large-scale commercial nursery production	Araújo <i>et al.</i> (2023); Sujith (2023)
Lettuce (<i>Lactuca sativa L.</i>)	Nutrient Film Technique (NFT)	A thin, continuously flowing film of nutrient solution circulates through channels, providing efficient nutrient uptake while maintaining root aeration.	Commercial leafy vegetable production, greenhouse cultivation, vertical farming, intensive year-round production.	• 6–10% higher yield efficiency than Floating Raft and Deep Flow Technique (DFT). • Fresh shoot weight: 97.78 g plant⁻¹; dry shoot weight: 10.25 g plant⁻¹. • Approximately 35% higher yield than soil cultivation. • About 90% reduction in water use. • Harvest within 30–35 days, enabling rapid crop turnover.	Mitova <i>et al.</i> (2017); Frassetta <i>et al.</i> (2021); El-Demerdash <i>et al.</i> (2026); Akter <i>et al.</i> (2026)

Adoption of Precision Dairy Farming Technologies by Farmers in Madhya Pradesh



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Introduction

Dairy farming is one of the most important livelihood activities in Madhya Pradesh, providing regular income, nutritional security and employment to millions of rural households. The state has witnessed steady growth in milk production over the past decade through breed improvement, expansion of artificial insemination services, better veterinary healthcare and increasing participation of dairy cooperatives. However, challenges such as rising production costs, labour shortages, climate change, disease outbreaks and declining profit margins are encouraging farmers to adopt modern technologies that improve efficiency and productivity. Precision Dairy Farming (PDF) has emerged as an innovative approach that integrates digital technologies, sensors, automation, artificial intelligence and data-driven decision-making to optimize dairy farm management. Although the adoption of these technologies is still at an early stage in Madhya Pradesh, increasing digital connectivity, government support and growing awareness are creating new opportunities for smart dairy farming.

Understanding Precision Dairy Farming

Precision Dairy Farming refers to the application of advanced technologies for monitoring individual animals and managing dairy farms based on real time information. Instead of treating all animals similarly, precision farming focuses on the specific nutritional, reproductive, health and behavioural needs of each animal. Information collected through wearable sensors, automated milking systems, milk analysers, digital weighing scales, activity monitors, climate sensors and computer-based management software enables farmers to make timely and accurate decisions. This scientific approach improves productivity, reduces production costs, enhances animal welfare and minimizes environmental impacts while increasing the overall efficiency of dairy enterprises.

Present Status in Madhya Pradesh

The adoption of Precision Dairy Farming technologies in Madhya Pradesh is gradually increasing, particularly among commercial dairy farms, progressive farmers, dairy cooperatives and institutional farms. Automatic milk analysers, digital milk collection systems, artificial insemination management software, mobile veterinary advisory services and electronic animal identification are becoming more common in organized dairy operations. Government initiatives promoting digital agriculture, livestock health monitoring and dairy infrastructure development have encouraged the gradual integration of technology into livestock management. However, the majority of smallholder dairy farmers still rely on conventional practices because of limited financial resources, inadequate awareness and insufficient technical training.

Key Precision Dairy Farming Technologies

Modern dairy farming utilizes a wide range of technologies to improve farm management and animal productivity. Wearable sensors attached to collars or ear tags continuously monitor animal movement, feeding behaviour, rumination, body temperature and activity levels, allowing early detection of disease and accurate identification of heat for timely breeding. Automatic milk analysers evaluate milk composition and quality within minutes, helping farmers maintain product standards and detect subclinical mastitis. Digital weighing systems monitor animal growth and nutritional status, while computerized herd management software maintains detailed records of breeding, vaccination, milk production, treatment history and reproductive performance. Mobile applications

provide weather forecasts, feeding recommendations, disease alerts, veterinary consultation and market information, enabling farmers to make informed management decisions even in remote villages.

Benefits to Dairy Farmers

Precision Dairy Farming offers numerous economic, managerial and environmental benefits. Continuous monitoring of animal health enables early diagnosis of diseases, reducing treatment costs and minimizing production losses. Accurate heat detection improves conception rates, shortens calving intervals and enhances reproductive efficiency. Balanced feeding based on individual nutritional requirements reduces feed wastage and improves milk yield, thereby increasing farm profitability. Automated record keeping simplifies herd management and supports scientific decision-making. Precision technologies also reduce labour requirements, improve milk quality, enhance animal welfare and promote efficient utilization of water, feed and energy resources. Collectively, these improvements increase the sustainability and competitiveness of dairy farming.

Role of Artificial Intelligence and the Internet of Things

Artificial Intelligence (AI) and the Internet of Things (IoT) are revolutionizing modern dairy farming by enabling continuous collection and analysis of farm data. Smart sensors installed on animals and within dairy sheds transmit real-time information to cloud-based platforms where AI algorithms identify abnormal behaviour, predict disease outbreaks, estimate milk production trends and recommend management interventions. Automated alerts sent directly to farmers smartphones enable rapid action before problems become severe. Such intelligent systems improve management precision while reducing unnecessary veterinary expenses and production losses.

Government Support and Institutional Initiatives

The Government of India and the Government of Madhya Pradesh are promoting digital transformation in agriculture and animal husbandry through various programmes aimed at improving dairy productivity and farmer incomes. Scientific breeding programmes, livestock health campaigns, digital veterinary services, strengthening of milk collection infrastructure and support for dairy entrepreneurship are creating an enabling environment for technology adoption. Agricultural universities, veterinary colleges, Krishi Vigyan Kendras (KVKs), the National Dairy Development Board (NDDB) and dairy cooperatives are conducting training programmes that familiarize farmers with modern dairy technologies. These institutions play an important role in demonstrating innovative technologies and encouraging their adoption among rural communities.

Case Studies of Progressive Dairy Farmers in Madhya Pradesh

The gradual adoption of precision dairy farming technologies by progressive dairy farmers in Madhya Pradesh demonstrates how scientific management and digital innovations can significantly improve productivity and profitability. These examples highlight that technology adoption is not limited to large commercial farms but is increasingly becoming relevant for medium and small dairy enterprises. A notable example is Khushihaal Kushwaha from Satna district, who transformed a small family dairy into a successful commercial enterprise through scientific dairy management. Beginning with a single cow purchased to support his family, he gradually expanded his herd by adopting balanced feeding, systematic breeding, hygienic milk production and improved housing practices. Today, his dairy enterprise generates a stable monthly income while providing employment opportunities in the local community. His success demonstrates that continuous investment in improved management practices and adoption of modern technologies can substantially enhance farm profitability.

Another inspiring example is Anita Charel, a tribal entrepreneur from Jhabua district, who established Khushi Milk Udyog with support from government development programmes. Initially collecting only about 15 litres of milk per day from six local farmers, she expanded the enterprise to collect nearly 180 litres of milk daily. The enterprise now provides market access and livelihood opportunities to around 35 rural families through milk collection, processing, and marketing. Although her business focuses on value addition, digital record keeping, organized milk procurement and quality assurance, it also illustrates how technology and entrepreneurship can strengthen rural dairy value chains in Madhya Pradesh.

The digital transformation of the cooperative dairy sector is equally encouraging. Sanchi Dairy, one of the largest dairy cooperatives in Madhya Pradesh, has introduced enterprise resource planning (ERP)-based digital management systems to improve milk procurement, processing, inventory management, and quality control. The cooperative handles more than three lakh litres of milk per day through an extensive network of milk chilling

centres and procurement routes. Such digital infrastructure demonstrates how precision technologies can improve traceability, operational efficiency, transparency and service delivery across the dairy value chain while benefiting thousands of milk producers associated with the cooperative. Recognizing the importance of technology-driven dairy development, the Government of Madhya Pradesh, in collaboration with the National Dairy Development Board (NDDB), has initiated programmes to modernize the dairy sector through the expansion of dairy cooperatives, implementation of Automatic Milk Collection Systems (AMCS), digitalization of milk procurement, quality testing and scientific herd management. These initiatives are expected to accelerate the adoption of precision dairy farming technologies among farmers across the state, particularly through cooperative institutions and farmer producer organizations. These success stories clearly demonstrate that the adoption of precision dairy farming is not merely about sophisticated equipment but about integrating scientific management, digital tools, organized marketing and continuous learning. With appropriate training, financial support and access to affordable technologies, many more dairy farmers in Madhya Pradesh can successfully transition from traditional dairy farming to efficient, technology enabled and sustainable dairy enterprises.

Challenges to Adoption

Despite the significant benefits of Precision Dairy Farming, several constraints continue to limit its widespread adoption in Madhya Pradesh. The high initial investment required for advanced equipment remains a major challenge, particularly for smallholder farmers. Limited awareness, inadequate digital literacy, unreliable internet connectivity in some rural areas, insufficient technical support, and lack of trained service personnel further restrict adoption. Many farmers are also unfamiliar with digital record keeping and data interpretation. The absence of affordable, locally developed technologies specifically designed for small and medium dairy farms continues to slow the pace of modernization.

Emerging Opportunities

The future of Precision Dairy Farming in Madhya Pradesh is highly promising due to increasing smartphone penetration, expansion of rural internet connectivity, growing demand for quality milk and supportive government policies. Affordable wearable sensors, cloud-based herd management software, artificial intelligence assisted veterinary diagnosis, automated milk testing, drone-assisted fodder monitoring and precision feeding technologies are expected to become increasingly accessible. The rapid growth of Farmer Producer Organizations (FPOs), dairy cooperatives and start-ups developing digital livestock solutions is creating new opportunities for technology dissemination. As these innovations become more affordable and user-friendly, even smallholder farmers will be able to benefit from smart dairy management practices.

Future Prospects

The future dairy sector in Madhya Pradesh will increasingly rely on digital technologies to improve productivity, profitability, and environmental sustainability. Precision Dairy Farming will support climate-smart livestock production through efficient feed utilization, reduced greenhouse gas emissions, improved water management, and better disease surveillance. Continued investment in farmer training, digital infrastructure, research, innovation, and public-private partnerships will accelerate the transition from conventional dairy farming to intelligent, data-driven livestock production systems. The integration of AI, IoT, robotics, and big-data analytics will further enhance farm resilience and strengthen the competitiveness of the dairy sector in national and global markets.

Conclusion

Precision Dairy Farming represents a significant technological advancement capable of transforming dairy production in Madhya Pradesh. By enabling real-time monitoring of animal health, reproduction, nutrition and productivity, these technologies help farmers make informed decisions that improve milk production, reduce production costs and enhance animal welfare. Although adoption is currently concentrated among progressive and commercial dairy farmers, increasing awareness, supportive government initiatives, expanding digital infrastructure and declining technology costs are expected to accelerate adoption across the state. Promoting affordable precision technologies, strengthening extension services and enhancing farmers' digital skills will play a vital role in building a modern, sustainable and competitive dairy industry in Madhya Pradesh.

References

- Food and Agriculture Organization (FAO). 2023. *Digital Technologies in Sustainable Livestock Systems*.
- Indian Council of Agricultural Research (ICAR). 2024. *Precision Livestock Farming in India*.
- National Dairy Development Board (NDDB). *Annual Report (latest edition)*.
- Department of Animal Husbandry and Dairying (DAHD), Government of India. *Annual Report (latest edition)*.
- Basic Animal Husbandry Statistics (BAHS), Government of India (latest edition).
- International Committee for Animal Recording (ICAR). *Guidelines for Precision Dairy Farming*.



Carbon Neutral Dairy Farming and Green Livestock Production: The Future of Sustainable Animal Husbandry



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Introduction

The livestock sector is a cornerstone of global agriculture, providing nutritious food, employment and livelihoods to millions of people. Dairy farming, in particular, contributes significantly to food security and rural economies. However, livestock production is increasingly challenged by climate change, which has led to rising temperatures, erratic rainfall, water shortages and declining natural resources. At the same time, dairy farming contributes to greenhouse gas emissions through enteric methane production, manure management, feed cultivation and energy use. As the world strives to achieve sustainable development and climate goals, the dairy sector is undergoing a transformation toward environmentally responsible production systems. Carbon-neutral dairy farming and green livestock production offer a practical pathway to reduce environmental impacts while maintaining profitability and ensuring long-term sustainability.

Understanding Carbon-Neutral Dairy Farming

Carbon-neutral dairy farming refers to a production system in which the greenhouse gases emitted during dairy production are balanced by measures that remove or offset an equivalent amount of carbon from the atmosphere. Instead of attempting to eliminate all emissions, farmers adopt practices that reduce methane, carbon dioxide and nitrous oxide emissions while increasing carbon sequestration through trees, healthy soils and improved pasture management. This approach aims to produce milk with a lower environmental footprint without compromising animal productivity, farm income or food quality. Carbon neutrality is achieved through a combination of efficient resource management, renewable energy adoption, improved feeding practices and conservation of natural ecosystems.

Importance of Green Livestock Production

Green livestock production represents an environmentally friendly approach to raising animals while ensuring economic viability and social responsibility. It emphasizes efficient use of natural resources, reduced pollution, improved animal welfare, and sustainable management of land and water resources. As global demand for milk continues to increase, environmentally sustainable production systems are becoming increasingly important for protecting biodiversity, conserving ecosystems and reducing the impacts of climate change. Green livestock farming also enhances farm resilience by improving resource-use efficiency, lowering production costs and creating healthier production environments for both animals and farmers.

Major Sources of Greenhouse Gas Emissions in Dairy Farming

Greenhouse gas emissions in dairy farming originate from several interconnected sources. The largest contributor is enteric fermentation, during which microorganisms in the rumen produce methane as part of the natural digestive process. Manure storage and decomposition also generate methane and nitrous oxide, particularly when manure is stored under anaerobic conditions. Feed production contributes additional emissions through fertilizer manufacture, irrigation, mechanized cultivation, harvesting, transportation and processing. Energy consumption for milking machines, milk cooling systems, lighting and water pumping further increases carbon emissions when fossil fuels are used. In addition, land-use changes such as deforestation for fodder cultivation or grazing reduce the natural capacity of ecosystems to absorb atmospheric carbon dioxide.

Climate-Smart Feeding Strategies

Efficient feeding practices play a critical role in reducing methane emissions while improving milk production. Balanced rations formulated according to the nutritional requirements of dairy animals enhance feed utilization and reduce the amount of methane produced per unit of milk. High-quality forages, improved pasture management, leguminous fodder crops and scientifically formulated total mixed rations improve digestibility and animal performance. Reducing feed wastage and utilizing locally available crop residues after appropriate treatment further improve sustainability. Scientifically validated feed additives can reduce enteric methane emissions when used according to approved guidelines. Together, these nutritional interventions contribute to both environmental protection and improved farm profitability.

Animal Health and Productivity

Maintaining excellent animal health is essential for achieving carbon neutral dairy production because healthy animals convert feed into milk more efficiently than diseased or stressed animals. Preventive healthcare through regular vaccination, deworming, disease surveillance, balanced mineral supplementation and proper reproductive management helps maintain high productivity while reducing greenhouse gas emissions per litre of milk produced. Comfortable housing, effective ventilation, clean drinking water and measures to reduce heat stress further improve animal welfare and performance. Investing in animal health not only increases milk yield but also reduces economic losses associated with disease and premature culling.

Sustainable Manure Management

Livestock manure should be regarded as a valuable agricultural resource rather than a waste product. Scientific manure management practices such as composting, vermicomposting and anaerobic digestion convert manure into nutrient-rich organic fertilizers while reducing methane emissions. Biogas technology is particularly beneficial because it transforms animal waste into renewable energy that can be used for cooking, heating, electricity generation or water pumping. The nutrient rich slurry produced after biogas generation serves as an excellent organic fertilizer, reducing dependence on chemical fertilizers and promoting soil health. Proper storage and timely application of manure further minimize nutrient losses and environmental pollution.

Renewable Energy in Dairy Farming

The adoption of renewable energy technologies has become an important component of green dairy farming. Solar-powered water pumps, rooftop photovoltaic systems, solar milk chilling units and biogas-based electricity generation significantly reduce dependence on fossil fuels while lowering operational costs. Energy-efficient equipment and improved farm infrastructure further decrease electricity consumption. Renewable energy systems not only reduce greenhouse gas emissions but also provide reliable energy supplies for remote rural communities where conventional electricity may be limited or expensive.

Carbon Sequestration through Agroforestry and Pastures

Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide in vegetation and soil. Integrating trees with dairy farming through agroforestry systems provides multiple environmental and economic benefits. Trees absorb carbon dioxide, provide shade to livestock, reduce heat stress, improve biodiversity, prevent soil erosion and supply fodder, fuelwood and timber. Well-managed grasslands and permanent pastures also store significant quantities of carbon below ground, improving soil fertility and water-holding capacity while contributing to climate change mitigation. Such integrated farming systems create resilient agricultural landscapes capable of sustaining livestock production under changing climatic conditions.

Water Conservation and Resource Efficiency

Water conservation has become increasingly important as climate change intensifies water scarcity in many dairy producing regions. Efficient water management practices such as rainwater harvesting, recycling of wastewater, leak prevention, efficient cleaning methods and micro-irrigation systems for fodder cultivation help reduce freshwater consumption. Growing drought tolerant fodder crops and adopting precision irrigation technologies further improve water use efficiency. Sustainable water management not only conserves valuable natural resources but also enhances the long-term productivity and resilience of dairy farms.

Digital Technologies Supporting Green Dairy Farming

Advances in digital technology are transforming dairy farming by enabling precise monitoring and efficient management of livestock. Precision feeding systems, wearable sensors, automated milk recording, artificial intelligence-based disease detection, climate monitoring devices and digital herd management software allow farmers to optimize feed use, monitor animal health, detect diseases early and improve reproductive performance. These technologies reduce unnecessary resource use, improve productivity and support data-driven decision-making that contributes to lower greenhouse gas emissions and higher farm efficiency.

Opportunities for India

India, as the world's largest milk producer, possesses enormous potential to lead the global transition toward climate-smart dairy farming. The country's vast livestock population, expanding dairy cooperative network, increasing adoption of renewable energy and strong research infrastructure provide excellent opportunities for implementing carbon neutral production systems. Government initiatives promoting biogas, climate-resilient agriculture, digital livestock services, indigenous breed conservation and sustainable dairy development can accelerate this transition. Furthermore, emerging carbon-credit markets may create additional income opportunities for farmers who adopt environmentally sustainable practices.

Challenges

Despite its many advantages, carbon-neutral dairy farming faces several practical challenges. Small landholdings, limited financial resources, inadequate awareness, insufficient technical expertise and restricted access to advanced technologies often hinder adoption among smallholder farmers. The initial investment required for renewable energy systems, precision farming equipment and improved infrastructure can also discourage implementation. Additionally, standardized methods for measuring farm-level carbon emissions and rewarding climate-friendly practices are still evolving in many developing countries. Overcoming these challenges will require coordinated efforts involving governments, research institutions, extension agencies, financial organizations and dairy cooperatives.

Future Prospects

The future of dairy farming will increasingly depend on balancing productivity with environmental sustainability. Continued research on methane mitigation, climate-resilient animal breeding, precision nutrition, renewable energy technologies and carbon accounting will support the development of more sustainable livestock systems. Strengthening farmer education, expanding climate-smart extension services, encouraging public-private partnerships and providing financial incentives for green technologies will further accelerate the adoption of carbon-neutral dairy farming. These efforts will help create resilient production systems capable of meeting growing food demands while protecting natural resources and mitigating climate change.

Conclusion

Carbon neutral dairy farming and green livestock production represent the future of sustainable animal husbandry. By integrating efficient feeding strategies, improved animal health, scientific manure management, renewable energy, water conservation, agroforestry and digital technologies, dairy farmers can substantially reduce greenhouse gas emissions while improving productivity and profitability. These environmentally responsible practices contribute not only to climate change mitigation but also to enhanced farm resilience, better animal welfare and improved livelihoods. As governments, researchers, dairy cooperatives, and farmers work together to adopt climate-smart livestock systems, carbon neutral dairy farming will play a vital role in ensuring food security, environmental sustainability and economic prosperity for future generations.

Organic Dairy Farming in Madhya Pradesh



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Introduction

Madhya Pradesh, often referred to as the Heart of India, possesses enormous potential for sustainable dairy farming due to its vast agricultural land, diverse climatic conditions, rich livestock resources and large rural population. Dairy farming serves as a vital source of income for millions of small and marginal farmers across the state. In recent years, increasing consumer awareness about food safety, environmental conservation and animal welfare has created a growing demand for organic milk and dairy products. Organic dairy farming has therefore emerged as an attractive alternative to conventional production systems. It combines traditional livestock management practices with scientifically validated organic principles, aiming to produce safe, nutritious milk while protecting the environment, conserving biodiversity and improving farmers' livelihoods.

Concept of Organic Dairy Farming

Organic dairy farming is a holistic livestock production system that emphasizes the use of natural resources, ecological balance and sustainable management practices. Unlike conventional dairy farming, it avoids the routine use of synthetic fertilizers, chemical pesticides, genetically modified organisms (GMOs), antibiotic growth promoters and hormone-based production enhancers. Organic dairy systems rely on organically produced feed, preventive healthcare, proper housing, balanced nutrition and good animal welfare practices. The objective is not only to produce chemical-residue-free milk but also to maintain soil fertility, reduce environmental pollution and promote long-term sustainability of livestock production.

Present Status of Dairy Farming in Madhya Pradesh

Madhya Pradesh has experienced remarkable growth in milk production during the past decade owing to improvements in dairy infrastructure, breed development programmes, artificial insemination services and government support. Indigenous cattle breeds such as Malvi, Nimari, Kenkatha and Gaolao, along with improved buffalo breeds including Murrah, play an important role in milk production across different regions of the state. The expansion of dairy cooperatives, private milk collection centres and rural dairy enterprises has further strengthened the dairy sector. However, increasing production costs, climate variability, fodder shortages and consumer demand for chemical free dairy products have encouraged interest in organic dairy farming as a sustainable alternative.

Why Organic Dairy Farming is Suitable for Madhya Pradesh

The geographical and agricultural characteristics of Madhya Pradesh make it particularly suitable for organic dairy production. Large areas of rainfed agriculture, availability of crop residues, diverse fodder resources and the widespread practice of mixed crop-livestock farming provide favourable conditions for organic management. Many smallholder farmers continue to use relatively low levels of synthetic inputs, making the transition to certified organic production comparatively easier than in highly intensive dairy systems. Furthermore, the increasing cultivation of organic crops in several districts offers opportunities for integrating organic crop and dairy enterprises, thereby creating circular farming systems that efficiently recycle nutrients and farm resources.

Organic Feeding and Nutrition

Nutrition is one of the most important pillars of organic dairy farming. Dairy animals should receive balanced diets prepared primarily from organically produced fodder, pasture grasses, crop residues and concentrate feeds

that are free from prohibited chemicals and genetically modified ingredients. Green fodder, leguminous forage crops, hay, silage, oilseed cakes and locally available feed resources contribute to maintaining animal health and milk productivity. Mineral mixtures and vitamin supplements permitted under organic standards may be used whenever nutritional deficiencies are identified. Emphasis is placed on maximizing grazing opportunities, improving rumen health and reducing dependence on purchased feed through efficient fodder production and conservation practices.

Animal Health and Welfare

Organic dairy farming places great importance on preventive healthcare and animal welfare. Healthy animals are maintained through balanced nutrition, clean housing, adequate ventilation, regular exercise, access to open grazing and effective biosecurity measures. Vaccination, deworming and disease surveillance continue to play essential roles in disease prevention in accordance with national veterinary recommendations and applicable organic standards. When animals become seriously ill, appropriate veterinary treatment should never be withheld. However, the use of medicines must follow the relevant organic certification requirements before products are marketed as organic. Providing comfortable housing, clean drinking water, sufficient resting space and opportunities to express natural behaviour contributes to improved welfare and sustainable productivity.

Organic Manure Management

One of the greatest advantages of organic dairy farming is the efficient recycling of livestock waste. Cow dung and urine are valuable farm resources that can be converted into compost, vermicompost, biogas and liquid organic fertilizers. Organic manure improves soil fertility, enhances microbial activity, increases water-holding capacity and reduces dependence on chemical fertilizers. Biogas plants provide clean renewable energy for rural households while producing nutrient rich slurry that can be returned to crop fields. This integrated approach reduces environmental pollution and strengthens the sustainability of both crop and livestock production systems.

Economic Opportunities

The market for organic milk and value-added dairy products is expanding rapidly in India due to increasing health consciousness among consumers. Organic milk, ghee, curd, paneer, butter and other dairy products often command premium prices compared with conventionally produced products when supported by credible certification and quality assurance. Farmer Producer Organizations (FPOs), dairy cooperatives, self-help groups and rural entrepreneurs in Madhya Pradesh have significant opportunities to establish local organic dairy value chains. Integration with agro-tourism, direct farm marketing and digital marketing platforms can further enhance farmers' incomes while strengthening consumer confidence in organic products.

Government Support and Certification

The Government of India and the Government of Madhya Pradesh have introduced several programmes that indirectly support sustainable and organic agriculture through capacity building, livestock development, natural farming and organic cultivation initiatives. Farmers interested in certified organic dairy production should follow recognized organic standards and maintain proper records related to feed sources, animal health, breeding, milk production and farm management. Certification under recognized organic systems enhances consumer trust and enables producers to access premium domestic and export markets. Training, technical guidance and cooperative participation are essential for successful adoption of certified organic dairy farming.

Challenges

Although organic dairy farming offers numerous environmental and economic advantages, farmers face several challenges during its adoption. Limited availability of certified organic feed, lack of organized marketing channels, relatively high certification costs, insufficient technical knowledge, lower productivity during the transition period and limited consumer awareness in rural markets are among the major constraints. Smallholder farmers may also encounter difficulties in maintaining documentation required for certification. Addressing these issues requires coordinated efforts involving government agencies, veterinary universities, dairy cooperatives, extension organizations and private stakeholders.

Future Prospects

The future of organic dairy farming in Madhya Pradesh appears promising as consumer demand for safe, nutritious and environmentally friendly food continues to increase. Advances in organic livestock nutrition,

natural disease management, climate-resilient fodder production, renewable energy technologies and digital traceability systems are expected to strengthen organic dairy enterprises in the coming years. Greater investment in farmer training, organic certification, research, value addition and market development will enable Madhya Pradesh to emerge as an important centre for sustainable dairy production in India.

Conclusion

Organic dairy farming represents a practical and environmentally responsible approach to achieving sustainable livestock development in Madhya Pradesh. By combining traditional knowledge with modern scientific management, farmers can produce high-quality milk while protecting soil health, conserving natural resources, improving animal welfare and reducing environmental pollution. With appropriate policy support, effective extension services, reliable certification systems, and growing consumer awareness, organic dairy farming has the potential to improve rural livelihoods, strengthen the dairy economy and contribute significantly to sustainable agricultural development in the state. Adopting organic dairy farming today will help build a healthier population, a cleaner environment and a more resilient agricultural future for Madhya Pradesh.

References

- Food and Agriculture Organization (FAO). 2023. *Organic Agriculture and Sustainable Livestock Production*.
Indian Council of Agricultural Research (ICAR). 2024. *Organic Livestock Production in India*.
Department of Animal Husbandry and Dairying (DAHD), Government of India. 2025. *Annual Report*.
National Programme for Organic Production (NPOP), Government of India.
APEDA. *National Standards for Organic Production (latest edition)*.
National Dairy Development Board (NDDB). *Sustainable Dairy Development in India*.



Women Entrepreneurship in Dairy and Livestock Farming



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Introduction

Women have always been the backbone of the livestock sector, contributing significantly to dairy farming, goat rearing, sheep husbandry, backyard poultry, piggery and other allied activities. In rural India, women perform a large share of the daily livestock management tasks, including feeding, milking, cleaning animal sheds, collecting fodder, caring for newborn animals along with marketing milk and milk products. Despite their substantial contribution, their work has often remained unrecognized and undervalued. In recent years, however, women are increasingly emerging as successful entrepreneurs in dairy and livestock farming by adopting scientific management practices, establishing dairy enterprises, forming self-help groups (SHGs) and participating in cooperative societies. Women entrepreneurship in livestock farming is not only strengthening household incomes but also promoting gender equality, rural employment, nutritional security and sustainable agricultural development.

Role of Women in Dairy and Livestock Farming

Women play a central role in almost every aspect of livestock production, making them indispensable to the success of the sector. They are actively involved in feeding animals, preparing balanced rations, fodder cultivation, milking, milk processing, calf care, disease observation, shed sanitation, manure management and record keeping. In many rural households, women are also responsible for producing value-added dairy products such as curd, butter, ghee, paneer and traditional sweets, which contribute additional income to family enterprises. Their close interaction with animals enables early detection of health problems and timely adoption of preventive healthcare measures. As dairy farming continues to evolve from subsistence production to commercial enterprise, women's knowledge, skills and experience have become valuable assets in improving livestock productivity and farm profitability.

Importance of Women Entrepreneurship

Entrepreneurship empowers women by providing them with economic independence, decision-making authority and greater participation in community development. Dairy and livestock enterprises require comparatively modest initial investments and generate regular income through the sale of milk, eggs, meat, wool, manure and breeding stock. These enterprises are therefore particularly suitable for rural women seeking sustainable livelihood opportunities. Income generated from livestock farming improves household nutrition, supports children's education, enhances healthcare access and strengthens financial resilience. Women entrepreneurs also contribute to rural economic growth by creating employment opportunities, encouraging local value addition, and promoting inclusive agricultural development.

Opportunities in Dairy and Livestock Enterprises

The livestock sector offers numerous entrepreneurial opportunities for women across rural and peri-urban areas. Commercial dairy farming remains one of the most profitable options due to the consistent demand for milk and dairy products throughout the year. Women are also successfully establishing goat farming units, backyard poultry enterprises, sheep production systems, piggery farms, duck farming, rabbit farming, fodder cultivation enterprises, vermicomposting units and biogas production systems. In addition to primary production, many women entrepreneurs are engaged in processing and marketing milk into products such as paneer, cheese, yogurt, flavoured milk, khoa and traditional dairy delicacies. The expansion of e-commerce platforms, direct farm

marketing and farmer producer organizations has further increased opportunities for women-led livestock enterprises.

Skill Development and Capacity Building

The success of women entrepreneurs depends greatly on access to knowledge, technical skills, and business management training. Veterinary universities, Krishi Vigyan Kendras (KVKs), agricultural universities, dairy cooperatives and government extension agencies regularly organize training programmes on scientific animal husbandry, balanced feeding, disease prevention, clean milk production, artificial insemination, value addition, record keeping, financial management and digital marketing. Continuous capacity building enables women to improve productivity, reduce production costs, adopt innovative technologies and efficiently manage commercial livestock enterprises. Entrepreneurial training also enhances confidence and leadership qualities, encouraging women to become successful business owners rather than remaining unpaid family workers.

Access to Finance and Government Support

Adequate financial support is essential for establishing and expanding livestock enterprises. Women entrepreneurs can access institutional credit through commercial banks, cooperative banks, regional rural banks, microfinance institutions and self-help group-based lending programmes. Several government initiatives promote women entrepreneurship in agriculture and livestock by providing subsidies, low-interest loans, insurance coverage, training and technical guidance. Dairy development programmes, livestock entrepreneurship promotion schemes, women self-help group initiatives and rural livelihood missions have significantly improved access to finance and market opportunities. These initiatives reduce financial barriers and encourage women to invest confidently in dairy and livestock businesses.

Technology and Digital Transformation

Modern technologies are creating new opportunities for women entrepreneurs to improve productivity and profitability. Mobile applications, digital payment systems, online veterinary consultation services, artificial intelligence-based herd management tools, wearable animal sensors, automatic milk analyzers and digital marketing platforms enable women to manage livestock enterprises more efficiently. Social media and e-commerce platforms allow entrepreneurs to promote and sell milk, dairy products, and livestock directly to consumers, eliminating intermediaries and improving profit margins. Digital literacy is therefore becoming an essential component of successful women-led livestock enterprises.

Challenges Faced by Women Entrepreneurs

Although women contribute enormously to livestock production, they continue to face several challenges that limit the growth of their enterprises. Limited ownership of land and livestock assets, restricted access to institutional credit, inadequate technical training, heavy household responsibilities, poor market linkages, limited mobility and gender-based social barriers often constrain entrepreneurial development. In many cases, women also have limited participation in financial decision-making despite being actively involved in livestock management. Climate change, fodder shortages, disease outbreaks and fluctuating market prices further increase the risks associated with livestock farming. Addressing these challenges requires gender-sensitive policies, improved access to education and financial services, stronger extension support and greater recognition of women's contributions to agriculture.

Success Through Collective Action

Women's self-help groups, dairy cooperatives, farmer producer organizations, and producer companies have demonstrated remarkable success in strengthening livestock-based entrepreneurship. Collective action enables women to access credit, purchase inputs at lower costs, receive technical training, process dairy products, negotiate better prices and reach larger markets. Group-based enterprises also promote leadership development, social inclusion, knowledge sharing and mutual support among rural women. Across many states in India, women-led dairy cooperatives have successfully increased household incomes while enhancing community participation in rural development programmes. Such collective approaches continue to play an important role in expanding women entrepreneurship in the livestock sector.

Future Prospects

The future of women entrepreneurship in dairy and livestock farming is highly promising due to increasing consumer demand for high-quality milk, value-added dairy products, organic foods and environmentally

sustainable production systems. Advances in climate-smart livestock farming, renewable energy, digital agriculture, precision feeding, disease surveillance and value chain development are creating new opportunities for women entrepreneurs. Government support for women led enterprises, expanding digital infrastructure, improved access to training and stronger market integration will further accelerate women participation in commercial livestock farming. Encouraging young rural women to adopt innovative agribusiness models will contribute significantly to employment generation, food security and sustainable rural development.

Conclusion

Women entrepreneurship in dairy and livestock farming has become a powerful driver of rural transformation, economic empowerment and sustainable agricultural development. By combining traditional knowledge with scientific livestock management, women are successfully establishing profitable enterprises that improve household income, nutritional security and community well-being. Strengthening woman's access to education, finance, technology, markets and institutional support will further unlock the enormous potential of the livestock sector. As India moves towards inclusive and climate resilient agricultural growth, empowering women entrepreneurs in dairy and livestock farming will remain essential for achieving sustainable development, reducing rural poverty and ensuring long-term prosperity.

References

- Food and Agriculture Organization (FAO). 2023. *The Status of Women in Agrifood Systems*.
Department of Animal Husbandry and Dairying (DAHD), Government of India. 2025. *Annual Report*.
National Dairy Development Board (NDDB). *Women in Dairy Development*.
Indian Council of Agricultural Research (ICAR). 2024. *Gender Mainstreaming in Livestock Development*.
National Rural Livelihoods Mission (NRLM). *Women Self-Help Groups and Rural Entrepreneurship*.
International Fund for Agricultural Development (IFAD). *Women's Economic Empowerment Through Livestock Development*.



Plant–Rhizosphere Microbial Interactions for Enhanced Organic Pollutant Remediation



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Abstract

Phytoremediation is a promising method of cleaning up contaminated environments. There is growing interest in extending the method's applications to include the removal or degradation of organic pollutants in the environment, even though it has only been used to remove dangerous heavy metals from contaminated soil. Both plants and soil bacteria have a hard time getting rid of or breaking down organic substances. Many of the restrictions may be overcome by plants that remove and/or break down hydrophobic substances and rhizosphere bacteria that make them more accessible, providing a useful foundation for enhancing clean-up of contaminated environments.

1. Introduction

The extensive use of synthetic organic compounds over the past several decades has created serious and long-lasting environmental challenges. Excessive application of pesticides in agriculture and public health programs has resulted in widespread contamination of food products, agricultural soils, and surface and groundwater resources. Persistent pesticide residues, particularly organochlorines, continue to remain in the environment even decades after their restriction or ban. In addition to pesticides, contaminants such as polychlorinated biphenyls (PCBs), petroleum-derived compounds including BTEX (benzene, toluene, ethyl benzene, and xylenes) and polycyclic aromatic hydrocarbons (PAHs), explosives, detergents, dyes, pigments, and toxic heavy metals have significantly contributed to environmental pollution and ecological degradation (Chaudhry *et al.* 2001). Growing environmental concerns and stricter regulatory frameworks have encouraged many countries to adopt rigorous soil and environmental protection policies. However, the high cost and technical limitations of conventional remediation technologies have restricted their large-scale application. Consequently, modern remediation strategies are increasingly focused on sustainable and risk-based approaches, aiming to minimize contaminant mobility and environmental hazards while preserving soil health and ecosystem functionality (Sheehan 1997).

2. Key Factors Affecting Organic Pollutant Biodegradation

2.1 Interactions between Bioavailability and Pollutant Toxicity

Biological remediation has great potential, yet it frequently has several drawbacks. The absorption of several soil-bound and soluble chemicals by remediating microorganisms and plants presents a unique challenge. When it comes to organic contaminants, this lack of availability is even more noticeable, which can occasionally severely limit plants' capacity to remediate. In many higher plants, the uptake and translocation of organic molecules through the transpiration stream may be severely limited for soil-bound and very hydrophobic chemicals, while it is ideal for mildly hydrophobic compounds (Bromilow and Chamberlain, 1995). In fact, the most crucial element influencing a remediation process's overall performance is the bioavailability of organic substances. For example, phytoremediation appeared to be a viable solution for a PAH-contaminated soil near Maarn, the Netherlands. However, this did not lead to any discernible removal or degradation of PAHs. A quick PAH-availability test (Cuypers *et al.* 2000) revealed that bound forms of PAHs were present in the soil. Since it was thought to be a stable-end situation where contamination appeared to pose little environmental impact, the authorities allowed the area's development into a park.

2.2 Microbial Dynamics in the Rhizosphere

There is strong evidence that plants can control rhizospheric bacteria's metabolic processes by releasing root exudates, creating a mutually advantageous plant-microbe relationship. In contaminated soils, these complimentary interactions are thought to be a crucial adaptive response of plants to chemical stress. The

substantially increased microbial population in the rhizosphere when compared to non-vegetated soils—which frequently reaches several orders of magnitude greater near the soil–root interface—is a clear sign of this interaction. The degree of these interactions, however, may differ based on the physicochemical characteristics of pollutants, especially hydrophobic organic substances, whose restricted soil diffusion limits microbial activity to a small rhizospheric zone. Rhizosphere-mediated biodegradation processes are also influenced by soil texture, organic matter concentration, and contaminant bioavailability (Corgié *et. al.* 2003).

3. Strategies for Enhancing Pollutant Degradation

3.1 Genetic modification

There have been successful instances of genetically engineering plants and rhizospheric bacteria with pollutant-degrading enzymes, despite the fact that the primary focus of plant biotechnology in recent years has been to increase agricultural yields and quality. For instance, microorganisms and plants with the ability to break down pesticides have been created using genes for insecticide detoxification enzymes in resistant insects, such as esterases and cytochromes P450 (Roe, 1998). Tobacco plants have also been shown to have a malian cytochrome P450, which is known to oxidize a variety of halogenated hydrocarbons. According to reports, this causes the transgenic plants to metabolize TCE up to 640 times faster, increasing the absorption and debromination of ethyl ene dibromide (Doty, 2000).

3.2 Rhizosphere-Mediated Enhancement of Microbial Activity

In general, enhanced microbial activity within the rhizosphere is expected to accelerate the degradation of soil contaminants through co-metabolic processes and diauxic growth mechanisms. Therefore, the availability of suitable nutrients and favorable growth conditions plays a critical role in regulating rhizospheric microbial populations and improving the bioremediation efficiency of contaminated soils. Previous studies have demonstrated that the application of fertilizers, maintenance of adequate soil moisture, and incorporation of organic manures significantly increase microbial abundance and activity in the rhizosphere. However, the microbial community composition differs considerably between soils amended with organic and inorganic fertilizers, which may subsequently influence contaminant degradation dynamics and soil ecological functions (Deavin *et. al.* 1981).

3.3 Root-Based Technologies for Environmental Remediation

The efficiency of contaminant uptake and remediation by plants largely depends on root length, root biomass, and spatial root architecture, which determine the plant's ability to access pollutants present in deeper soil layers and groundwater. Generally, phytoremediation is considered most effective for contaminants located within 0.5–1.0 m of soil depth; however, deep-rooted tree species such as poplar and certain perennial plants can extract contaminants from depths exceeding 10 m. Therefore, enhancing root growth and optimizing root system architecture represent important strategies for improving phytoextraction and phytodegradation efficiency in contaminated soils. In this context, the use of beneficial strains of *Agrobacterium tumefaciens*, a naturally occurring soil bacterium known for its plant–microbe interactions, has emerged as a promising approach for stimulating root development and enhancing phytoremediation potential (Cunningham *et.al.* 1996).

4. Conclusions

Plant–microbial interactions in the rhizosphere offer an effective and sustainable approach for the remediation of environments contaminated with persistent organic pollutants

Reference

- Bromilow RH, Chamberlain K (1995): Principles governing up take and chemicals in Plant Contamination: Modelling and Simulation of Organic Chemical Processes. Trapp S McFarlane JC (Eds), Lewis Publishers, pp 37–68
- Chaudhry Q, Schroeder P, Werck-Reichhart D, Grajek W, Marecik R (2001): Prospects and limitations of phytoremediation for the removal of persistent pesticides in the environment. *Environ Sci Pollut Res* 9, 4–17
- Corgié SC, Joner EJ, Leyval C (2003): Rhizospheric degradation of phenanthrene is a function of proximity to roots. *Plant Soil* 257, 143–150
- Cunningham SD, Anderson T, Schwab AP, Hsu FC (1996): Phytoremediation of soils contaminated with organic pollutants. *Adv Agron* 56, 55–114

- Cuypers C, Grotenhuis T, Joziass J, Rulkens W (2000): Rapid persulfate oxidation predicts PAH bioavailability in soils and sediments. *Environ Sci Technol* 34, 2057–2063
- Deavin A, Horsgood RK, Rusch V (1981): Rhizosphere micro flora in relation to soil conditions. Part I: Comparison of bacteria in soil, rhizosphere and rhizoplane. *Zentralblatt für Bakteriologie, Parasitenkunde, Infektionskrankheiten und Hygiene, II* 136, 613–618
- Doty SL, Shang TQ, Wilson AM, Tangen J, Westergreen AD, Newman LA, Strand SE, Gordon MP (2000): Enhanced metabolism of halogenated hydrocarbons in transgenic plants containing mammalian cytochrome P450 2E1. *Proc Natl Acad Sci (USA)* 97, 6287–6291
- Roe RM, Hodgson E, Rose RL, Thompson DM, Devorshak C, Anspaugh DD, Linderman RJ, Harris SV, Tomalski MD (1998): Basic principles and rationale for the use of insect genes in bioremediation: esterase, phosphotriesterase, cytochrome P450 and epoxide hydrolase. In: Kuhr RJ, Motoyama N (eds), *Pesticides and the future: minimizing chronic exposure of humans and the environment*, IOS Press, Amsterdam, Netherlands, 1998, pp 169–178
- Sheehan D (1997): *Bioremediation Protocols. Methods in Biotechnology*, Vol 2. Humana Press, Totowa, NJ. 1997, 339 pp



From Plantation to Prosperity: Reimagining Sericulture as a Rural Livelihood Engine in Kalahandi and Nuapada



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Abstract

Sericulture in Odisha has considerable potential to contribute to rural livelihoods, particularly in areas where agriculture is constrained by small landholdings, rain dependence, limited irrigation and inadequate employment opportunities. The Kalahandi Zone, comprising Kalahandi and Nuapada districts, presents an interesting case where different branches of sericulture, including Tasar, Eri and Mulberry, are being linked with plantation development, government livelihood programmes and rural infrastructure. The present article examines the existing sericulture landscape of the zone, the proposed interventions for 2026-27, beneficiary coverage, plantation activities under VBG-RAM-G, and the institutional challenges affecting implementation.

The available departmental data indicate a planned coverage of 500 beneficiaries during 2026-27 across Tasar, Mulberry and Eri activities. The action plan includes 215 acres of castor plantation, maintenance of 4 acres of Mulberry gardens, assistance to 430 beneficiaries for Eri rearing and mounting equipment, and prophylactic support for 550 rearers. At the same time, 50 hectares of plantation activity is being undertaken in Komna Block of Nuapada under VBG-RAM-G. However, against a sanctioned staff strength of 21, only 8 personnel are presently in position, leaving 13 vacancies. This represents a major institutional constraint.

The article argues that the future of sericulture in Kalahandi and Nuapada should move beyond isolated beneficiary assistance towards an integrated cluster-based livelihood model involving host-plant development, rearing infrastructure, technical support, capacity building, convergence and market-oriented production. With appropriate institutional strengthening, the region can develop a more sustainable and diversified sericulture economy.

Keywords: Sericulture, Tasar, Eri, Mulberry, Kalahandi, Nuapada, VBG-RAM-G, rural livelihood, tribal development, plantation, Odisha

1. Introduction

Rural development is not simply a question of increasing agricultural production. It is also about creating diversified livelihood opportunities that can provide income to households while making productive use of local resources. In this context, sericulture occupies a distinctive position because it connects agriculture, forestry, livestock-like biological production, rural employment and cottage-based economic activities.

Kalahandi and Nuapada districts of Odisha provide an important setting for examining this potential. The sericulture activities of the Kalahandi Zone cover both districts and include Castor cultivation, Asan and Arjun plantation, Mulberry and Eri activities, Tasar silkworm rearing and cocoon production. The stated objective is to promote livelihood opportunities for rural communities, particularly small and marginal farmers.

The significance of such a model lies in diversification. A rural household need not depend exclusively on one crop or one season. Plantation-based Tasar activity, Eri rearing, Mulberry cultivation and associated activities can potentially create multiple points of income and employment.

The challenge, however, is to transform these activities from individual interventions into a coordinated livelihood system. Plantation without adequate maintenance, rearing without technical guidance, equipment without capacity building and beneficiaries without market support may not produce the desired long-term impact.

Therefore, the central question is not merely how many beneficiaries receive assistance. The more important question is: Can sericulture be developed as a sustainable rural economic ecosystem in Kalahandi and Nuapada?

2. Spatial Dynamics and Agro-Ecological Mapping of the Kalahandi Frontier.

The Kalahandi Zone comprises Kalahandi and Nuapada districts. According to the available departmental information, Kalahandi has three MRCS and four government units, while Nuapada has two TRCS. Sericulture activities extend across several blocks and villages.

Table 1. Sericulture Activities and Institutional Coverage in Kalahandi Zone

District	Reported Sericulture Units	Major Sericulture Activities
Kalahandi	3 MRCS and 4 Government Units	Tasar, Eri, Mulberry, Castor cultivation and related activities
Nuapada	2 TRCS	Tasar, plantation and related sericulture activities
Total Zone	9 reported units	Tasar, Eri, Mulberry and Castor-based activities

Source-Office of the Assistant Director of Sericulture, Kalahandi.

In Kalahandi, the documented areas include Thuamul Rampur, Dharmagarh, Junagarh, Lanjigarh and M. Rampur. In Nuapada, Komna is identified among the principal areas covered by the reported activities.

This geographical spread is important because sericulture development does not have to be concentrated in a single location. Different ecological and agricultural conditions can support different components of the sector.

The region therefore offers an opportunity to develop a **multi-species sericulture model**:

- **Tasar** linked with suitable host plantations;
- **Eri** linked with castor cultivation and rearing;
- **Mulberry** in locations where irrigation conditions permit;
- **Plantation development** as the long-term foundation of Tasar production;
- **Cluster infrastructure** to reduce individual production constraints.

Such diversification can be particularly valuable for rural households because it allows livelihood activities to be distributed across agricultural seasons and resource conditions.

3. 2026-27: A Significant Opportunity for Expansion

The proposed action plan for 2026-27 demonstrates that the zone is moving towards a broader scale of intervention.

Table 2. Action Plan for Sericulture Activities, 2026-27

Sl. No.	Component	Physical Target	Financial Target
1	Area of plantation - Castor	215 acres	Rs. 38,70,000
2	Maintenance of Mulberry garden	4 acres	Rs. 1,88,800
3	Publicity and propaganda	10	Rs. 1,50,000
4	Assistance for Eri rearing and mounting equipment	430 beneficiaries	Rs. 43,75,000
5	Assistance for prophylactic measures	550 beneficiaries	Rs. 9,57,000
6	Cost of Castor seed	645 kg	Rs. 1,61,250

Source-Office of the Assistant Director of Sericulture, Kalahandi.

The plan includes 215 acres of castor plantation, with a financial target of Rs. 38.70 lakh. It also provides for maintenance of 4 acres of Mulberry Garden with a financial target of Rs. 1.888 lakh. Publicity and propaganda activities have a target of 10 programmes/units with an allocation of Rs. 1.50 lakh.

One of the most significant components is assistance for Eri rearing and mounting equipment, with a physical target of 430 beneficiaries and a financial target of Rs. 43.75 lakh.

Another 550 rearers are targeted for assistance related to prophylactic measures, with an allocation of Rs. 9.57 lakh.

The action plan also includes 645 kg of castor seed at a financial target of Rs. 1.6125 lakh.

These figures indicate that sericulture development is being approached through several complementary inputs rather than through a single intervention.

This is significant because successful silkworm production depends upon a chain of activities. Host plants, quality seed, rearing equipment, disease prevention, technical knowledge and farmer support are interconnected. Weakness in one component can affect the performance of the entire production system.

Therefore, the 2026-27 plan can be viewed not simply as an expenditure programme but as an opportunity to strengthen the production ecosystem.

4. Asset Creation under VB-G RAM-G: Assessing Phased Plantation Stability.

Plantation development is particularly important for Tasar sericulture because the availability of suitable host plants forms the biological foundation of the production system.

Table 3. VBG-RAM-G Plantation Progress in Komna Block, Nuapada

Financial Year	Plantation Area	Location	Status
2022-23	20 ha	Dumerpada and Murlibahal	Plantation completed; formal closure pending material fund sanction
2025-26	20 ha	Lakhna GP, Murlibahal	Maintenance work ongoing
2026-27	10 ha	Lakhna GP, Mouza Murlibahal	TS and FS completed; nursery raised and ready
Total	50 ha	Komna Block	Phased plantation development

The reported progress under VBG-RAM-G in Nuapada is noteworthy. A total of 50 hectares of plantation work is being taken up in Komna Block. This includes 20 hectares from FY 2022-23, another 20 hectares from FY 2025-26 and 10 hectares planned for FY 2026-27.

The 20-hectare plantation associated with FY 2022-23 at Dumerpada and Murlibahal has been completed, while formal closure is linked with sanction of the material fund.

The 20-hectare maintenance plantation under FY 2025-26 at Lakhna GP and Murlibahal is ongoing.

For the additional 10 hectares under FY 2026-27 at Mouza Murlibahal in Lakhna GP, both Technical Sanction and Financial Sanction have been completed, and the nursery has been raised and is ready for plantation work.

This progression demonstrates an important principle: plantation is an investment in future production rather than an immediate production activity.

A plantation created today may become economically meaningful only after appropriate establishment, maintenance and management. Consequently, plantation programmes should be assessed not only by area planted but also by survival, maintenance, accessibility, utilization and eventual contribution to silkworm rearing.

5. The Untapped Tasar Potential of Kalahandi

While the current documented plantation activity under VBG-RAM-G is highlighted in Nuapada, the departmental recommendations identify considerable scope for expansion of Asan and Arjun plantation in suitable areas of Lanjigarh and M. Rampur Blocks of Kalahandi.

This recommendation deserves particular attention.

Lanjigarh already has an existing PPC, which has been identified as having potential to function as a technical and demonstration centre for Tasar expansion. A technical and demonstration centre can play a role far beyond simply maintaining departmental infrastructure.

It can become a local knowledge hub where farmers can observe improved practices, receive technical guidance, learn disease-management methods and understand plantation and rearing systems.

The proposal for forming a new Tasar society at Lanjigarh or M. Rampur is another potentially important step.

A society or producer-oriented institution can provide a platform for collective action. Individual rearers frequently face difficulties related to access to inputs, technical advice, aggregation and marketing. Collective organization can potentially reduce some of these barriers.

Thus, the development strategy for Kalahandi should not stop at planting host trees. It should create the institutional architecture necessary to convert those trees into a sustainable Tasar livelihood.

6. Eri Sericulture: An Important Livelihood Component

Tasar often receives considerable attention in discussions about forest-based sericulture, but Eri can also make an important contribution to household livelihoods.

The 2026-27 beneficiary plan identifies 430 Eri beneficiaries in Kalahandi. The category-wise distribution consists of 236 ST beneficiaries, 85 SC beneficiaries and 109 OBC beneficiaries.

The Eri component is supported through assistance for rearing and mounting equipment.

This combination of beneficiary support and equipment assistance can be viewed as an opportunity to develop Eri clusters. Instead of treating every beneficiary as an isolated production unit, groups of farmers could potentially be linked with common training, technical support, input planning and aggregation.

The role of castor is particularly relevant because the action plan includes 215 acres of castor plantation and provision for castor seed.

This creates the possibility of linking crop production with silkworm rearing.

Such integration is one of the attractive features of sericulture. A crop can serve not only as an agricultural commodity but also as a biological resource supporting another livelihood activity.

7. Mulberry: A Cluster-Based Possibility

The plan includes maintenance of four acres of Mulberry gardens and identifies the possibility of introducing Mulberry cluster rearing in M. Rampur Block in areas having assured irrigation.

The emphasis on assured irrigation is important. Mulberry-based sericulture requires continuity of host-plant management, and the feasibility of such an activity depends upon local resource conditions.

Rather than attempting indiscriminate expansion, Mulberry should therefore be promoted in areas where the necessary conditions exist.

The recommended cluster approach is also significant. The proposal for establishing cluster rearing houses for groups of 10 farmers each could provide a more organized production environment.

A cluster house can potentially facilitate better management, training, hygiene and technical supervision. It may also encourage farmers to work collectively rather than independently.

8. The Extension Personnel Deficit: Institutional Vulnerability in Field Operations.

One of the strongest findings emerging from the available data is not related to plantation or finance. It is related to manpower.

The sanctioned staff strength of the Kalahandi Zone is 21. However, only 8 personnel are presently in position, leaving 13 vacancies. In percentage terms, only about 38 percent of the sanctioned workforce is available, while approximately 62 percent of posts remain vacant.

The vacancies affect several technical and administrative positions, including Production Officer, Technical Inspector, Senior Assistant, Senior Tasar Assistant, Eri Tasar Mistry, Peon and Watchman.

This issue deserves greater attention because sericulture is a field-oriented activity.

Unlike programmes that can be implemented primarily through financial transfers, sericulture requires regular interaction with farmers. Plantation management, silkworm rearing, disease prevention, technical supervision and capacity building all require human resources.

Expansion without adequate technical manpower could create a paradox: the programme may grow on paper faster than the capacity to implement it on the ground.

Therefore, filling critical vacancies should be considered an essential part of sericulture development rather than a separate administrative matter.

9. Outcome Metrics: Shifting from Input Distribution to Capacity Saturation.

The 2026-27 beneficiary plan covers a total of 500 beneficiaries.

Table 4. Beneficiary Coverage under Sericulture Activities, 2026-27

District	Variety	Total Farmers	ST	SC	OBC
Nuapada	Tasar	50	40	4	6
Kalahandi	Mulberry	20	5	1	14
Kalahandi	Eri	430	236	85	109
Total	All varieties	500	281	90	129

Nuapada's Tasar component includes 50 farmers, consisting of 40 ST, 4 SC and 6 OBC beneficiaries.

Kalahandi's Mulberry component covers 20 farmers, consisting of 5 ST, 1 SC and 14 OBC beneficiaries.

The Eri component covers 430 farmers, comprising 236 ST, 85 SC and 109 OBC beneficiaries. The total is 500 beneficiaries.

The composition demonstrates a substantial focus on ST beneficiaries, particularly in the Eri and Tasar components.

However, beneficiary coverage should ideally be evaluated over time using indicators beyond the number of persons assisted.

For example:

1. How many beneficiaries remain active after receiving assistance?
2. How much production is generated?
3. What is the average household income generated?
4. How many farmers form functioning clusters?
5. What proportion of produce reaches organized markets?
6. What are the major technical constraints faced by rearers?
7. How effectively are plantations utilized for production?

Such indicators would help distinguish between input distribution and livelihood transformation.

The ultimate objective of a livelihood programme should not merely be to distribute assets. It should be to create productive assets, productive skills and sustainable income.

10. Convergence: The Key to Long-Term Sustainability

The departmental recommendations emphasize convergence with suitable schemes for plantation, irrigation, rearing infrastructure and livelihood promotion.

This may be one of the most important strategic directions for the region.

Sericulture does not exist in isolation. Plantation development may require support from one programme, irrigation from another, rural infrastructure from another and livelihood training from another.

A convergence-based model can therefore combine these resources around a single village or cluster.

Imagine a village where:

- suitable land is identified;
- host plants are established;
- farmers receive technical training;
- rearing houses are developed;
- disease-management support is available;
- cocoon production is aggregated;
- farmers receive market information; and
- technical staff regularly monitor production.

This would be fundamentally different from providing isolated assistance to individual households.

The future model should therefore be **cluster-centred rather than beneficiary-centred**.

11. Building a Local Sericulture Knowledge System

The success of sericulture depends heavily on farmer knowledge.

A farmer may receive equipment, but without knowledge of rearing hygiene, disease identification, feeding management, mounting practices and environmental management, the equipment alone cannot guarantee productivity.

This makes capacity building and handholding essential. The departmental recommendations specifically identify strengthening technical support, capacity building and farmer handholding as areas requiring attention.

The existing PPC at Lanjigarh could potentially support this approach by functioning as a demonstration and technical centre.

Such centres could be developed around a simple principle:

See - Learn - Practice - Improve - Share.

Farmers can first observe a recommended practice, learn its technical basis, apply it under guidance, identify problems and then share successful experiences with neighbouring farmers.

This can gradually create a local knowledge network.

12. Strengthening Institutions Alongside Infrastructure

Physical infrastructure alone cannot create a strong sericulture sector.

A rearing house is useful only when farmers use it effectively. A plantation is productive only when it survives and is properly maintained. A society is effective only when its members participate actively. Equipment becomes economically meaningful only when it improves production.

Therefore, institutional strengthening must accompany physical investment.

The issue concerning the designation of the Assistant Director of Sericulture as Programming Officer under the relevant programme in Nuapada illustrates the importance of administrative coordination. The available report states that the designation had not yet been reflected in the software or online system, and the matter had been brought to the notice of the Collector and CDO-cum-EO, Zilla Parishad, Nuapada.

Such procedural issues may appear administrative, but their consequences can affect programme implementation and closure.

Efficient digital systems, clear institutional responsibilities and timely administrative action are therefore also components of rural development.

13. A Possible Roadmap for Kalahandi and Nuapada

A long-term sericulture strategy for the Kalahandi Zone could be built around seven pillars.

13.1 Expand Host-Plant Resources

Suitable areas of Lanjigarh and M. Rampur should be assessed for expansion of Asan and Arjun plantation, as already suggested in the departmental recommendations.

13.2 Develop Demonstration Clusters

The PPC at Lanjigarh could be used as a demonstration and technical centre for Tasar expansion.

13.3 Establish Farmer Clusters

Groups of farmers can be organized around common rearing houses, technical support and production planning.

13.4 Strengthen Eri Production

The large Eri beneficiary base provides an opportunity to establish organized Eri clusters connected with castor cultivation.

13.5 Promote Irrigation-Linked Mulberry

Mulberry clusters should be promoted selectively in areas with assured irrigation rather than through uniform expansion.

13.6 Improve Human Resources

Critical vacancies should be addressed so that expanding programmes receive adequate technical supervision. The existing staffing position shows a gap of 13 posts against the sanctioned strength of 21.

13.7 Measure Outcomes

Programme evaluation should gradually move from measuring only physical and financial achievements towards measuring production, productivity, income, active beneficiaries, plantation survival and market participation.

14. The Larger Development Opportunity

The real potential of sericulture in Kalahandi and Nuapada lies in its ability to connect different dimensions of rural development.

- I. A plantation can become a long-term biological asset.
- II. A silkworm can transform plant biomass into a valuable product.
- III. A farmer can become a rearer.
- IV. A group of rearers can become a production cluster.
- V. A production cluster can become a rural enterprise.
- VI. And a rural enterprise can contribute to household income and local economic activity.

15. Conclusion

Kalahandi and Nuapada possess an important opportunity to strengthen sericulture as a sustainable rural livelihood activity. The existing programme architecture covers multiple components including Tasar, Eri and Mulberry, while plantation development provides the foundation for future expansion.

The 2026-27 action plan proposes 215 acres of castor plantation, support for 430 Eri beneficiaries, prophylactic assistance for 550 rearers and other interventions. Meanwhile, 50 hectares of plantation work under VBG-RAM-G in Komna Block of Nuapada demonstrates the potential for convergence between plantation development and livelihood programmes.

The documented beneficiary plan covers 500 farmers across Tasar, Mulberry and Eri activities, with significant participation of ST beneficiaries.

At the same time, the 62 percent vacancy rate in the sanctioned staff structure represents a serious challenge.

The future of the sector will therefore depend on more than financial allocation. It will require plantation, people, infrastructure, technical knowledge, institutions and markets to work together.

Kalahandi and Nuapada should not aim merely to increase the number of beneficiaries. The larger objective should be to create functioning sericulture clusters where farmers have access to host plants, technology, infrastructure, training and organized production systems.

If this approach is pursued consistently, sericulture can evolve from a scheme-based activity into a community-based rural enterprise system.

The journey is therefore not simply from silkworm to silk.

It is from plantation to production, from production to enterprise, and from enterprise to prosperity.

References

Office of the Assistant Director of Sericulture, Kalahandi, Bhawanipatna. (2025). *District Sericulture Activities and Administrative Records, Kalahandi*. Office of the Assistant Director of Sericulture, Near TV Tower, Naktiguda, Bhawanipatna-766001, Kalahandi, Odisha.

Directorate of Textiles and Handlooms, Government of Odisha. (2025). *Sericulture Development and Field-Level Implementation in Odisha*. Government of Odisha, Bhubaneswar.

Central Silk Board. (2024–2025). *Annual Report 2024–25*. Ministry of Textiles, Government of India, Bengaluru.

Central Silk Board. (2025). *Silk Samagra-2: Development of Sericulture and Silk Industry*. Ministry of Textiles, Government of India.



Advances in Agricultural Drainage Engineering for Sustainable Water Management



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Abstract

Agricultural drainage engineering is an essential component of sustainable land and water management. Excess water in the soil can cause waterlogging, poor aeration, restricted root development, delayed farm operations and loss of crop productivity. In irrigated agriculture, inadequate drainage may also contribute to rising groundwater levels and soil salinity. Traditional drainage systems were mainly designed to remove surplus water rapidly; however, modern drainage engineering increasingly focuses on regulating water rather than simply disposing of it. Advances such as controlled drainage, subsurface drainage, drainage subirrigation, precision land leveling, GIS, remote sensing, IoT-based monitoring and simulation models are improving the planning and management of agricultural drainage systems. These technologies help identify waterlogged areas, monitor groundwater levels and operate drainage infrastructure according to soil, crop and climatic conditions. This article highlights important advances in agricultural drainage engineering and discusses their role in improving water-use efficiency, soil health, crop productivity and environmental sustainability.

Keywords: Agricultural drainage, sustainable water management, controlled drainage, subsurface drainage, waterlogging, precision agriculture, IoT, GIS, remote sensing

1. Introduction

Water is one of the most important resources for agricultural production, but excessive water can be as harmful to crops as water scarcity. When water remains in the root zone for prolonged periods, soil pores become filled with water and the availability of oxygen decreases. Such conditions restrict root respiration and nutrient uptake, reduce microbial activity and ultimately affect crop growth and yield. Excess moisture also delays tillage, sowing and harvesting operations.

Agricultural drainage engineering provides scientific methods for collecting, controlling and removing excess surface and subsurface water. Drainage is particularly important in flat agricultural lands, heavy soils, regions with high rainfall and irrigated areas where groundwater levels may rise. In addition to controlling waterlogging, effective drainage plays a major role in preventing soil salinity and maintaining long-term land productivity.

Modern agriculture is changing the conventional concept of drainage. Instead of continuously removing water from agricultural land, advanced drainage systems aim to manage water according to crop requirements and climatic conditions. This approach allows water to be removed during wet periods and retained when it can support crop growth during dry periods. Therefore, modern drainage engineering is becoming an important component of integrated and sustainable agricultural water management.

2. Importance of Agricultural Drainage

A properly designed drainage system creates a favorable soil environment for crop production. Its primary function is to maintain an appropriate balance between water and air in the root zone. Agricultural drainage also improves soil workability and supports timely agricultural operations. Major benefits include:

Prevention of waterlogging and prolonged soil saturation.

Improvement of soil aeration and root development.

Control of shallow groundwater tables.

Reduction in the risk of secondary soil salinity.
Improved trafficability for agricultural machinery.
Better integration of irrigation and soil-water management.
Protection of long-term agricultural land productivity.

3. Major Advances in Agricultural Drainage Engineering

3.1 Controlled Drainage

Controlled drainage is one of the most important developments in modern agricultural water management. In a conventional drainage system, water is allowed to flow freely whenever hydraulic conditions permit. In controlled drainage, adjustable structures are installed at drainage outlets to regulate water discharge and groundwater depth. During periods of excess rainfall, drainage structures can be opened to remove surplus water and prevent crop damage. During dry periods, the outlet level can be raised to retain water within the soil profile. This approach can improve water availability to crops and reduce unnecessary drainage losses. Controlled drainage therefore transforms drainage infrastructure from a passive disposal system into an active water-management tool.

3.2 Subsurface Drainage and Drainage Subirrigation

Subsurface drainage uses buried perforated pipes or drains to collect excess groundwater and maintain a suitable water-table depth. It is especially useful in poorly drained soils and irrigated areas affected by waterlogging. An important advancement is drainage subirrigation, in which the same underground drainage network can perform two functions. During wet periods, it removes excess water, while during dry periods water can be introduced into the system to raise the water table and supply moisture to the root zone through capillary movement. This dual use of infrastructure represents an efficient integration of irrigation and drainage engineering.

3.3 Precision Drainage Design

Agricultural fields often have considerable variation in soil texture, slope, hydraulic conductivity and groundwater conditions. Uniform drainage design may therefore not provide the best solution across an entire field. Precision drainage uses site-specific information to identify areas that require different drainage intensities.

Digital elevation models, soil maps and spatial analysis can identify depressions, water accumulation zones and natural drainage pathways. Such information can assist engineers in selecting appropriate drain locations, depths and spacing. Precision drainage can improve performance while reducing unnecessary installation costs.

3.4 GIS, Remote Sensing and UAV Applications

Geographic Information Systems and remote sensing have become valuable tools for drainage assessment and planning. GIS can integrate information related to topography, soil characteristics, land use and hydrology. Digital elevation models help determine slopes, drainage directions and potential water accumulation areas.

Satellite images and unmanned aerial vehicles can assist in identifying persistent wet areas and crop stress associated with poor drainage. Repeated observations allow comparison of field conditions over time and can help distinguish temporary rainfall effects from long-term drainage problems. These technologies improve the efficiency of field surveys and support more informed drainage planning.

3.5 IoT-Based Monitoring and Automation

The Internet of Things provides opportunities for continuous monitoring of agricultural drainage systems. Water-table sensors, soil-moisture sensors, rainfall gauges and flow meters can transmit data to digital dashboards or mobile applications. This information enables farmers and engineers to monitor drainage performance in real time.

Automated drainage systems can use sensor data to operate adjustable structures according to predetermined water-level thresholds. Weather forecasts can also be incorporated into drainage decisions. Such systems can provide early action during intense rainfall and improve water conservation during dry conditions.

4. Drainage and Sustainable Water Management

Sustainable water management requires a balance between removing harmful excess water and conserving water for future crop use. Modern drainage engineering supports this objective by regulating the movement of water rather than treating all drainage water as waste.

Controlled drainage can retain water within agricultural fields when crop requirements are low, while drainage-water storage and reuse may provide an additional source of water where quality conditions are suitable. The integration of drainage with irrigation scheduling can further improve water-use efficiency. For example, information on soil moisture and groundwater depth can help determine whether irrigation is actually required or whether water stored within the soil profile is sufficient.

Drainage engineering is also essential for salinity management. Salts introduced through irrigation can accumulate in the soil as water is used by crops and evaporates. Appropriate leaching combined with adequate drainage is required to move excess salts below the crop root zone. Therefore, irrigation and drainage should always be considered as connected components of agricultural water management.

5. Environmental Considerations

Although drainage improves agricultural productivity, drainage water may carry nutrients, sediments, salts and other agricultural contaminants into downstream water bodies. Sustainable drainage design must therefore consider water quality in addition to hydraulic performance.

Several practices can reduce environmental impacts, including controlled drainage, vegetative buffer strips, constructed wetlands and appropriate nutrient management. These measures can slow water movement, promote sediment deposition and reduce the transport of pollutants. Where technically feasible, drainage water may also be collected, treated or reused.

Climate change further increases the importance of adaptive drainage systems. Intense rainfall events can cause temporary flooding, while longer dry periods increase the value of stored water. Future drainage systems should therefore have the flexibility to remove excess water rapidly and retain water when conditions become dry.

6. Challenges and Future Scope

Despite significant progress, several challenges remain in the adoption of modern drainage technologies. Subsurface drainage systems may require high initial investment, while accurate design requires reliable information on soil properties and groundwater conditions. Drainage systems also require regular maintenance because sediment, root intrusion and damaged outlets can reduce their effectiveness.

Digital technologies present additional challenges related to sensor reliability, communication infrastructure, power supply and data interpretation. However, continued development of low-cost sensors and automated systems is expected to make smart drainage technologies more accessible.

Future research should focus on AI-assisted drainage planning, real-time groundwater management, digital twins of drainage networks, climate-resilient design and safe drainage-water reuse. Integration of IoT, remote sensing and decision-support systems can help develop intelligent drainage systems that respond automatically to changing weather and soil conditions.

7. Integrated Framework for Sustainable Agricultural Drainage

The following flow diagram summarizes the progression from agricultural drainage problems to modern technologies, sustainable practices and long-term benefits.

8. Conclusion

Agricultural drainage engineering is evolving from a conventional approach focused on rapid water removal toward an integrated system for sustainable water management. Controlled drainage, subsurface drainage, drainage subirrigation, precision design, GIS, remote sensing and IoT-based monitoring are improving the ability to manage agricultural water according to crop and environmental requirements.

The future of drainage engineering lies in adaptive systems capable of removing excess water during wet periods while conserving water during dry periods. Integration with irrigation scheduling and precision agriculture can further improve water productivity, soil health and crop performance. By combining sound engineering principles with digital technologies, agricultural drainage can contribute significantly to climate-resilient and sustainable farming systems.

References

Ritzema, H. P. (Ed.). Drainage Principles and Applications. International Institute for Land Reclamation and Improvement (ILRI), Wageningen.

Skaggs, R. W., and van Schilfgaarde, J. Agricultural Drainage. Agronomy Monograph, American Society of Agronomy.

Food and Agriculture Organization (FAO). Agricultural Water Management and Drainage Resources. FAO, Rome.

International Commission on Irrigation and Drainage (ICID). Agricultural Drainage and Water Management Resources.

USDA Natural Resources Conservation Service (NRCS). National Engineering Handbook: Drainage and Water Management.



Biofloc Technology: An Innovative Approach to Intensive Aquaculture



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Abstract

Biofloc Technology (BFT) is an innovative aquaculture approach that promotes nutrient recycling through the activity of beneficial microorganisms. As conventional aquaculture faces increasing challenges from rising feed costs, water scarcity, disease risks and environmental concerns, BFT offers an alternative method for improving resource-use efficiency. In biofloc systems, organic matter and nitrogenous wastes are converted into microbial biomass through controlled carbon addition and continuous aeration. The resulting bioflocs can help maintain water quality while providing an additional nutritional resource for cultured fish and shrimp. The technology enables reduced water exchange, supports high-density production and can be adapted to small-scale and urban farming systems. However, successful BFT operation requires careful management of dissolved oxygen, pH, ammonia, nitrite, alkalinity, carbon sources, feeding and suspended solids. Emerging technologies such as sensors, automation and Internet of Things (IoT) systems can further improve monitoring and management. Overall, BFT offers promising opportunities for efficient, circular and sustainable aquaculture.

Keywords: Biofloc Technology, Aquaculture, Nutrient Recycling, Microbial Biomass, Water Conservation, Sustainable Aquaculture

Introduction

Aquaculture is one of the fastest-growing food-producing sectors in the world. As the demand for fish and shrimp continues to increase, farmers are looking for innovative technologies that can produce more aquatic food using less land and water. At the same time, rising feed costs, limited water availability, disease risks and environmental concerns are creating new challenges for aquaculture producers. One promising approach is Biofloc Technology (BFT), an innovative aquaculture system that uses beneficial microorganisms to recycle nutrients within the culture environment. Instead of treating organic matter and nitrogenous wastes simply as unwanted pollutants, BFT encourages microbial communities to convert these wastes into microbial biomass, or bioflocs, which can contribute to water-quality management and provide an additional food resource for cultured fish and shrimp. The concept is simple but powerful: turn waste into a resource. In a well-managed biofloc system, microorganisms utilize organic carbon and nitrogenous compounds, helping to recycle nutrients within the culture system while producing suspended microbial aggregates. These bioflocs can subsequently be consumed by cultured animals, creating an additional pathway for nutrient utilization (Bossier and Ekasari, 2017). Thus, biofloc technology offers an interesting approach to intensive aquaculture, water conservation and nutrient recycling, making it an increasingly important technology for more sustainable aquatic food production.

From Waste to Wealth

In conventional aquaculture, uneaten feed, faeces and metabolic wastes can accumulate in the culture water and deteriorate water quality. Biofloc Technology (BFT) takes a different approach by recycling these wastes through beneficial microorganisms.

Heterotrophic bacteria use organic carbon and nitrogenous compounds to produce microbial biomass. Together with algae, protozoans and organic particles, this biomass forms bioflocs, which help recycle nutrients and can provide an additional



Figure 1: Biofloc Technology

food source for fish and shrimp (Avnimelech, 1999; De Schryver et al., 2008). Thus, BFT transforms waste into a useful resource, creating a more efficient and sustainable aquaculture system.

What Exactly Is a Biofloc?

A biofloc is more than just a group of bacteria. It is a mixture of beneficial bacteria, algae, protozoans, zooplankton and organic particles, including uneaten feed and faecal matter, held together as suspended aggregates in the culture water. These microbial communities help recycle nutrients, support water quality and provide an additional food source for cultured fish and shrimp (De Schryver et al., 2008). This is why biofloc technology is often described as “microbial farming” farmers are not only growing fish or shrimp but also managing a living microbial community that supports production.



Figure 2: Measurement of biofloc concentration using Imhoff settling cones

How Does Biofloc Technology Work?

The success of biofloc technology depends largely on maintaining a suitable carbon-to-nitrogen (C) balance in the culture water. Fish and shrimp release nitrogenous wastes, particularly ammonia, into the system. When an appropriate carbon source is added, heterotrophic bacteria use the carbon and available nitrogen to grow and form microbial biomass, helping to recycle nutrients within the system. Common carbon sources include molasses, jaggery, tapioca products and wheat flour. However, excessive carbon addition can increase microbial activity and oxygen demand, potentially affecting water quality. Therefore, carbon should be added carefully based on the culture conditions and regular water-quality monitoring (Bossier and Ekasari, 2017).

Less Water, More Production

One of the major advantages of Biofloc Technology (BFT) is its ability to operate with limited water exchange. Instead of frequently replacing water to remove wastes, biofloc systems recycle nutrients through microbial activity, helping to conserve water and reduce nutrient discharge (Emerenciano et al., 2013; Bossier and Ekasari, 2017). This makes BFT particularly useful in areas where water availability is limited. However, reduced water exchange does not mean reduced management. Farmers must regularly monitor dissolved oxygen, pH, ammonia, nitrite, alkalinity and suspended solids to maintain a healthy culture environment.

Biofloc: An Additional Food Factory

One of the most interesting features of Biofloc Technology is that the microorganisms growing in the culture water can become part of the food chain. Bioflocs contain microbial protein and other nutrients that can be consumed by fish and shrimp, helping to recycle nutrients that would otherwise be lost as waste. Studies have reported positive effects of biofloc on feed utilization and production performance, particularly in species such as Nile tilapia and Pacific white shrimp (Bossier and Ekasari, 2017; Ahmad et al., 2017). However, biofloc is not a complete replacement for formulated feed. Instead, it acts as an additional nutritional resource that can complement the regular feeding programme and improve nutrient utilization within the culture system.

Which Species Can Be Cultured?

Biofloc technology has been investigated for a variety of fish and shrimp species. Some important candidates include: Nile tilapia (*Oreochromis niloticus*) is particularly suitable because of its ability to consume suspended microbial particles and its tolerance to intensive culture conditions. Pacific white shrimp (*Litopenaeus vannamei*) is another major species used in biofloc systems, particularly in intensive shrimp farming. Other species, including certain carp and catfish species, have also been studied. However, the success of BFT depends on the biological characteristics of the species, its tolerance to suspended solids, stocking density and the management of water quality (Emerenciano et al., 2013; Ahmad et al., 2017). Therefore, biofloc is not a one-size-fits-all technology. System design and management must be adapted to the species being cultured.

Aeration: The Heart of the System

If microorganisms are the workforce of a biofloc system, aeration is the lifeline that keeps the system functioning. Biofloc tanks contain large populations of microorganisms along with densely stocked fish or shrimp, all of which

require sufficient oxygen. Continuous aeration maintains dissolved oxygen, keeps bioflocs suspended, supports microbial activity and prevents excessive accumulation of organic matter. Since aeration must operate continuously, electricity is a major consideration in biofloc farming, and a power failure can rapidly reduce dissolved oxygen and threaten the cultured animals. Therefore, a reliable backup aeration system is essential for successful and safe biofloc production.

Keeping the Water Healthy

Successful biofloc farming depends on maintaining a stable microbial environment and suitable water-quality conditions. Regular monitoring helps farmers detect problems early and maintain healthy fish or shrimp growth.

Table 1: Optimum water quality parameters

Water-quality parameter	Recommended range
Temperature	27–30°C
Dissolved oxygen (DO)	>5 mg/L
pH	7.0–8.5
Ammonia (NH ₃ -N)	<0.05 mg/L
Nitrite (NO ₂ -N)	<1 mg/L
Alkalinity	100–150 mg/L as CaCO ₃
Biofloc volume	10–20 ml/L

Advantages of Biofloc Technology

- **Water Conservation:** Requires limited water exchange, helping to reduce water consumption.
- **Nutrient Recycling:** Converts nitrogenous wastes and organic matter into microbial biomass instead of releasing them as waste.
- **Additional Natural Food:** Bioflocs provide a supplementary source of protein and other nutrients for fish and shrimp.
- **High-Density Production:** Enables intensive fish or shrimp production in relatively small culture areas.
- **Better Feed Utilization:** Bioflocs can contribute to nutrition and improve nutrient utilization under suitable conditions.
- **Reduced Environmental Impact:** Lower water exchange and nutrient recycling can reduce effluent discharge and the environmental footprint of intensive aquaculture (Bossier and Ekasari, 2017).
- **Suitable for Limited-Space Farming:** Tank-based BFT can be adapted for urban, backyard and small-scale aquaculture where land and water are limited.

But Biofloc Is Not a Magic Solution

- **High Management Requirement:** Biofloc requires continuous monitoring and careful day-to-day management.
- **Continuous Aeration:** Fish, shrimp and microorganisms require adequate oxygen, making uninterrupted aeration essential.
- **Power Dependency:** Power failure can rapidly reduce dissolved oxygen and increase the risk of animal mortality.
- **Carbon Management:** Excessive or insufficient carbon addition can disturb the microbial balance and water quality.
- **Feeding Management:** Overfeeding increases organic waste and can lead to excessive biofloc formation.
- **High Stocking Density:** Excessive stocking can increase oxygen demand and waste accumulation.
- **Suspended Solids:** Excessive biofloc and solids can negatively affect water quality and animal health.
- **Technical Knowledge:** Successful BFT requires knowledge of water quality, microbial management, feeding and system operation.
- **Energy Cost:** Continuous aeration can result in significant electricity consumption and operating costs.

Is Biofloc Economically Viable?

- **Lower Water Costs:** Limited water exchange can reduce water requirements and associated costs.
- **Feed Utilization:** Bioflocs can provide additional nutrients and may improve feed utilization when properly managed.

- Initial Investment: Tanks, blowers, aeration systems, pumps and water-quality testing equipment require initial capital investment.
- Electricity Cost: Continuous aeration makes electricity one of the major recurring expenses in biofloc farming.
- Labour and Management: Skilled labour is required for feeding, carbon management, water-quality monitoring and daily system operation.
- Other Operating Costs: Farmers should account for seed, feed, carbon sources, electricity, labour, water-quality inputs, maintenance and equipment depreciation.
- Profitability: Production volume alone does not determine success. Survival rate, growth, feed conversion, production cost and market price all influence profitability.

A Promising Option for Urban Aquaculture

- Space Efficient: Biofloc systems can be operated in tanks, making them suitable for areas with limited land.
- Urban and Backyard Farming: The technology can be adapted for rooftops, backyards and small urban spaces with proper structural and water-management considerations.
- Suitable for Entrepreneurs: BFT offers an opportunity for small-scale entrepreneurs to enter intensive fish or shrimp farming without requiring large ponds.
- Water Efficient: Limited water exchange makes the system attractive where water availability is restricted.
- Start Small: Beginners should start with a small, manageable unit to gain practical experience before expanding.
- Learn Before Scaling: Understanding biofloc development, feeding, aeration, stocking density and water-quality changes is essential before moving to commercial-scale production.

The Future: Smart Biofloc Farming

The future of biofloc farming is moving towards automation, sensors and digital technologies that can make system management more precise and efficient.

- Real-Time Monitoring: Sensors can continuously monitor temperature, dissolved oxygen, pH and other important water-quality parameters.
- Automated Aeration: Smart systems can automatically adjust aeration when dissolved oxygen levels fall.
- Smart Feeding: Automated feeders can deliver feed at scheduled times and help improve feeding consistency.
- IoT Connectivity: Water-quality sensors, aeration equipment and feeding systems can be connected through Internet of Things (IoT) platforms.
- Mobile Alerts: Farmers can receive real-time notifications when water-quality parameters move beyond safe limits.
- Data-Based Management: Continuous data collection can help farmers identify trends, prevent problems and make better production decisions.

Recent research highlights the potential of combining BFT with IoT, sensors and smart aquaculture technologies for improved monitoring and farm management.

From Waste Management to Resource Management

The real innovation of Biofloc Technology is not simply the use of tanks, aerators or carbon sources, it is the way we rethink aquaculture waste.

- Waste as a Resource: Organic matter and nitrogenous wastes are captured and converted into microbial biomass.
- Nutrient Recycling: Instead of being discharged, nutrients remain within the production system and are reused.
- Circular Aquaculture: BFT supports a more circular approach by converting waste into useful microbial biomass and additional natural food.

- Efficient Resource Use: Recycling nutrients can help reduce water exchange and improve the overall efficiency of intensive aquaculture.
- Future Innovation: Continued research on microbial management, carbon sources, automation, sensors and species-specific systems could further improve BFT performance.

Ultimately, biofloc technology represents a shift from simply managing waste to managing and recycling resources—an approach that could contribute to the future of sustainable aquaculture.

Conclusion

Biofloc Technology offers a promising approach to modern intensive aquaculture by combining high production with efficient use of water, nutrients and space. Its ability to convert organic and nitrogenous wastes into microbial biomass can help improve nutrient recycling while providing an additional food resource for cultured fish and shrimp. This makes BFT particularly attractive for water-limited and space-constrained farming systems. However, biofloc farming is not a simple or maintenance-free technology. Successful production depends on continuous aeration, balanced feeding, appropriate carbon management, regular water-quality monitoring and skilled farm management. The economic success of a system also depends on controlling energy and operational costs. With advances in IoT, sensors, automation and real-time water-quality monitoring, biofloc systems are expected to become more precise and efficient. Ultimately, the greatest strength of BFT lies in its ability to turn waste into a resource, offering a practical pathway towards more sustainable, efficient and responsible aquaculture.

References

- Avnimelech, Y. (1999). Carbon/nitrogen ratio as a control element in aquaculture systems. *Aquaculture*, 176(3–4), 227–235.
- De Schryver, P., Crab, R., Defoirdt, T., Boon, N., and Verstraete, W. (2008). The basics of bio-flocs technology: The added value for aquaculture. *Aquaculture*, 277(3–4), 125–137.
- Emerenciano, M., Gaxiola, G., and Cuzon, G. (2013). Biofloc technology (BFT): A review for aquaculture application and animal food industry. In *Biomass Now – Cultivation and Utilization*. IntechOpen.
- Bossier, P., and Ekasari, J. (2017). Biofloc technology application in aquaculture to support sustainable development goals. *Microbial Biotechnology*, 10(5), 1012–1016. <https://doi.org/10.1111/1751-7915.12836>.
- Ahmad, I., Rani, A. M. B., Verma, A. K., and Maqsood, M. (2017). Biofloc technology: An emerging avenue in aquatic animal healthcare and nutrition. *Aquaculture International*, 25, 1215–1226.
- Khanjani, M. H., and Sharifinia, M. (2020). Biofloc technology: An emerging microbial biotechnology for the improvement of aquaculture productivity. *Aquaculture International*, 28, 2041–2060.
- Jan, S., Bhat, F. A., Mushtaq, S., Iqbal, G., Shah, T. H., et al. (2026). Biofloc technology: An emerging tool for enhancing aquaculture production. *Green Technology, Resilience, and Sustainability*, 6, Article 3.
- The application and future of biofloc technology (BFT) in aquaculture industry: A review. (2023). *Journal of Environmental Management*.

The Rise of the Agri Influencer: Redefining Agricultural Extension



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Introduction

Agriculture has always been driven by knowledge, innovation and timely access to reliable information. From traditional farmer-to-farmer interactions to modern digital advisory platforms, agricultural extension has continuously evolved to meet the changing needs of farming communities. Traditionally, extension systems relied on extension personnel, demonstrations, training programmes and institutional communication channels to transfer scientific technologies from research organizations to farmers. However, increasing challenges such as climate variability, market uncertainties, emerging pests and diseases, and the growing demand for real-time information have created the need for more dynamic and accessible advisory mechanisms (Anderson & Feder, 2007).

The rapid expansion of smartphones, internet connectivity and social media platforms has introduced a new generation of agricultural communicators known as **Agri Influencers**. These digital knowledge creators, including progressive farmers, agricultural professionals, entrepreneurs and content creators, are using platforms such as YouTube, Instagram, WhatsApp and Facebook to disseminate farm-related information, share experiences and influence agricultural decisions. Digital communication tools have transformed extension from a conventional one-way information delivery approach into a more interactive, participatory and farmer-centric system (Aker, 2011).

Agri influencers are emerging as potential partners in agricultural extension by bridging the gap between scientific innovations and farming practices. Their ability to communicate in local languages, demonstrate real-time farm experiences and engage large farmer communities positions them as important actors in the future of digital agricultural advisory services. This article explores the emerging role, opportunities and challenges of agri influencers in strengthening extension advisory services.

Statistical highlights relevant to agri-influencers in India:

Indicator	Latest available data
Active internet users in India (2024)	886 million
Rural internet users (2024)	488 million (55% of total internet users)
Urban internet users (2024)	397 million
Internet users in India (Jan 2025)	806 million (55.3% penetration)
Social media users in India (Jan 2025)	491 million
Social media users in India (Jan 2024)	462 million
Rural youth (15–29 years) using the internet	92.7%
Rural smartphone ownership among mobile users	79.2% men; 75.6% women
4G network population coverage (2024)	95% of India's population
Average mobile data cost (2024)	~₹9 per GB

(Sources: IAMAI & Kantar (2024), DataReportal (2025), Government of India (2025), and TRAI.)

The most important statistic is that rural India had **488 million internet** users in **2024**, meaning rural users now outnumber urban users. This is highly relevant because the primary audience of agri-influencers is rural and

semi-rural farmers. The rapid expansion of rural internet access has created a large digital audience for agricultural content creators. Another important indicator is that social media users **increased from 462 million in 2024 to 491 million in 2025**, showing the growing reach of platforms where agri-influencers operate, particularly YouTube, Instagram, Facebook and WhatsApp.

Types of agri-influencers

Agri-influencers can be categorized into several groups based on their background and the nature of their content.

- **Progressive farmer influencers** share their personal farming experiences, innovations, and successful practices. Farmers often relate to them because their recommendations are based on field-level experience and local conditions.
- **Agricultural experts and scientists** provide research-based information on crop production, soil health, integrated pest management, climate-smart agriculture, and new agricultural technologies. Their content helps improve the scientific understanding of farming practices.
- **Agri-entrepreneurs and agribusiness influencers** focus on value addition, food processing, farm startups, input businesses, digital agriculture, and agricultural marketing. They encourage farmers to view agriculture as a profitable enterprise rather than only a production activity.
- **Organic and natural farming influencers** promote sustainable agriculture, bio-inputs, ecological farming methods, and chemical-free cultivation practices. Their content has gained popularity among farmers interested in environmentally friendly farming systems.
- **Government and institutional influencers** include Krishi Vigyan Kendras (KVKs), agricultural universities, extension departments, and farmer producer organizations that use social media to disseminate advisories, training materials, and policy-related information.

Characteristics of effective agri-influencers:

Not every social media creator becomes an effective agri-influencer. Those who make a meaningful impact usually possess a combination of technical knowledge, communication ability, and social credibility.

- **Credibility and trustworthiness** are the most important qualities. Farmers tend to follow influencers who provide accurate information, demonstrate results, and maintain transparency regarding product promotions and partnerships.
- **Practical orientation** makes their content highly useful. Effective agri-influencers explain technologies through field demonstrations, videos, and step-by-step guidance rather than relying only on theoretical explanations.
- **Consistency in content creation** helps build long-term engagement. Regular updates on seasonal crop practices, pest outbreaks, weather conditions, and market trends keep farmers connected and informed.
- **Communication in local languages** significantly increases outreach and comprehension. Content presented in simple language with local examples is more accessible to small and marginal farmers.
- **Digital engagement skills** are equally important. Successful influencers interact with their audience, respond to farmer queries, conduct live sessions, and create communities where farmers can exchange experiences and learn from one another.
- **Problem-solving ability** enhances their influence. Farmers value creators who address real challenges such as disease identification, irrigation management, input selection, and price fluctuations.
- **Ethical responsibility** is becoming increasingly important. Since agricultural decisions directly affect farmers' livelihoods, responsible influencers verify information before sharing it, acknowledge uncertainties, and avoid misleading claims. Promoting evidence-based and farmer-centric content strengthens their long-term credibility (OECD, 2023).

Role of agri-influencers in modern agriculture

Agri-influencers have emerged as powerful contributors to modern agricultural development by changing the way farming knowledge is shared and accessed. Using digital platforms such as YouTube, Instagram, Facebook, and WhatsApp, they deliver practical, easy-to-understand, and timely information to farmers. Their content covers a wide range of topics, including crop cultivation techniques, pest and disease control, weather updates, market

trends, government support programmes, and emerging agricultural technologies. By providing relevant information at the right time, they enable farmers to make better production and marketing decisions (FAO, 2022). A major strength of agri-influencers lies in their ability to encourage the adoption of improved farming practices. Through field demonstrations, personal experiences, and locally relevant success stories, they simplify technical recommendations and make them more applicable to everyday farming situations. Their content also motivates farmers to adopt crop diversification, value addition, agribusiness ventures, and environmentally sustainable agricultural practices. Communicating in regional languages further enhances their reach and builds confidence among small and marginal farmers.

In addition, agri-influencers promote farmer-to-farmer learning by creating digital communities where farmers exchange experiences, discuss production challenges, and explore new market opportunities. Their interactive approach allows followers to ask questions, receive quick guidance, and learn from the experiences of other farmers. As digital agriculture continues to grow, agri-influencers are becoming valuable partners in agricultural extension, innovation dissemination, and rural entrepreneurship, strengthening the overall agricultural knowledge ecosystem alongside universities, Krishi Vigyan Kendras, and government extension agencies (FAO, 2022).

Impact of agri-influencers on farmers and agriculture

Agri-influencers are creating a significant impact on farmers and the agricultural sector by improving access to timely, practical, and location-specific information. Their digital content enables farmers to learn about improved cultivation practices, pest and disease management, water conservation, farm mechanization, and market opportunities without depending solely on traditional extension channels. As a result, many farmers are able to make more informed production and marketing decisions.

One of the most important impacts of agri-influencers is the faster dissemination of agricultural innovations. Demonstrations of successful farming practices, modern technologies, and locally adapted solutions encourage farmers to experiment with new methods and adopt improved practices. This can contribute to higher productivity, reduced production risks, and better resource management. Agri-influencers also play a crucial role in spreading awareness about climate-resilient agriculture, organic farming, integrated pest management, and value addition, helping farmers adapt to changing environmental and market conditions.

In addition, agri-influencers strengthen social learning among farmers. Digital communities created through social media platforms encourage farmers to exchange experiences, discuss challenges, and share practical solutions. This interactive environment builds confidence, promotes peer learning, and reduces the isolation often experienced by small and marginal farmers. Many influencers also connect farmers with input suppliers, buyers, government schemes, financial services, and training opportunities, thereby expanding their access to agricultural support systems. Overall, agri-influencers are enhancing agricultural knowledge, encouraging innovation, supporting entrepreneurship, and improving communication within the farming community. Their growing influence is helping make agriculture more knowledge-driven, digitally connected, and responsive to the evolving needs of farmers.

Agri-influencers in India: Current scenario

The emergence of agri-influencers has become one of the most noticeable developments in India's agricultural communication landscape. The widespread availability of smartphones, low-cost internet services, and the increasing use of social media in rural areas have enabled farmers to access agricultural information more easily than ever before. Digital platforms such as YouTube, Instagram, Facebook, and WhatsApp are now widely used for learning about crop cultivation, pest and disease control, weather forecasts, market prices, government schemes, and farm business opportunities. As a result, agri-influencers are increasingly shaping farmers' knowledge, attitudes, and farming decisions.

India's agri-influencer ecosystem includes a wide range of contributors, including progressive farmers, agricultural professionals, agri-startup founders, scientists, rural communicators, Krishi Vigyan Kendras (KVKs), and agricultural universities. A major advantage of these influencers is their ability to communicate in regional languages, making technical agricultural information easier to understand and apply in local farming conditions.

Their content is often based on field demonstrations, practical experiences, success stories, innovative farming methods, and market-oriented advisory services, which enhances its credibility and usefulness.

An important trend is the rapid growth of short video formats and mobile-based agricultural advisory content. Farmers frequently turn to digital creators for immediate guidance on crop nutrition, irrigation practices, pest management, and market-related decisions. Many agri-influencers also help farmers connect with input suppliers, buyers, financial institutions, and training opportunities, thereby strengthening their access to agricultural services and markets. However, the expansion of digital influence also presents challenges. Inaccurate information, excessive product promotion, and the lack of scientific verification can sometimes mislead farmers. Therefore, stronger collaboration among agri-influencers, agricultural universities, research organizations, and extension agencies is essential to ensure that online agricultural content remains reliable, ethical, and evidence-based. Overall, agri-influencers have become an integral part of India's digital agricultural ecosystem, complementing conventional extension services and accelerating the spread of agricultural innovations and knowledge.

Conclusion

Agri-influencers are transforming the way agricultural knowledge is shared, learned, and applied in India. By combining digital technology with practical farming experience, they have made agricultural information more accessible, timely, and engaging for farmers across diverse regions. Their growing presence on social media platforms has strengthened farmer-to-farmer learning, encouraged the adoption of improved technologies, promoted sustainable farming practices, and created new opportunities for agricultural entrepreneurship. At the same time, the increasing influence of digital content creators highlights the need for accuracy, transparency, and scientific validation of the information being disseminated.

The future of agricultural communication lies in the effective integration of traditional extension systems with digital platforms. Collaborative efforts among agri-influencers, agricultural universities, Krishi Vigyan Kendras, research institutions, and government agencies can enhance the credibility and impact of digital extension services. As India moves toward a more technology-driven and knowledge-intensive agricultural sector, responsible and well-informed agri-influencers can play a crucial role in empowering farmers, improving agricultural productivity, and supporting sustainable rural development.

References

- Aker, J. C. (2011). Dial "A" for agriculture: A review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*, 42(6), 631–647. <https://doi.org/10.1111/j.1574-0862.2011.00545.x>
- Anderson, J. R., & Feder, G. (2007). Agricultural extension. In R. E. Evenson & P. Pingali (Eds.), *Handbook of Agricultural Economics* (Vol. 3, pp. 2343–2378). Elsevier. [https://doi.org/10.1016/S1574-0072\(06\)03044-1](https://doi.org/10.1016/S1574-0072(06)03044-1)
- BestMediaInfo. (2025, January 17). *Rural India makes up 55% of the 886 million internet users in 2024: Report*. <https://bestmediainfo.com/insights/rural-india-makes-up-55-of-the-886-million-internet-users-in-2024-report-8628510>
- Food and Agriculture Organization. (2021). *Digital technologies in agriculture and rural areas: Status report*. FAO. <https://www.fao.org>
- Food and Agriculture Organization. (2022). *The State of Food and Agriculture 2022: Leveraging automation in agriculture for transforming agrifood systems*. FAO. <https://doi.org/10.4060/cb9479en>
- India Brand Equity Foundation. (2025, January 17). *India's internet users to exceed 900 million in 2025, driven by Indic languages*. <https://www.ibef.org/news/india-s-internet-users-to-exceed-900-million-in-2025-driven-by-indic-languages>
- International Food Policy Research Institute. (2022). *Digital agriculture and extension services: Global trends and lessons for developing countries*. IFPRI. <https://www.ifpri.org>
- Internet and Mobile Association of India, & Kantar. (2025). *Internet in India 2024*. <https://www.iamai.in/research/internet-india-2024-kantariamai-report>
- Ministry of Agriculture & Farmers Welfare. (2023). *Digital agriculture initiatives in India*. Government of India. <https://agriwelfare.gov.in>

National Bank for Agriculture and Rural Development. (2022). *Rural digital transformation and agricultural innovation in India*. NABARD. <https://www.nabard.org>

Organisation for Economic Co-operation and Development. (2023). *Digital agriculture: Opportunities, challenges and policy responses*. OECD Publishing. <https://www.oecd.org>

Telecom Regulatory Authority of India. (2024). *The Indian telecom services performance indicators*. <https://www.trai.gov.in>

The Indian Express. (2025, January 16). *India's internet users to surpass 900 million in 2025; regional content driving growth: IAMAI-Kantar report*. <https://indianexpress.com/article/technology/tech-news-technology/indias-internet-users-to-surpass-900-million-in-2025-regional-content-driving-growth-iamai-kantar-report-9781881/>

United Nations. (2022). *The Sustainable Development Goals Report 2022*. United Nations. <https://unstats.un.org/sdgs/report/2022/>



“Bioinoculants in Modern Agriculture: Microbial Diversity, Mechanisms, Bioformulations, Applications and Future Prospects”



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Abstract

Bioinoculants are microbial formulations containing beneficial microorganisms that enhance nutrient availability, plant growth, soil biological activity, and crop productivity while reducing dependence on synthetic inputs. Important bioinoculants include *Rhizobium*, *Azospirillum*, *Azotobacter*, phosphate-solubilizing bacteria, *Bacillus*, *Pseudomonas*, *Trichoderma*, and mycorrhizal fungi. They promote plant growth through nitrogen fixation, nutrient solubilization, phytohormone and enzyme production, pathogen suppression, and induction of plant defense responses. Carrier-based, liquid, granular, encapsulated, hydrogel, and nano-enabled formulations can improve microbial viability, stability, shelf life, and field performance. Bioinoculants also contribute to climate-smart agriculture by improving nutrient-use efficiency and plant resilience to environmental stresses. However, limited shelf life, inconsistent field performance, quality-control issues, storage constraints, regulatory challenges, and low farmer awareness remain major limitations. Future research should focus on efficient formulations, strain–crop–soil compatibility, quality standards, and location-specific field validation. Overall, bioinoculants offer promising solutions for sustainable, nutrient-efficient, and climate-resilient agriculture.

1. Introduction

Bioinoculants are formulations containing beneficial microorganisms that improve soil fertility, nutrient availability, plant growth, and disease suppression. They contain viable or dormant cells of efficient microbial strains capable of biological nitrogen fixation, phosphorus solubilization, organic matter decomposition, and production of plant growth-promoting substances. These microorganisms can produce phytohormones, enzymes, siderophores, organic acids, and antimicrobial compounds such as hydrogen cyanide (HCN), which contribute to improved nutrient acquisition and suppression of phytopathogens. Some bioinoculants also enhance plant defense responses and are used for seed treatment, bioremediation, and sustainable crop production.

Bioinoculants can be classified according to their functions as nitrogen-fixing microorganisms, phosphorus-solubilizing microorganisms, and biocontrol agents. Based on their formulation, they are commonly available as carrier-based or liquid formulations. Important microorganisms used as bioinoculants include *Rhizobium* spp., *Azospirillum* spp., *Azotobacter* spp., phosphate-solubilizing bacteria (PSB), *Bacillus* spp., *Pseudomonas* spp., *Trichoderma* spp., and mycorrhizal fungi. Their application provides an environmentally sustainable alternative to excessive chemical inputs by improving nutrient cycling, plant growth, and soil fertility.

2. Global and Indian Bioinoculant Market Scenario

The global demand for microbial bioinoculants is increasing, driven by the growing emphasis on sustainable agriculture and reduced dependence on synthetic agricultural inputs. The global biofertilizer market was estimated at USD 2.5 billion in 2024 and is projected to reach USD 5.6 billion by 2034, according to Global Market Insights. A separate recent estimate by Fortune Business Insights reported a global market value of USD 2.81 billion in

2025, projected to reach USD 8.09 billion by 2034, with a CAGR of 12.60%. Despite this expansion, challenges related to formulation stability, microbial viability, shelf life, quality control, storage, distribution, and variable field performance continue to restrict wider adoption.

In India, the biofertilizer market was valued at USD 50.6 million in 2024 and is projected to reach USD 111.6 million by 2030, representing a CAGR of 14.2% during 2025–2030. Notably, phosphate-solubilizing biofertilizers are identified as the fastest-growing product segment, making this trend particularly relevant to phosphorus-solubilizing bacterial (PSB) research.

Table 1. Global and Indian Bioinoculant Market Size and Growth Projections.

Region	Year	Market value	Projection / Growth
Global	2024	USD 2.5 billion	—
	2025	USD 2.7 billion	—
	2034	—	USD 5.6 billion
India	2024	USD 50.6 million	—
	2030	—	USD 111.6 million
	2025–2030	—	14.2% CAGR

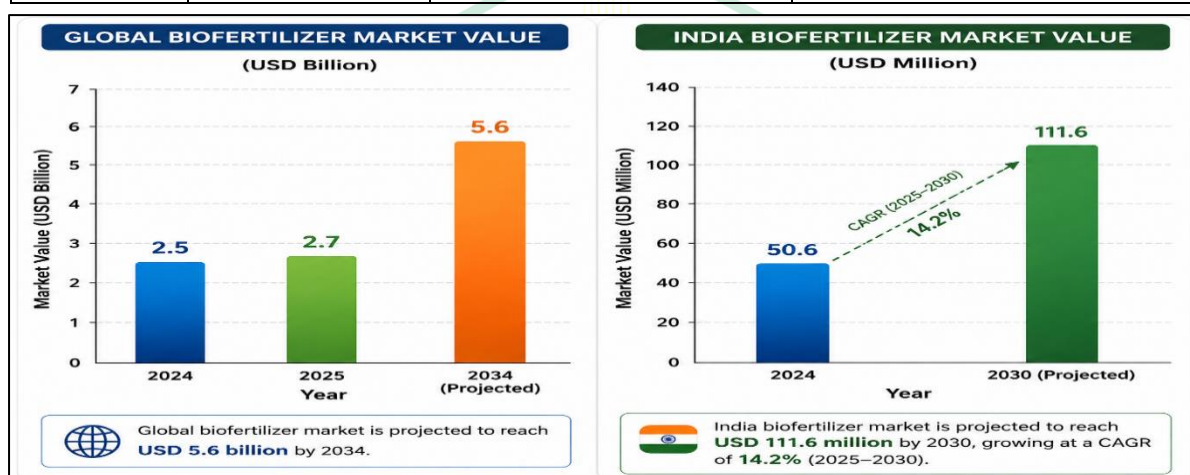


Fig. 1. Global and Indian biofertilizer market value and growth projections (2024–2034).

3. Bioinoculants for Climate-Smart Agriculture?

Bioinoculants are important components of **climate-smart agriculture (CSA)** because they improve nutrient-use efficiency, soil biological activity, crop growth, and resilience to climate stresses while reducing dependence on synthetic inputs. Beneficial microorganisms such as *Rhizobium*, *Azospirillum*, *Bacillus*, *Pseudomonas*, phosphate-solubilizing bacteria (PSB), and mycorrhizal fungi enhance nutrient availability through nitrogen fixation, phosphorus solubilization, organic matter decomposition, and production of plant growth-promoting substances. They can also improve plant tolerance to drought, salinity, and temperature stress by promoting root development and plant defense mechanisms. Thus, bioinoculants contribute to the three major goals of CSA: enhancing productivity, improving climate resilience, and reducing greenhouse-gas emissions through efficient nutrient management.

4. Classification and Types of Bioinoculants

Bioinoculants are beneficial microorganisms applied to seeds, seedlings, or soil to enhance plant growth, nutrient availability, and productivity. For example, *Rhizobium* improves nitrogen availability in leguminous crops, reducing dependence on synthetic fertilizers. Beneficial microbes also solubilize and mobilize essential nutrients, improve soil properties, and produce plant-growth-promoting substances such as phytohormones, antibiotics, secondary metabolites, and signaling molecules. These microbial biostimulants further enhance plant physiological and metabolic processes, contributing to sustainable crop production.

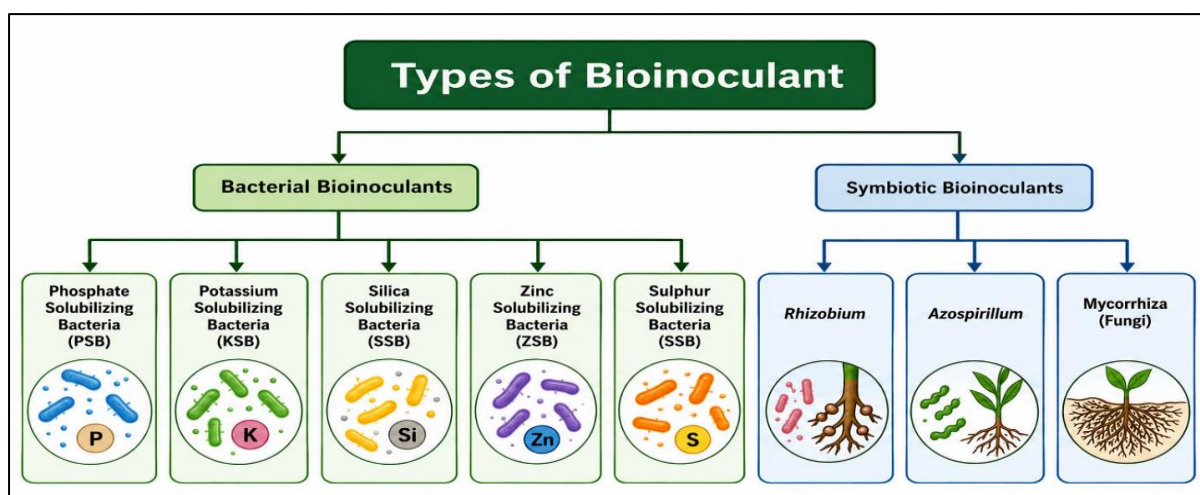


Fig. 2. Classification and Types of Bioinoculants

Table. 2. Classification and Types of Bioinoculan

Bioinoculant Type	Major Function / Mechanism	Primary Benefits to Plants	Examples
Rhizobium	Forms root nodules with legumes and fixes atmospheric N ₂ into plant-available nitrogen.	Improves biological nitrogen fixation, plant N nutrition, growth, and yield.	<i>Rhizobium</i> , <i>Bradyrhizobium</i>
Azospirillum	Associative PGPR that promotes plant growth through biological N fixation, phytohormone production, and improved nutrient acquisition.	Enhances root development, nutrient uptake, and plant growth.	<i>Azospirillum brasilense</i> , <i>A. lipoferum</i>
Mycorrhizae (AMF)	Forms symbiotic associations with plant roots; extraradical hyphae increase the soil volume explored by roots.	Enhances P, N, K, and micronutrient uptake and improves tolerance to environmental stresses.	Arbuscular mycorrhizal fungi
Phosphate-solubilizing bacteria (PSB)	Solubilize insoluble phosphates through organic acid production, chelation, and phosphatase activity.	Increases plant-available P and improves root growth and nutrient uptake.	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Enterobacter</i>
Silicate-solubilizing bacteria (SSB)	Mobilize silicon from insoluble silicate minerals through microbial activity and organic acid production.	Improves Si availability, plant defense, disease resistance, and stress tolerance.	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Paenibacillus</i>
Sulfur-solubilizing bacteria	Convert poorly available sulfur compounds into forms that can be utilized by plants.	Improves sulfur availability and supports protein and enzyme synthesis.	<i>Thiobacillus</i> , <i>Rhodococcus</i>
Potassium-solubilizing bacteria (KSB)	Release K from insoluble minerals through organic acid production and mineral weathering.	Increases available K and improves plant growth, water regulation, and stress tolerance.	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Azotobacter</i>
Zinc-solubilizing bacteria (ZSB)	Solubilize insoluble Zn compounds and increase Zn availability in soil.	Improves Zn nutrition, plant growth, and physiological development.	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Acinetobacter</i>
Plant growth-promoting bacteria (PGPB/PGPR)	Promote plant growth through nutrient mobilization, phytohormone production, siderophore production, and stress alleviation.	Enhances root development, nutrient uptake, growth, and stress tolerance.	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Azospirillum</i>

5. Mechanisms of Action of Bioinoculants

Direct mechanisms involve promoting plant growth by improving nutrient availability and uptake through phosphate solubilization, nitrogen fixation, siderophore production, and production of plant growth-promoting substances.

Indirect mechanisms involve protecting plants from pathogens through induced systemic resistance (ISR), antibiosis, secretion of lytic enzymes, competition for nutrients and ecological niches, and production of antimicrobial/volatile compounds.

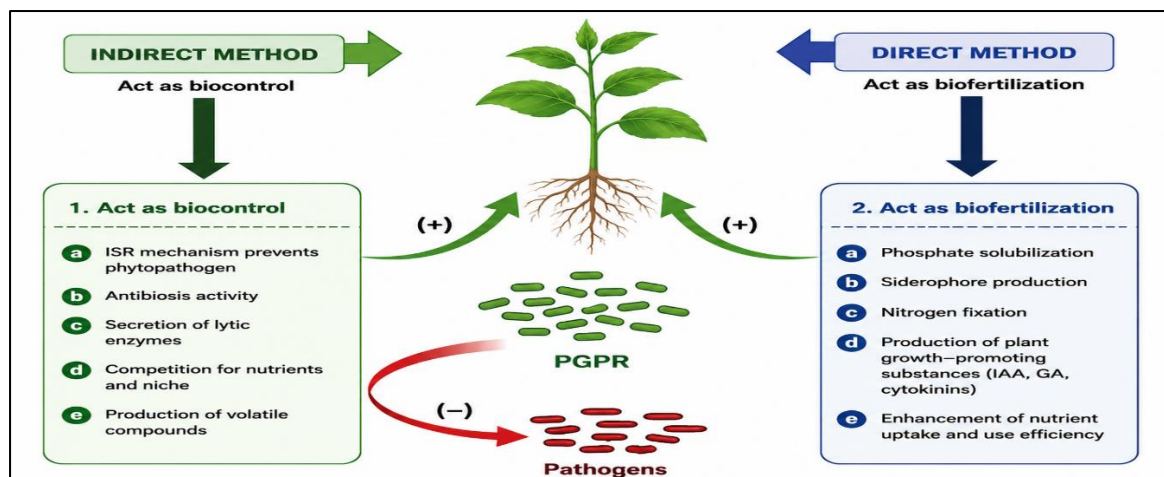


Fig. 3. Mechanisms of Action of Bioinoculants for Nutrient Mobilization, Plant Growth Promotion and Biocontrol.

6. Bioinoculant Formulation and Delivery Technologies

Commercialization of microbial formulations involves microbial isolation, identification, characterization, fermentation optimization, formulation development, storage, patenting, and product launch. Beneficial microorganisms are isolated from suitable environments and screened for biological functions. Carrier-based formulations are developed to maintain high microbial viability and stability during storage and application. Optimal fermentation conditions, including 25–28°C temperature, 90–100% dissolved oxygen, suitable pH, and agitation, are established to maximize microbial growth. Protective agents such as glycerol, sugars, and amino acids may improve cell survival under environmental stresses. Suitable carriers should support controlled release and bioavailability of microbial products. Finally, formulations are evaluated for quality, stability, efficacy, and commercial potential.

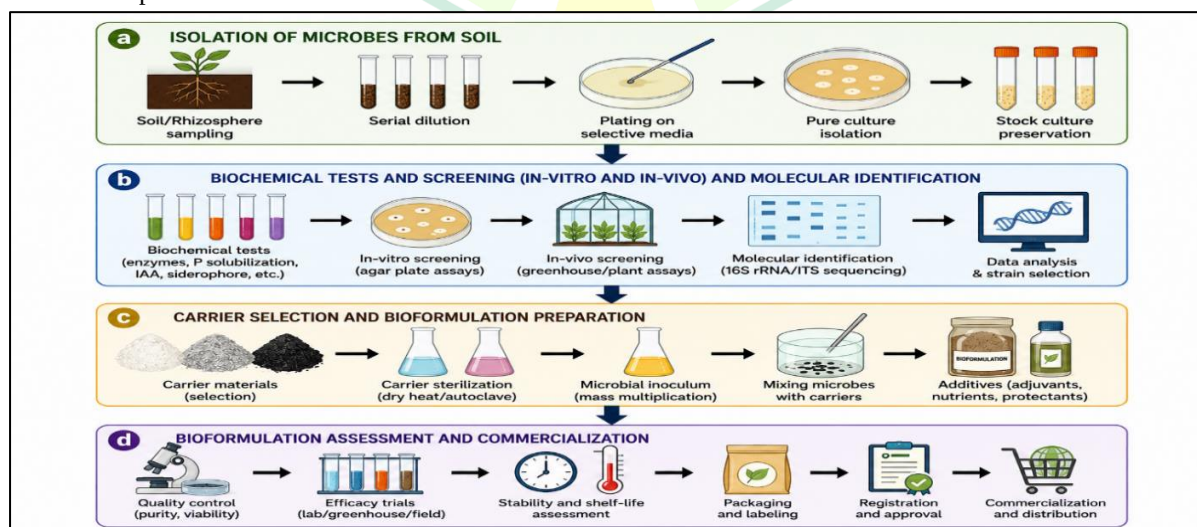


Fig. 4. Schematic Representation of Bioinoculant Formulation and Production Process

7. Types of Bioformulations

Bioinoculant formulation is the process of combining beneficial microorganisms with suitable carrier materials and protective agents to maintain their viability, stability, shelf life, and field efficacy. The major forms include solid, liquid, nano-formulated, and encapsulated formulations, which improve microbial survival, application, delivery, and controlled release.

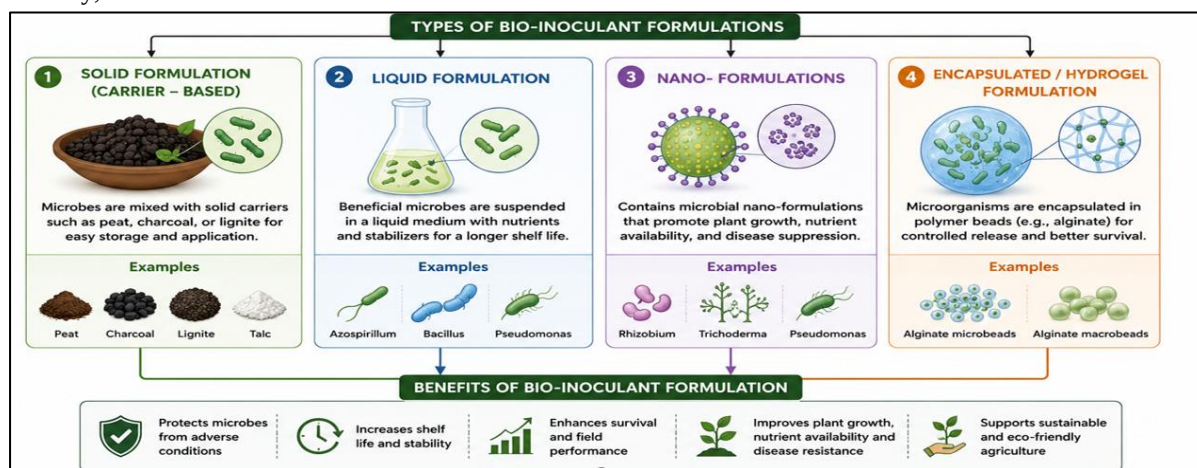


Fig. 5. Major types of bioinoculant formulations and their key benefits.

Table 2. Types, Characteristics and Examples of Bioinoculant Formulations

Main Category	Subcategory	Characteristics	Examples
Solid	Granular	Dry, non-dusty particles containing 5–20% active substances; particle size 100–1000 µm.	MET52® (<i>M. anisopliae</i> var. <i>anisopliae</i> strain F52), <i>Trichoderma virens</i>
	Wettable Powder	Contains 15–45% filler, 1–10% dispersant, 3–5% surfactant, and 50–80% powder.	Trichox WP (<i>Trichoderma harzianum</i>)
	Dust	Finely pulverized formulation containing typically 10% active substance; particle size 50–100 µm.	Biofox C (<i>Fusarium oxysporum</i>)
	Water-Dispersible Granules	Uses dispersion and wetting agents similar to wettable powders, usually with a higher concentration of dispersing agents.	Contans WG (<i>Coniothyrium minitans</i>), AQ 10 WG (<i>Ampelomyces quisqualis</i> AQ10)
Liquid	Suspension Concentrate	Dust-free, measurable, and easy to pour for spraying.	Cerall (<i>Pseudomonas chlororaphis</i> MA342)
	Oil Emulsion Formulations	Suspension of active components in a water-insoluble solvent.	DiTera
	Oil-Miscible Flowable Concentrate (OMFC)	Water-dispersible and safe for use.	BioOilFlow Pro (<i>Trichoderma afroharzianum</i> T22 and <i>Azotobacter</i>)
Encapsulated Bioformulations	Macro- and Microencapsulation	Microbial cells are coated within polymeric materials; macrobeads are mm–cm in size and microbeads are 1–1000 µm.	Molt-X
Hydrogel-Based Bioformulations		Polymeric hydrogels containing hydrophilic functional groups that absorb large amounts of water.	BioGelPro, MicroGelBoost (<i>Lactobacillus bulgaricus</i>)

8. Application Methods and Recommended Practices

Methods of bio-inoculant application are the techniques used to deliver beneficial microorganisms to seeds, roots, soil, or plant surfaces to ensure effective colonization and promote plant growth and nutrient availability.

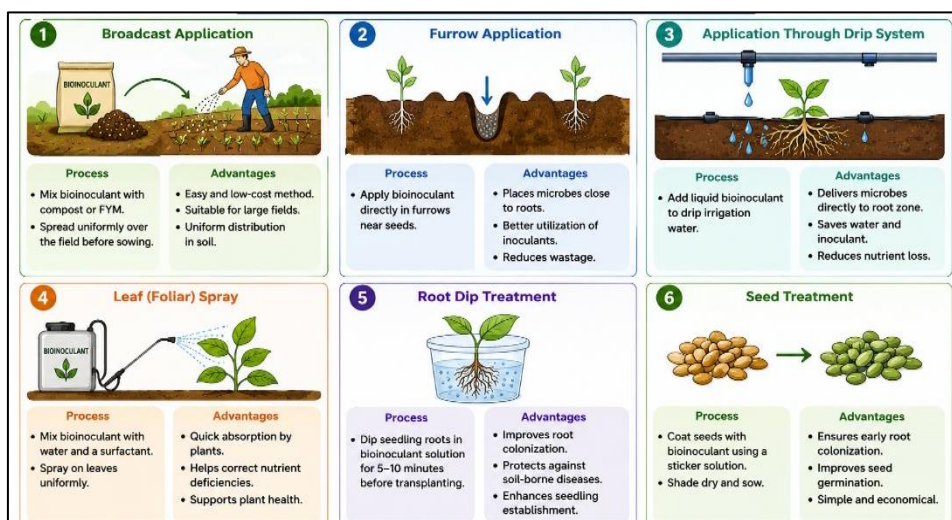


Fig. 6. Major methods of bioinoculant application in agricultural crops.

Table 3. Recommended Application Methods and Doses of Common Bioinoculants

Bioinoculant	Crop	Application Method	Recommended Dose
<i>Rhizobium</i>	Pulses	Seed treatment	5–10 ml/kg seed
<i>Azotobacter</i>	Tomato	Seedling dip	0.2 kg/litre water
<i>Trichoderma</i>	Groundnut	Seed treatment	4 g/kg seed
Mycorrhiza	Maize	Soil application	4 kg/acre

Table 4. Major Bioinoculants Used in Indian Agriculture: Microbial Type, Function and Benefits

Bioinoculant	Type of Microorganism	Mode of Action	Formulation	Benefits
Rhizobium spp.	Nitrogen-fixing bacteria	Biofertilizer	Carrier-based	Nitrogen fixation
Azospirillum spp.	Nitrogen-fixing bacteria	Phyto stimulant	Liquid-based	Nitrogen fixation, phytohormone production
Azotobacter spp.	Nitrogen-fixing bacteria	Biofertilizer	Carrier-based	Nitrogen fixation, phytohormone production
Phosphate Solubilizing Bacteria (PSB)	Phosphorus-fixing bacteria	Biofertilizer	Carrier-based	Phosphate solubilization
Bacillus spp.	Beneficial bacteria	Biopesticide	Liquid-based	Plant growth promotion, biocontrol
Trichoderma spp.	Fungal biocontrol agent	Biopesticide	Carrier-based	Plant growth promotion, biocontrol
Pseudomonas spp.	Beneficial bacteria	Phyto stimulant	Liquid-based	Plant growth promotion, biocontrol
Mycorrhizal fungi	Fungal symbionts	Biofertilizer	Carrier-based	Improves nutrient uptake

Table 5. Effects of Major Bioinoculants on Plant Growth, Nutrient Availability and Soil Fertility.

Bioinoculant	Major function	Mechanism	Major benefit
<i>Rhizobium</i>	Nitrogen fixation	Symbiotic N fixation	Increased N availability
<i>Azospirillum</i>	Plant growth promotion	Associative N fixation, phytohormones	Root development
PSB	P mobilization	Organic acids, phosphatases	Increased P availability
<i>Bacillus</i>	Growth promotion/biocontrol	Phytohormones, enzymes, ISR	Growth and disease suppression
<i>Pseudomonas</i>	Growth promotion/biocontrol	Siderophores, antibiotics, ISR	Disease suppression
<i>Trichoderma</i>	Biocontrol	Antagonism, lytic enzymes, ISR	Disease reduction
AMF	Nutrient mobilization	Hyphal exploration	P and micronutrient uptake

9. Performance and Field Evidence of Bioinoculants in Major Indian Crops

Bioinoculants containing beneficial microorganisms have shown promising potential for improving crop yield, nutrient-use efficiency, plant growth, and stress tolerance. In India, *Rhizobium* is widely used in pulse crops and can increase yield by approximately 10–35%, while phosphate-solubilizing bacteria (PSB) are used across a wide range of crops, with reported yield increases of 5–30%. *Azotobacter* and *Azospirillum* are important biofertilizers for cereals and other crops, generally contributing to 10–20% yield improvement. Global field studies and meta-analyses similarly report average yield improvements of approximately 9–20%, depending on crop, soil, climate, microbial strain, formulation, and application method. Overall, bioinoculants are promising tools for sustainable, nutrient-efficient, and climate-smart agriculture.

10. Benefits of Bioinoculants

Bioinoculants offer several benefits for sustainable crop production by improving nutrient availability, plant growth, soil fertility, and stress tolerance. Key benefits include:

Table 6. Benefits of Bioinoculants in Sustainable Crop Production

Benefit	Simple Description
Improved Nutrient Availability	Enhances the availability and uptake of N, P, K, Zn, and other nutrients.
Biological Nitrogen Fixation	<i>Rhizobium</i> , <i>Azotobacter</i> , and <i>Azospirillum</i> increase nitrogen availability to plants.
Phosphorus Mobilization	Phosphate-solubilizing microorganisms convert unavailable P into plant-available forms.
Plant Growth Promotion	Produces phytohormones, enzymes, and siderophores that improve root and shoot growth.
Biocontrol	Suppresses plant pathogens through antagonism, antimicrobial compounds, and induced resistance.
Improved Stress Tolerance	Helps plants tolerate drought, salinity, and other environmental stresses.
Enhanced Soil Biological Activity	Promotes microbial activity, decomposition, and nutrient cycling.
Reduced Chemical Inputs	Reduces dependence on synthetic fertilizers and pesticides.
Sustainable Crop Production	Improves soil fertility, nutrient-use efficiency, crop productivity, and climate resilience.

11. Challenges and future prospects

Despite the benefits of bioinoculants, their widespread adoption faces challenges. Limited shelf life, variable performance across different agro-zones, and lack of farmer awareness hinder their use. These microbes also provide slower results compared to synthetic chemicals. Additionally, regulatory hurdles complicate their registration and commercialization. However, with increasing focus on sustainable agriculture, bioinoculants hold great potential. Future research should focus on location- and crop-specific studies, improving shelf life, and

raising awareness through extension programs and government schemes. Subsidies for biofertilizers and pesticides could boost adoption, contributing to sustainable agricultural production.

12. Conclusion

Bioinoculants are promising microbial inputs for sustainable and climate-smart agriculture because they improve nutrient availability, plant growth, soil biological activity, and crop resilience while reducing dependence on synthetic inputs. Microorganisms such as *Rhizobium*, *Azospirillum*, phosphate-solubilizing bacteria, *Bacillus*, *Pseudomonas*, *Trichoderma*, and mycorrhizal fungi contribute through nutrient fixation and mobilization, phytohormone production, pathogen suppression, and stress tolerance. Advances in carrier-based, liquid, encapsulated, hydrogel, and nano-enabled formulations can further improve microbial viability, stability, shelf life, and field performance. However, inconsistent field efficacy, limited shelf life, quality control, storage, commercialization, and farmer awareness remain important challenges. Future research should focus on efficient formulations, strain–crop–soil compatibility, quality standards, and location-specific field validation to promote wider adoption of bioinoculants and strengthen sustainable agricultural production.

References

- Arun Karnwal, A., Dohroo, A., & Malik, T. (2023). *Unveiling the potential of bioinoculants and nanoparticles in sustainable agriculture for enhanced plant growth and food security*. *BioMed Research International*, 2023, Article 6911851. <https://doi.org/10.1155/2023/6911851>.
- Bhattacharyya, C., Banerjee, S., Acharya, U., Mitra, A., Mallick, I., Haldar, A., Haldar, S., Ghosh, A., & Ghosh, A. (2020). Evaluation of the efficacy of biofertilizers toward sustainable agriculture: A review. *Journal of Soil Science and Plant Nutrition*, 20(4), 2338–2355.
- Chaudhary, T., Dixit, M., Gera, R., Shukla, A. K., Prakash, A., Gupta, G., & Shukla, P. (2020). Techniques for improving formulations of bioinoculants. *3 Biotech*, 10, 199. <https://doi.org/10.1007/s13205-020-02182-9>.
- Global Market Insights Inc. (2025). *Biofertilizers Market Size & Share, 2025–2034*. Global biofertilizer market: USD 2.5 billion in 2024, projected to reach USD 5.6 billion by 2034.
- Grand View Research (2024/2025). *India Biofertilizers Market Size & Outlook, 2025–2030*.
- Indian Council of Agricultural Research (ICAR). (2025). *Indian Farming*, December 2025.
- Kumar, R., Farda, B., Mignini, A., Djebaili, R., Koolman, L., Paul, A., Mondal, S., Joel, J. M., Pandit, A., Panneerselvam, P., et al. (2025). Microbial solutions in agriculture: Enhancing soil health and resilience through bio-inoculants and bioremediation. *Bacteria*, 4, 28. <https://doi.org/10.3390/bacteria4030028>.
- Satya Narayana, Jagetiya, P., Mathur, R., Mishra, R., & Chauhan, S. (2025). *Biofertilizer commercialization: Future prospects and challenges*. *Agricultural Research Journal*, 62(1), 1–15. DOI: 10.5958/2395-146X.2025.00001.8.
- Trabelsi, D., & Mhamdi, R. (2013). Microbial inoculants and their impact on soil microbial communities: A review. *BioMed Research International*, 2013, Article 863240. <https://doi.org/10.1155/2013/863240>.
- Yadav, A. N., Verma, P., Kumar, S., Kumar, V., Kumar, M., Sugitha, T. C. K., Singh, B. P., Saxena, A. K., & Dhaliwal, H. S. (2022). *Liquid biofertilizers as a sustainable solution for agriculture*. *Heliyon*, 8(12), e12609.

Arbuscular Mycorrhizal Fungi: Invisible Partners in Sustainable Agriculture



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1. Introduction

Modern agriculture faces the challenge of producing more food for a growing population while conserving natural resources. Although chemical fertilizers have significantly increased crop productivity, their excessive and prolonged use has resulted in soil degradation, nutrient imbalances, declining microbial diversity, and environmental pollution. According to the Food and Agriculture Organization (FAO), nearly 95% of global food production depends on healthy soils, yet about one-third of the world's soils are degraded, highlighting the need for sustainable nutrient management.

Among the eco-friendly alternatives, biofertilizers have emerged as an important tool for sustainable agriculture. These beneficial microorganisms improve nutrient availability, enhance nutrient-use efficiency, promote plant growth, and restore soil biological activity. Their adoption has increased rapidly due to the expansion of organic farming, rising fertilizer costs, and growing awareness of soil health. Reflecting this trend, the global biofertilizer market is projected to grow from USD 3.33 billion in 2024 to USD 5.69 billion by 2029, at a CAGR of 11.3%. Likewise, the Indian biofertilizer market is expanding steadily, with mycorrhizal biofertilizers representing one of the largest and fastest-growing segments.

Biofertilizers include several beneficial microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria, potassium-solubilizing microorganisms, and mycorrhizal fungi. Among them, Arbuscular Mycorrhizal Fungi (AMF) are unique because they establish a direct symbiotic association with plant roots. Through an extensive network of fungal hyphae, AMF function as a natural extension of the root system, enabling plants to absorb phosphorus, micronutrients, and water more efficiently while improving soil health and resilience to environmental stresses.

Today, nearly 80–90% of terrestrial plant species form associations with AMF, making them one of the most successful and widespread plant symbionts on Earth. Their ability to improve crop productivity while reducing dependence on chemical fertilizers has made AMF an indispensable component of sustainable and climate-resilient agriculture. This article highlights the biology, functions, production technologies, commercial potential, and future prospects of AMF in modern agriculture.

2. Why AMF? What Makes It Special?

Among the various biofertilizers used in agriculture, Arbuscular Mycorrhizal Fungi (AMF) are unique because they form a close, mutually beneficial partnership with plant roots rather than living freely in the soil. The term mycorrhiza comes from the Greek words *mykes* (fungus) and *rhiza* (root), meaning "fungus-root." In this natural partnership, the plant supplies the fungus with carbohydrates produced through photosynthesis, while the fungus helps the plant absorb water and essential nutrients from the soil.

The name "arbuscular" refers to the tiny, tree-like structures called arbuscules that develop inside the root cells. These structures serve as nutrient exchange centres where the plant and fungus share resources. AMF also produce vesicles, which store nutrients and lipids, and an extensive network of fine hyphae that extends far beyond the root system. These hyphae act as a natural extension of the roots, allowing plants to explore a much larger volume of soil for phosphorus, zinc, copper, sulfur, and water.

AMF belong to the fungal phylum Glomeromycota and are among the oldest plant partners on Earth, with a history dating back more than 450 million years. Today, they naturally associate with nearly 80–90% of terrestrial plant species, including most agricultural, horticultural, and forestry crops. What truly distinguishes AMF from other biofertilizers is their obligate symbiotic lifestyle. Unlike *Rhizobium*, *Azotobacter*, phosphate-solubilizing bacteria, or *Trichoderma*, which can be grown on artificial culture media, AMF cannot survive or

multiply without a living host plant. This dependence on plant roots makes their production more challenging but also enables them to establish a highly efficient nutrient-delivery system that no other biofertilizer can provide.

3. How Does AMF Help Plants?

Once established inside plant roots, Arbuscular Mycorrhizal Fungi (AMF) function as a natural extension of the root system (Fig 1). Their fine fungal hyphae explore a much larger volume of soil than roots alone, enabling plants to absorb relatively immobile nutrients such as phosphorus, along with zinc, copper, sulfur, and water more efficiently. As a result, plants exhibit better nutrient-use efficiency, vigorous root growth, and reduced dependence on chemical fertilizers. Beyond improving nutrient acquisition, AMF enhance plant tolerance to drought, salinity, and nutrient-deficient conditions while improving soil health through the production of glomalin-related soil protein (GRSP), which stabilizes soil aggregates and improves soil structure. These multiple benefits have made AMF an important component of climate-smart and sustainable agriculture.

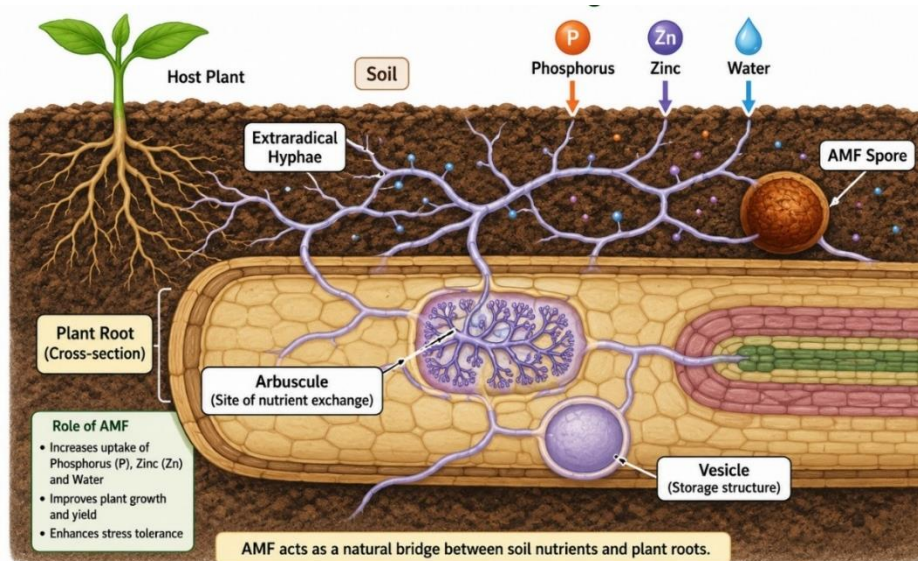


Fig 1: Structure of AMF and nutrient exchange with plant roots

The beneficial effects of AMF have been demonstrated in several economically important crops (Table 1). Recent studies have shown improvements in nutrient uptake, crop productivity, stress tolerance, and disease resistance following AMF inoculation.

Table 1. Recent studies demonstrating the benefits of AMF in major crops

Crop	Major findings	Reference
Rice (<i>Oryza sativa</i>)	Improved phosphorus uptake, grain yield, and resistance to rice blast disease under field conditions.	Campo et al. (2020)
Maize (<i>Zea mays</i>)	Enhanced nutrient uptake, plant growth, and yield, particularly under stress conditions.	Chandrasekaran (2020); Diagne et al. (2020)
Tomato (<i>Solanum lycopersicum</i>)	Increased nutrient uptake, fruit yield, and tolerance to abiotic and biotic stresses.	Giovannini et al. (2020); Diagne et al. (2020)
Blackgram (<i>Vigna mungo</i>)	AMF (<i>Glomus intraradices</i>) primed plant defence responses against <i>Spodoptera litura</i> , demonstrating the potential of AMF in improving crop resilience.	Selvaraj et al. (2020),

4. AMF: A Growing Business Opportunity

The growing demand for sustainable agriculture and reduced dependence on chemical fertilizers is creating a strong and expanding market for biofertilizers. In India, the biofertilizer market is also expanding steadily, driven by the increasing adoption of biological inputs, organic farming, and sustainable agricultural practices. Within this sector, mycorrhiza-based biofertilizers represent a significant commercial opportunity. A recent global

market assessment estimated the mycorrhizae-based biofertilizer market at approximately US\$1.8 billion in 2024, with projections reaching US\$3.6 billion by 2030, representing an estimated CAGR of 11.5%. Although market estimates vary depending on the products and categories included, the overall trend indicates increasing commercial interest in mycorrhiza-based agricultural biologicals. Table 2 presents some major companies involved in the development and commercialization of AMF- or mycorrhiza-based agricultural biological products across global and Indian markets.

Table 2. Major companies involved in AMF-based biofertilizers

Company	Headquarters
Premier Tech Horticulture	Rivière-du-Loup, Quebec, Canada
Groundwork BioAg	Mazor, Israel
Koppert Biological Systems	Berkel en Rodenrijs, Netherlands
IPL Biologicals Ltd.	Gurugram, Haryana, India
Kan Biosys Pvt. Ltd.	Pune, Maharashtra, India

With continued investment in research and development, efficient AMF multiplication technologies, product formulation, quality control, commercialization, and farmer awareness, AMF-based biofertilizers are expected to play an increasingly important role in improving soil health, enhancing nutrient-use efficiency, reducing dependence on chemical fertilizers, and supporting sustainable crop production. This growing market also provides considerable scope for the development of locally produced, crop-specific AMF formulations and entrepreneurial ventures in India.

5. AMF Production Technologies

Being obligate biotrophs, AMF requires living roots to culture them. This unique characteristic makes AMF production more challenging than that of bacterial biofertilizers such as *Rhizobium* and *Azotobacter*. Several production technologies have been developed to multiply AMF inoculum, each differing in scale, infrastructure, and intended application. The most commonly used methods include pot culture, Root Organ Culture (ROC), and substrate/greenhouse culture (Table 3). The choice of method depends on the production capacity, available facilities, and quality requirements.

Table 3. Common methods of AMF production

Production method	Principle	Suitable for	Advantages
Pot culture	AMF multiplied on living host plants (maize, sorghum, grasses) grown in sterilized substrate	Universities, research laboratories, small entrepreneurs	Simple, economical, and easy to adopt
Root Organ Culture (ROC)	AMF propagated on transformed carrot roots under sterile conditions	Research institutes, biotechnology laboratories	High-quality, contamination-free inoculum with high spore density
Substrate/Greenhouse culture	Host plants grown under controlled greenhouse conditions for mass multiplication	Commercial biofertilizer industries	Large-scale production with consistent quality

Advances in production technologies are improving inoculum quality, consistency, and commercial availability, making AMF increasingly accessible for sustainable agriculture and biofertilizer industries.

6. Entrepreneurship Opportunities in AMF Production

The increasing demand for eco-friendly agricultural inputs has made Arbuscular Mycorrhizal Fungi (AMF) production a promising business opportunity. With the rapid expansion of organic farming, natural farming, protected cultivation, and precision agriculture, the demand for quality AMF inoculants is expected to increase steadily in the coming years. This creates excellent opportunities for agri-startups, agricultural graduates, Farmer Producer Organizations (FPOs), Self-Help Groups (SHGs), and rural entrepreneurs. AMF production units can

be established at different scales depending on the available infrastructure and investment. Small-scale units can cater to local nurseries and farmers, whereas medium and large units can supply biofertilizer companies, horticultural farms, and commercial markets. Technical training from agricultural universities, ICAR institutes, and biotechnology organizations can further support successful enterprise development.



Fig 2. Investment requirement for AMF production units

*Investment may vary depending on production capacity, technology adopted, and land availability.

Government agencies such as ICAR, NABARD, MSME, BIRAC, and the Ministry of Agriculture & Farmers Welfare provide training, technical guidance, funding opportunities, and entrepreneurship support for bio-input production. With increasing awareness of soil health and supportive government policies, AMF production has the potential to become a profitable and sustainable agri-enterprise.

7. Challenges and Future Prospects

Despite their considerable potential, the large-scale adoption of arbuscular mycorrhizal fungi (AMF) faces several challenges. As obligate biotrophs, AMF depend on living host plants for growth and cannot be cultured on conventional artificial media, making their mass production more complex and costly than that of many other microbial biofertilizers. Their efficacy may also vary depending on crop species, soil properties, climatic conditions, and agricultural management practices. Furthermore, the production of high-quality and viable inoculum, standardization of formulations, quality assurance, storage stability, and limited farmer awareness remain important constraints to their wider adoption.

Nevertheless, the future prospects of AMF are highly promising. Advances in biotechnology, improved mass-production techniques, efficient carrier and formulation technologies, and better quality-control methods are enhancing the effectiveness and commercial viability of AMF-based products. The growing emphasis on organic farming, natural farming, climate-smart agriculture, and the reduction of chemical fertilizer inputs is expected to further increase the demand for AMF technologies.

In India, government initiatives such as the National Mission on Natural Farming (NMNF), Paramparagat Krishi Vikas Yojana (PKVY), National Mission for Sustainable Agriculture (NMSA), and PM-PRANAM provide an enabling environment for the development and adoption of sustainable agricultural inputs. The rapid growth of the biofertilizer industry, coupled with increasing interest in environmentally friendly agricultural practices, is creating new opportunities for AMF research, commercialization, and entrepreneurship. Continued efforts by research institutions, agricultural universities, and private industries, along with farmer training and awareness programmes, are expected to accelerate the adoption of AMF-based technologies across diverse cropping systems. With continued research, technological advancement, quality assurance, and effective farmer education, AMF have the potential to become an important component of sustainable and resource-efficient agriculture.

8. Conclusion

Arbuscular Mycorrhizal Fungi (AMF) are among the most promising biofertilizers for promoting sustainable and climate-resilient agriculture. By enhancing nutrient and water uptake, improving soil health, increasing crop

productivity, and reducing dependence on chemical fertilizers, AMF offer an eco-friendly solution for meeting future agricultural demands. Although challenges related to mass production and quality assurance remain, continued advances in production technologies and increasing farmer awareness are paving the way for wider use of AMF. By integrating science, industry, and policy support, these invisible fungal partners have the potential to play a vital role in improving soil fertility, enhancing farm profitability, and ensuring a more sustainable future for agriculture.

References

- Begum, N., Qin, C., Ahanger, M. A., Raza, S., Khan, M. I., Ashraf, M., Ahmed, N., & Zhang, L. (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. *Frontiers in Plant Science*, 10, 1068.
- Berruti, A., Lumini, E., Balestrini, R., & Bianciotto, V. (2016). *Arbuscular mycorrhizal fungi as natural biofertilizers: Let's benefit from past successes*. *Frontiers in Microbiology*, 6, 1559. <https://doi.org/10.3389/fmicb.2015.01559>
- Campo, S., Martín-Cardoso, H., Olivé, M., et al. (2020). Effect of root colonization by arbuscular mycorrhizal fungi on growth, productivity and blast resistance in rice. *Rice*, 13, 42.
- Chandrasekaran, M. (2020). A meta-analysis of arbuscular mycorrhizal fungi inoculation effects on plant growth and nutrient uptake. *Agriculture*, 10, 370.
- Diagne, N., Ngom, M., Djighaly, P. I., Fall, D., Hoher, V., & Svistoonoff, S. (2020). Roles of arbuscular mycorrhizal fungi on plant growth and performance: Importance in biotic and abiotic stress regulation. *Diversity*, 12, 370.
- FAO. (2015). *Status of the World's Soil Resources (SWSR): Main Report*. Food and Agriculture Organization of the United Nations.
- Giovannini, L., Palla, M., Agnolucci, M., Avio, L., & Turrini, A. (2020). Arbuscular mycorrhizal fungi improve tomato growth, nutrition, and tolerance to environmental stresses. *Agronomy*.
- Ijdo, M., Cranenbrouck, S., & Declerck, S. (2011). Methods for large-scale production of arbuscular mycorrhizal fungi: Past, present, and future. *Mycorrhiza*, 21, 1–16. <https://doi.org/10.1007/s00572-010-0313-z>
- MarketsandMarkets. (2024). *Biofertilizers Market – Global Forecast to 2029*.
- Mordor Intelligence. (2024). *India Biofertilizer Market – Growth, Trends, COVID-19 Impact, and Forecast (2024–2029)*.
- Mordor Intelligence. (2024). *India Biofertilizer Market – Industry Analysis and Forecast*.
- Smith, S. E., & Read, D. J. (2008). *Mycorrhizal Symbiosis* (3rd ed.). Academic Press.
- Selvaraj, A., Thangavel, K., & Uthandi, S. (2020). Arbuscular mycorrhizal fungi (*Glomus intraradices*) and diazotrophic bacterium (*Rhizobium* BMBS) primed defense in blackgram against herbivorous insect (*Spodoptera litura*) infestation. *Microbiological Research*, 231, 126355.

Nature's Engineering in the Patterns of the Mithun Head Diversity in Arunachal Pradesh



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Introduction.

The well-known bovine in northeast India, Mithun (*bos frontalis*), finds its place in the culture, economy, and traditions of tribal communities. Also known as the “pride of the hills,” mithun are maintained under free-range systems and considered adaptive, strong, and socially and culturally influential. Although body size and horn morphology are the main focus of anthropological research in some species, the head with respect to poll region and cranial width (CRW) shape can be considered as a yardstick to describe the natural variation in morphological traits. The poll region, the patch at the top back of the head between the horns, is key to muscle attachment, structural strength, and head conformation. Likewise, the distance between the bases of the horns or cranial width (CRW) shape is related to mithun as it provides clues towards the head posture as well as skull structure. Collectively, these two parameters are critical determinants of head shape and act as practical visual indicators for the farmer. Such features facilitate rapid identification and classification of animals at the field level even during the earlier stages of life and therefore also play an important role in traditional livestock management and for scientific assessment. Field study with 2,500 mithun (720 males and 1,780 females) was held in four districts in Arunachal Pradesh—Anjaw, Lower Subansiri, East Siang, and Longding over the period of 3 years w.e.f 2018-2021. Due to variation by poll prominence and cranial width shape, four unique head types were detected, revealing considerable phenotypic differences within the mithun populations in this area

1. Prominent Poll with Convex Cranial Width (Hump-like)—47%

Number of animals: 1,175

Features:

- Poll region well-developed and raised
- Cranial width is broad and convex
- Head looks massive, strong, and convex (hump-like)

Field importance: This is the most common and typical mithun head type. Farmers prefer such animals because they are associated with strength, dominance, and are better adapted to the environment. The expansive cranial width contributes to the overall impressiveness.

2. Less Prominent Poll with Straight Cranial Width — 43%

Number of animals: 1075

Features:

- Poll is smooth and less raised
- Cranial width is moderate and straight
- Head looks more balanced and less bulky

Field importance: They are widely distributed and efficient in their functional roles. Less noticeable than the former type, these animals perform well under field conditions and represent a typical intermediate variety.

3. Non-Prominent Poll with Narrow Cranial Width (V-like) — 8%

Number of animals: 200

Features:

- Poll region undeveloped or slightly depressed

- Cranial width is V shape
- V-like head is visible

Field importance: This kind is unique and but has less appeal in traditional selection.

4. Raised Tip Poll with W-like Cranial Width — 2%

Number of animals: 50

Features:

- Poll shows a central raised point
- Depressions on either side create a W-like cranial pattern
- Horn bases are distinctive in structure

Field importance: It is a rare form, and its unique pattern reflects the hidden diversity within mithun populations. It is important from both the genetic and documentation point of view.

5. Comparative Overview of Mithun Head Types N= 2500 (*bos frontalis*)

Pattern Type	Male	Female	Number	Percentage	Key Features
1. Prominent poll + convex CRW	379	796	1,175	47%	Convex, massive head
2. Smooth poll + straight CRW	51	1024	1075	43%	Balanced head
3. Depressed poll + V-shaped CRW	5	195	200	8%	V-shaped head
4. Raised tip + W-shaped CRW	0	50	50	2%	Unique W-shaped pattern

The head morphology of Mithun (*Bos frontalis*) was assessed in a total population of 2,500 animals, comprising 435 males and 2,065 females. Based on the configuration of the poll and the shape of the cranial ridge/wattle region (CRW), four distinct head-type patterns were identified. The distribution indicates considerable morphological variation, with the prominent poll + convex CRW pattern being the most prevalent, followed by the smooth poll + straight CRW pattern.

The Prominent poll + convex CRW type was the most common morphological pattern, accounting for 1,175 animals (47%) of the total population (Pic No1 & 2). This pattern was observed in 379 males and 796 females. Animals belonging to this category were characterized by a prominent poll and a distinctly convex cranial profile, giving the head a broad, massive and robust appearance. The relatively high frequency of this type suggests that the convex and massive head configuration represents one of the principal morphological characteristics of the Mithun population studied.

The second most frequent pattern was Smooth poll + straight CRW, comprising 1,075 animals (43%), including 51 males and 1,024 females (Pic No 3 & 4). Animals in this group exhibited a relatively smooth poll with a straight cranial profile, resulting in a balanced and proportionate head structure. Together, the first two patterns accounted for 2,250 animals, or 90% of the entire population, indicating that prominent/convex and smooth/straight head configurations constitute the predominant forms of head morphology in Mithun.

The Depressed poll + V-shaped CRW pattern was comparatively less frequent. A total of 200 animals (8%) exhibited this morphology, comprising 5 males and 195 females (Pic No 5 & 6). The defining feature of this group was a depressed poll accompanied by a V-shaped cranial profile. This configuration produced a distinctly V-shaped head, differentiating these animals from the broader and more balanced head types observed in the first two categories. Although less common, its presence in the population demonstrates additional morphological diversity within the species.

The least frequent pattern was Raised tip + W-shaped CRW, which was recorded in only 50 animals (2%), all of which were (Pic No7 & 8). This type was distinguished by a raised tip and a characteristic W-shaped cranial profile, producing a unique W-shaped head pattern. The absence of this pattern among males and its very low overall frequency suggest that it represents a relatively uncommon morphological variant within the population examined.

Overall, the findings demonstrate that Mithun possess considerable variation in head morphology, although the variation is strongly concentrated in the first two major types. The 47% prominent poll + convex CRW and 43% smooth poll + straight CRW patterns together represented 90% of the observed population, whereas the V-shaped and W-shaped patterns accounted for only 10%. The marked predominance of these two major head types may be useful in phenotypic characterization, breed description, morphological documentation and conservation of Mithun genetic resources. The occurrence of the less common V-shaped and W-shaped patterns also highlights the importance of documenting morphological variants when developing breed descriptors and evaluating population diversity.

What Do These Results Signal?

Dominance of Strong Head Type Since most of them (47%) have prominent poll and convex cranial width, it confirms this as the dominant and characteristic conformation in mithun. It encompasses both natural selection and past preference of farmers over generations.

Presence of Diversity

The remaining patterns (53%) emphasize considerable variation, critical for:

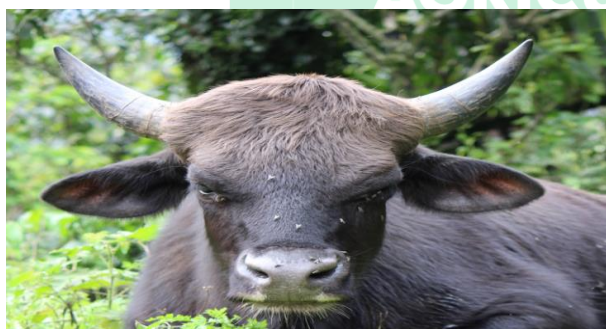
- Adaptability to variations in the natural environment
- Preserving genetic diversity
- Further refinements in breeding

Role of Environment

Skull development may be affected by nutrition, grazing status, and management behavior. Better nutritional status of the animals may lead to the development of wider and more prominent head structures.

Conclusion

The evidence of 2,500 mithun clearly shows that natural engineering has generated specific structures in the head, such as the poll region and cranial width. Although the poll with a big, broad cranial width is still the most abundant variety, other forms such as straight, V-shaped, and W-shaped patterns are also found. Knowledge of these patterns has implications on mithun selection, breeding, and conservation so that the culturally and economically important breed of mithun can continue to flourish in its native regions.



Pic No. 1 Prominent poll + convex CRW Female



Pic No. 2 Prominent poll + convex CRW Male



Pic No. 3 Smooth poll + straight CRW, Female



Pic No. 4 Smooth poll + straight CRW, Male



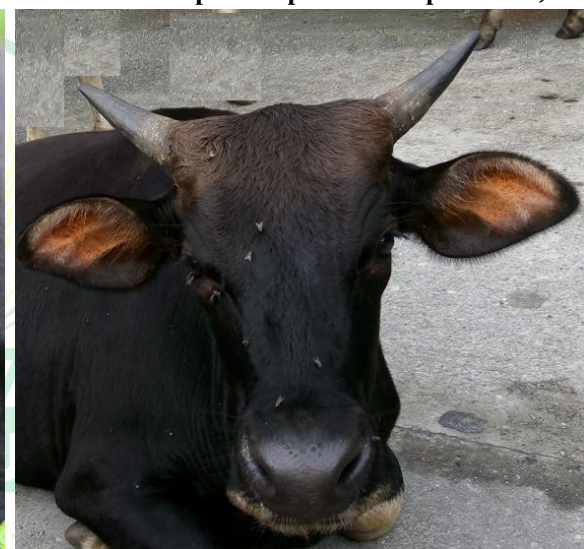
Pic No. 5 Depressed poll + V-shaped CRW, Female



Pic No. 6 Depressed poll + V-shaped CRW,



Pic No. 7 Raised tip + W-shaped CRW, Female



Pic No. 8 Raised tip + W-shaped CRW, Female



Pic No. 9 Group photo of Mithun during survey

Nutrigenomics: Where Food Meets Your Genes



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The recent emergence of the Omics era has resulted in an upsurge of the new term “Nutritional Genomics”. Nutrigenomics is a portmanteau of nutritional genomics and describes an area of science that encompasses the human genome, nutrition, and health. Folks who work in this field are interested in figuring out how nutrients affect gene expression (i.e. turning genes on or off). For example, beta carotene. “[Beta carotene converts into Vitamin A](#)”, which is the “bioavailable” form of the vitamin our bodies can use.

Different variants of the same gene can dramatically alter how well a person is able to digest, absorb, metabolize, and synthesize certain nutrients.

- Nutrigenomics – the study of how your diet affects your genes, including regulating changes in protein production and metabolism
- Nutrigenetics – the study of how your specific gene variants affect your response to dietary nutritional components.

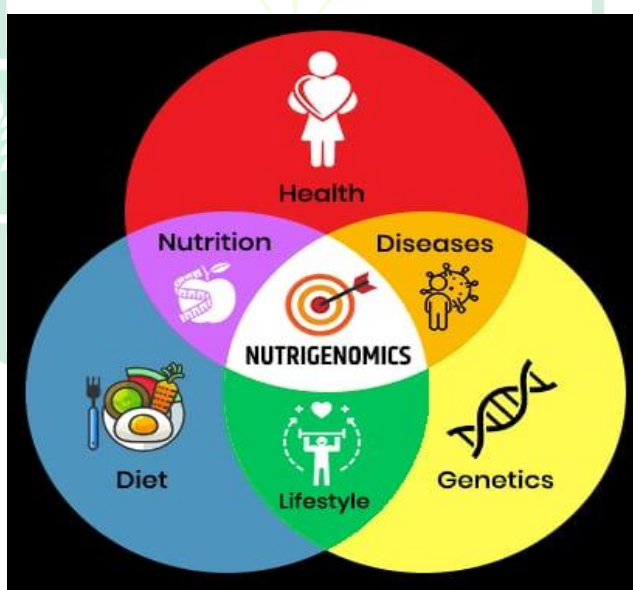


Fig: 1. Advantages of nutrigenomics

Principle:

Genetic variability among individuals significantly influences the interaction between diet and human physiology. Variations in genes involved in nutrient metabolism, absorption, transport, and utilization contribute to differences in nutritional requirements and modulate individual responses to dietary components.

The main goals of Nutrigenomics:

- To elucidate the interactions between nutrients and the genome
- To identify genetic variations that affect nutrient metabolism and dietary responses
- To develop personalized nutrition strategies
- To prevent and manage chronic diseases
- To optimize nutrient utilization and metabolic health

- To identify biomarkers of dietary intake and disease risk

Nutrition–gene interaction

1. **Direct interactions:** Nutrients, after interacting with a receptor, behave as transcription factors that can bind to DNA and induce gene expression.
 - Some nutrients bind to specific cellular receptors, particularly nuclear receptors.
 - Once activated, these receptors can interact with specific DNA sequences called response elements.
 - The receptor–nutrient complex can then function as a transcriptional regulator, increasing or decreasing the expression of particular genes.
 - This can influence metabolic pathways involved in lipid metabolism, glucose homeostasis, inflammation, antioxidant defense, and cell growth.

Examples:

- Vitamin D: The active form, calcitriol, binds to the vitamin D receptor (VDR). The VDR complex interacts with DNA and regulates genes involved in calcium metabolism, immunity, and cell differentiation.
 - Retinoic acid (vitamin A derivative): It interacts with retinoic acid receptors (RARs) and retinoid X receptors (RXRs), regulating genes involved in development, differentiation, and cellular functions.
2. **Epigenetic interactions:** Nutrients can alter the structure of DNA so that gene expression is altered.

The major mechanisms include:

a. DNA methylation

- Addition of methyl groups to DNA, usually at cytosine residues in CpG sites, can alter gene expression.
- Nutrients such as folate, vitamin B12, choline, methionine and vitamin B6 participate in one-carbon metabolism, which provides methyl groups required for DNA methylation.
- Changes in the availability of these nutrients can therefore influence the methylation status of particular genes.

b. Histone modification

DNA is packaged around proteins called histones. Chemical modifications of histones can make DNA more or less accessible to transcription machinery.

- Nutrients and their metabolites can influence enzymes responsible for histone acetylation, methylation and other modifications.
- For example, acetyl-CoA, a metabolite produced during nutrient metabolism, provides acetyl groups used in histone acetylation.

c. Non-coding RNA

Dietary factors can also influence regulatory molecules such as microRNAs (miRNAs).

- miRNAs can bind to messenger RNA (mRNA).
- This can reduce translation into proteins or promote mRNA degradation.
- Consequently, changes in miRNA activity can influence metabolic and physiological processes.

Example: Maternal nutrition during pregnancy can influence epigenetic patterns in the developing fetus, potentially affecting metabolism and disease susceptibility later in life.

3. **Genetic variation:** Common genetic variations such as single-nucleotide polymorphisms (SNPs) can alter the expression or functionality of genes.

SNPs can influence nutrition in several ways:

a. Altered protein function

A SNP occurring within a protein-coding region may change the amino acid sequence of a protein and consequently alter its function.

b. Altered gene expression

SNPs located in regulatory regions may influence how strongly a gene is expressed.

c. Altered nutrient metabolism

Genetic variants can affect enzymes involved in the absorption, transport, metabolism or utilization of nutrients.

Examples:

- LCT gene: Genetic variants associated with lactase persistence determine whether an individual continues producing sufficient lactase enzyme into adulthood. This influences the ability to digest lactose.
- MTHFR gene: Certain variants can alter the activity of the MTHFR enzyme, which participates in folate and one-carbon metabolism.

Practical applications of Nutrigenomics

- Personalized Nutrition
- Prevention of Chronic Diseases
- Clinical Nutrition and Medical Nutrition Therapy
- Weight Management
- Sports and Exercise Nutrition
- Nutrient Deficiency Management
- Precision Medicine
- Nutraceutical and Functional Food Development
- Maternal and Infant Nutrition
- Public Health and Preventive Nutrition

Advantages

- Increased focus on a healthy diet and lifestyle
- Increased awareness of risk of certain conditions
- Improved health quantity of life
- Focus on prevention of diseases
- Decreased morbidity and premature mortality
- Reduced health care costs
- Better understanding of the mechanisms involved in disease susceptibility

Disadvantages

- Attention is drawn away from other modifiable risk factors.
- Focus only specific nutrients/foods.
- Misleading claims.
- Increased costs associated with personalized diets and designer foods.

Future prospects

- More precise dietary recommendations
- Integration with multi-omics
- AI-supported precision nutrition
- Prevention and management of chronic disease
- Improved adherence to healthy diets
- Personalized supplements and functional foods
- Clinical decision-support tools

References

- Vyas, S. (2022). Advances in Nutrigenomics and Applications in Public Health: A Recent Update. *Current Research in Nutrition and Food Science Journal*, 10(3), 1092–1104.
- Noor M, Parveen R, Abbasi KS, Saeeduddin M, Yasir MH, Qudoos MY, Imran S, Mumtaz A, Moawia MA and Sarwar T, 2025. Nutrigenomics: The interaction between nutrition and genes. In: Şahin T, Ameer K, Abid M and Tahir S (eds), *Nutritional Foundations of Holistic Health: From Supplements to Feed Strategies*. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 219-226. <https://doi.org/10.47278/book.HH/2025.326>
- Gardner, A. (2023). Nutrigenomics 101: Understanding the Basics of DNA Diets. *Gene Food*. Updated January 31, 2023.
- Welocity Genetics. Advantage Nutrigenomics: Nutritional Genomics—Towards Personalized Nutrition. Welocity Genetics. Available at: Welocity Genetics – Advantage Nutrigenomics

Smart Packaging: The Future of Fresh Fruits and Vegetables



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Abstract

Fresh fruits and vegetables are highly perishable, leading to significant postharvest losses. These losses lead to reduction in farmers' income, affect food quality, and increase food waste. Smart packaging offers an innovative solution by using sensors, indicators, RFID tags, QR codes, and active materials to monitor freshness, control package environment, and provide real-time information about produce condition. This article discusses the need for smart packaging in fresh produce, its main types and working principles, recent innovations, and its growing applications in India and Andhra Pradesh. It also explains the challenges of adoption and the future potential of technologies. *This paper synthesizes technological innovations and case studies to demonstrate how smart packaging can transform food loss into food gain in India.*

Keywords: Smart packaging, Postharvest losses, Intelligent packaging, Active packaging, RFID tags, QR codes, Biosensors.

Introduction

Fresh fruits and vegetables are rich sources of essential nutrients, but they are highly perishable and often lose quality after harvest due to improper handling, inadequate packaging, poor storage, and transportation delays (FAO, 2019). These postharvest losses reduce farmers' income, increase food waste, and limit the availability of fresh produce to consumers (Kumar *et al.*, 2026).

Smart packaging is emerging as a game-changing solution, using sensors, indicators, and intelligent materials to monitor freshness, extend shelf life, and reduce food waste (Singh & Rao, 2023). By reducing postharvest losses and improving food safety, smart packaging has the potential to transform the future of fresh fruits and vegetables while supporting a more sustainable food system (Gulati, *et al.*, 2024).

The Need for Smart Packaging in Fresh Produce

Fresh fruits and vegetables are highly perishable, which means they can lose freshness, texture, colour, and nutritional value very quickly after harvest (FAO, 2019). Traditional packaging provides physical protection but cannot indicate whether the food is still fresh or monitor critical conditions such as temperature, humidity, or gases that accelerate spoilage (Kumar *et al.*, 2026).

Smart packaging technologies help preserve quality and extend shelf life by incorporating sensors, indicators, and intelligent materials that monitor freshness and detect environmental changes (Singh & Rao, 2023). These innovations also reduce problems that occur during transport, storage, and retail display, thereby minimizing food loss and improving consumer confidence in food safety (Patel & Singh, 2022).

What is Smart Packaging?

Smart packaging is a modern type of packaging that goes beyond simply holding and protecting food; it also monitors quality, freshness, and storage conditions (FAO, 2019). It uses tools such as freshness indicators, time-temperature indicators, QR codes, RFID tags, and sensors to provide useful information about the product during storage and transport (Singh & Rao, 2023).

By detecting quality changes and extending shelf life, smart packaging helps reduce postharvest losses and ensures safer, high-quality food reaches consumers (Patel & Singh, 2022; Zhang, *et al.*, 2020). This innovation represents a significant step toward building a sustainable food system by integrating technology into food supply chains.

Types of Smart Packaging

Smart packaging is mainly classified into active packaging and intelligent packaging. Active packaging helps keep fruits and vegetables fresh by controlling factors such as oxygen, moisture, or ethylene, thereby slowing down spoilage and extending shelf life (Singh & Rao, 2023). In contrast, intelligent packaging monitors freshness and provides information through sensors, indicators, RFID tags, or QR codes, enabling real-time tracking of food quality during storage and transport (Patel & Singh, 2022). When these systems work together, they significantly reduce postharvest losses, improve food safety, and extend the shelf life of produce (FAO, 2019; Kumar *et al.*, 2026).

How Smart Packaging Works

Smart packaging works by using sensors, indicators, and active materials to monitor the condition of fruits and vegetables inside the package. It can detect changes in temperature, humidity, and gas levels, providing real-time information about food quality (Singh & Rao, 2023). In some cases, smart packaging also incorporates active components that absorb moisture or gases such as ethylene, slowing down spoilage and keeping produce fresher for longer (Kumar *et al.*, 2021). By combining monitoring and active control, smart packaging helps reduce postharvest losses, improves food safety, and ensures that high-quality food reaches consumers (FAO, 2019; Zhang, *et al.*, 2020).

Innovations in Smart Packaging

Smart packaging is becoming more advanced with technologies such as freshness indicators, time-temperature indicators, RFID tags, QR codes, biosensors, and Internet of Things (IoT)-based monitoring systems, which help track product quality throughout the supply chain (Zhang, *et al.*, 2020). Edible coatings like chitosan, aloe vera gel, and starch improve the shelf life of produce by reducing moisture loss and microbial growth (Kumar, *et al.*, 2021). These new technologies enable real-time monitoring of produce, detecting changes in temperature or gas composition, and in some cases actively slowing spoilage. As a result, packaging becomes smarter, more sustainable, and more useful for both sellers and consumers (Singh & Rao, 2023; FAO, 2019).

Success Stories from India and Andhra Pradesh

India is slowly adopting smart packaging technologies to improve the quality and shelf life of fresh fruits and vegetables. In Andhra Pradesh, research and innovation are moving forward, including work at the National Institute of Technology (NIT) Andhra Pradesh, where researchers have developed nanoparticles-based food packaging materials. These materials enhance shelf life, maintain quality, and can even detect pathogens, pesticides, and toxins, showing how local institutions are contributing to safer and smarter food packaging (NIT Andhra Pradesh, 2021; Devdiscourse, 2021).

Similarly, mango processing industries in Chittoor use advanced packaging and cold chain facilities to preserve mango pulp and frozen mango products. These are processed for both domestic consumption and export markets, particularly to Europe and Gulf countries, ensuring better farmer incomes and reduced wastage (PLR Foods, 2022; Sri Varsha Food Products, 2022).

These initiatives demonstrate that smart packaging and postharvest technologies can reduce losses, improve quality, raise farmers' income, and strengthen India's horticultural supply chain (FAO, 2019; Gulati *et al.*, 2024).

Challenges in Adopting Smart Packaging

Despite its potential, smart packaging faces several limitations. It is often more expensive than traditional packaging, requiring better infrastructure and advanced supply chain systems (FAO, 2019). Recycling and environmental concerns also arise, as many smart packaging materials incorporate sensors, indicators, or nanomaterials that are not easily biodegradable (Kumar *et al.*, 2026).

Another challenge is consumer awareness—many consumers are still unfamiliar with how smart packaging works or why it matters, which limits its acceptance in the market (Singh & Rao, 2023). Small and marginal

farmers, who form the majority of India's agricultural workforce, often find it difficult to afford these technologies due to high costs and lack of access to training (Gulati, *et al.*, 2024).

Increasing awareness, providing training, and improving infrastructure can help make smart packaging more accessible and encourage its wider adoption in the horticultural sector (Patel & Singh, 2022).

The Future of Smart Packaging

The future of smart packaging is promising as new technologies continue to improve the safety, quality, and shelf life of fresh fruits and vegetables. The integration of artificial intelligence (AI) for predictive quality assessment and supply chain optimization is expected to make packaging more efficient and responsive (Patel & Singh, 2022). Similarly, the Internet of Things (IoT) enables real-time monitoring of storage and transport conditions, ensuring freshness and reducing losses (Zhang *et al.*, 2020).

The development of biodegradable and sustainable packaging materials addresses environmental concerns while maintaining food quality (FAO, 2019). Advanced sensors, freshness indicators, and time-temperature indicators will further enhance consumer confidence by providing transparent information about product safety and quality (Singh & Rao, 2023).

Together, these innovations point toward a future where smart packaging not only reduces postharvest losses but also supports a more sustainable and consumer-friendly food system (Kumar *et al.*, 2026).

Conclusion

Smart packaging is transforming the way fresh fruits and vegetables are preserved, transported, and marketed. By integrating innovative technologies with sustainable packaging materials, it helps maintain product quality, extend shelf life, reduce postharvest losses, and improve food safety (FAO, 2019).

The use of sensors, indicators, and intelligent materials ensures that freshness is monitored and spoilage is minimized, while biodegradable and eco-friendly packaging solutions address environmental concerns (Singh & Rao, 2023). These advancements not only benefit consumers by providing safer, high-quality food but also improve farmer incomes and strengthen the horticultural supply chain (Kumar *et al.*, 2026; Gulati *et al.*, 2024). Thus, smart packaging represents a critical step toward building a sustainable food system where technology and innovation work together to reduce waste and ensure food security for future generations (Patel & Singh, 2022).

References

- FAO. (2019). *The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction*. Rome: Food and Agriculture Organization of the United Nations.
- Gulati, A., Das, R., & Winter-Nelson, A. (2024). *Reducing post-harvest losses in India: Farmer-level interventions and grain management strategies*. Indian Council for Research on International Economic Relations (ICRIER) Report 24-r-03. New Delhi, India.
- Kumar, P., Kumbhare, N. V., Nain, M. S., Bishnoi, S., Biswas, A., Kumar, P., & Prasad, S. (2026). Analysis of post-harvest losses of TOP crops and their determinants under Operation Greens. *Frontiers in Sustainable Food Systems*, 10, Article 1773566.
- Singh, R., & Rao, V. (2023). Advances in modified atmosphere packaging for fruits and vegetables: A review. *Journal of Food Packaging and Shelf Life*, 35, 100987.
- Patel, H., & Singh, A. (2022). Artificial intelligence applications in postharvest management of fruits and vegetables. *Postharvest Biology and Technology*, 185, 111741.
- Zhang, Y., Li, J., Wang, H., & Chen, X. (2020). IoT-based cold chain logistics monitoring system for perishable food. *Computers and Electronics in Agriculture*, 170, 105247.
- NIT Andhra Pradesh. (2021). Nanoparticles-based food packaging materials research. *National Institute of Technology Andhra Pradesh News Release*. Retrieved from Devdiscourse.
- PLR Foods. (2022). *Company profile and product portfolio*. PLR Foods Private Limited, Chittoor, Andhra Pradesh.
- Sri Varsha Food Products. (2022). *Fruit pulp processing and export operations*. Sri Varsha Food Products India Pvt. Ltd., Tirupati, Andhra Pradesh.

Sowing Capital, Harvesting Futures: Blended Financial Models as the New Frontier for Agricultural Transformation in India



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“If agriculture goes wrong, nothing else will have a chance to go right.”
Dr. M. S. Swaminathan, Father of India’s Green Revolution

Introduction

Agriculture remains the soul of the Indian economy. Even as the country advances towards becoming the world's third largest economy, the sector supports more than 46 per cent of the population and contributed close to 16 per cent of Gross Domestic Product in FY 2024-25 (Ministry of Agriculture & Farmers Welfare [MAFW], 2025). Yet for all its centrality, agriculture is chronically under financed, technologically fragmented and unusually exposed to climatic risk. The paradox is sharp: a nation that harvested a record 357.73 million tonnes of foodgrain in 2024-25 (MAFW, 2025) still contends with agrarian distress and rural poverty.

The resolution may lie less in how much capital reaches agriculture than in how that capital is structured. Financing built almost entirely on government grants, subsidised bank credit and donor aid is neither deep enough nor durable enough for the task, particularly as climate pressures mount and the rural infrastructure deficit widens. Blended financial models offer a different route: a deliberate layering of public, private and philanthropic capital designed to reduce risk, draw in commercial finance and align profit with purpose.

Understanding Blended Finance

The Organisation for Economic Co-operation and Development defines blended finance as the strategic use of development finance and philanthropic funds to mobilise private capital for emerging and frontier markets. Its architecture rests on a layered capital stack: concessional or grant capital absorbs the first loss, lowering the risk borne by commercial investors in the senior tranche, while mezzanine finance from development finance institutions and impact investors sits between the two. Instruments range from guarantees and concessional loans to results based financing and equity co-investments, all aimed at improving the risk return profile of investments in sectors the market persistently undervalues. It is less a technique than a development philosophy, one that accepts market failure without abandoning market mechanisms.

The Global Picture: Scale, Gaps and Momentum

The world requires roughly USD 1.1 trillion each year to bring agrifood systems onto a net zero pathway (Climate Policy Initiative [CPI] & Food and Agriculture Organization [FAO], 2024), yet actual climate finance reaching them stands at about USD 95 billion annually, or 8.3 per cent of the requirement (CPI & Consortium on Leading Initiatives in Climate [CLIC], 2025). Against the USD 1.31 trillion mobilised across all sectors, agrifood systems capture a modest 7.2 per cent (CPI, 2024). Distribution is uneven too: Western Europe and East Asia absorb close to three quarters of agrifood investment while South Asia and Sub-Saharan Africa remain underserved, and crops and livestock draw over 40 per cent of funding, leaving post harvest infrastructure, soil health and water management short (CPI & CLIC, 2025).

Momentum is nonetheless building. Climate focused blended finance reached USD 15.5 billion across 84 deals in 2024, the second highest annual total in six years, with institutional investors committing USD 1.6 billion, comfortably above pre-2023 averages (Convergence, 2025). Mitigation oriented investments dominated, taking 56 per cent of deals and 64 per cent of flows between 2019 and 2024. Even so, the Sustainable Development Goals financing gap keeps widening; the United Nations Department of Economic and Social Affairs places it at USD 4 trillion a year, and a 2025 dialogue at Seville concluded that existing models have yet to realise their potential (United Nations, 2025).

India's Financing Landscape and the Architecture of Public Capital

India has built a substantial agricultural finance ecosystem, with meaningful scope to deepen it further. The Union Budget 2025-26 allocated Rs. 1.52 lakh crore to agriculture and allied sectors (MAFW, 2025). The Kisan Credit Card, the flagship short term credit instrument, recorded 7.75 crore operational accounts as of March 2024 with Rs. 9.81 lakh crore outstanding (Press Information Bureau [PIB], 2025a), and PM-Kisan Samman Nidhi has credited more than Rs. 3.90 lakh crore directly to 11 crore farmers across 20 instalments (MAFW, 2025).

Institutional credit nevertheless reaches the most vulnerable unevenly. Marginal farmers holding less than a hectare, women cultivators, tribal communities and growers in arid zones remain at the edge of formal lending. Non-performing asset ratios in the agricultural portfolio temper commercial risk appetite, while private capital is discouraged by fragmented land markets, price volatility, thin collateral frameworks and uneven rural digital infrastructure. It is exactly this terrain, where public finance falls short and private capital hesitates, that blended models are built for.

Several schemes already supply the public capital layer. The Agriculture Infrastructure Fund, a Rs. 1 lakh crore facility, is the closest existing approximation of a blended vehicle in Indian agriculture, offering medium to long term debt for post harvest infrastructure and community farming assets. By December 2024 it had sanctioned Rs. 52,738 crore across 87,548 projects, mobilising total investment of Rs. 86,798 crore (PIB, 2025b), and its combination of credit guarantees, interest subvention and institutional lending demonstrates disciplined risk sharing. Pradhan Mantri Fasal Bima Yojana pairs crop insurance with agricultural credit; its linkage with Kisan Credit Card loans lifts lender confidence, and connecting payouts to satellite based index insurance would reduce basis risk and shorten claim settlement.

PM-KUSUM, promoting solar powered irrigation, and the Ethanol Blending Programme, which reached 19.05 per cent blending by July 2025 with attendant foreign exchange savings and higher sugarcane incomes, represent the green economy dimension of agricultural finance (MAFW, 2025). Both create farm level revenue streams that can be monetised to attract private capital. Anchoring the structure is the National Bank for Agriculture and Rural Development (NABARD), which channels refinance to regional rural banks, cooperative banks and microfinance institutions. Its Kisan Rin Portal, launched in September 2023, digitised interest subvention and had processed claims worth Rs. 1,08,336.78 crore by December 2024, benefiting 5.9 crore farmers under the Modified Interest Subvention Scheme-KCC (PIB, 2025a). These digital rails are the foundation on which blended products can scale cheaply.

Lessons from Global Practice

Aceli Africa has mobilised over USD 300 million across 3,500 loans, reaching 1.5 million farmers and agricultural workers in East Africa (World Economic Forum [WEF], 2025). Donor funded incentives lower the cost of lending for commercial banks and make smallholder credit commercially viable, an approach Indian regional rural banks could adopt through frameworks co-funded by NABARD, state governments and bilateral donors. In Italy, Intesa Sanpaolo deployed a EUR 23 billion programme of reduced rate loans across 172 agrifood supply chains (WEF, 2025), showing how one large bank can anchor an entire ecosystem.

The Africa Agriculture and Trade Investment Fund, initiated by Germany's KfW, received EUR 30 million in first loss capital from the European Union and on-lends to local financial institutions and agribusiness enterprises (European Commission, 2025). That layer shielded senior investors and drew private capital into a market it would otherwise have avoided, a design a NABARD led platform could replicate. GrowBeyond's USD 100 million vehicle, meanwhile, pairs capital with digital agronomy platforms that gather farm level data across ASEAN economies, narrowing information asymmetry and enabling risk based pricing (WEF, 2025). India's Agristack initiative has established precisely that kind of ecosystem.

Challenges and Pathways

Regulatory fragmentation is the first constraint. The Securities and Exchange Board of India's Master Circular for Alternative Investment Funds (May 2024) strengthened oversight and investor safeguards, though greater clarity on risk sharing and concessional capital structures would further assist blended initiatives in agriculture (Anuram & Anuram, 2025). How social impact metrics should sit alongside financial returns also remains open, and the Reserve Bank of India, SEBI, NABARD and the Insurance Regulatory and Development Authority of

India each govern a portion of the field without a unifying architecture. An inter-regulatory task force under the Ministry of Finance could build a coherent Blended Agricultural Finance Framework, supported by a sandbox that lets innovation proceed under supervision.

Information asymmetry is the second. Lenders read agricultural credit as high risk because of weather dependence, price volatility and weak collateral, and sparse farm level data makes credit scoring difficult while raising transaction costs. Closer convergence between Agristack and the PM-Kisan database would strengthen farmer identification, and embedding satellite based crop monitoring data into loan origination would support dynamic pricing that rewards sound farming practice.

A thin pipeline of bankable projects is the third: capital cannot deploy without investment ready proposals in post harvest infrastructure, agritech and climate adaptation, even where willing investors exist. A dedicated Project Development Facility under NABARD could help Farmer Producer Organisations, agri-SMEs and state agencies structure viable proposals, with technical assistance grants from the World Bank and the Asian Development Bank defraying preparation costs.

The Bank as Catalyst

For public sector banks, regional rural banks and cooperative banks, blended finance is a practical route to expanding the agricultural book while keeping risk contained. Participating as senior lenders in blended structures gives access to first loss protection from government agencies or development finance institutions, lowering effective credit risk while preserving commercially viable spreads; the Agriculture Infrastructure Fund, with subvention and guarantees already embedded, offers a ready template.

Banks leading in agricultural ESG lending are also well placed to issue green bonds and tap international markets at finer pricing, a pathway made credible by India's sovereign green bond framework of 2023 and sustained global demand. There is a franchise argument too: a farmer taking a blended finance irrigation loan is a natural customer for crop insurance, warehouse receipt finance and, as incomes rise, savings products, and lifetime value far exceeds the first loan. With priority sector norms requiring 18 per cent of adjusted net bank credit for agriculture, qualifying blended products serve business targets and development objectives at once.

The Way Forward

Moving from isolated pilots to systemic change calls for several ideas pursued together. India could establish an Agriculture Blended Finance Facility under NABARD, seeded with Rs. 10,000 crore from the Union government and co-invested by multilateral institutions and domestic impact investors, extending first loss guarantees, concessional subordinated debt and technical assistance to lower the risk of commercial lending to Farmer Producer Organisations, agri-SMEs and climate smart projects, with tiered refinance incentives for banks exceeding priority sector targets. Alongside it, Agri-Blended Green Bonds issued jointly by state governments, large public sector banks and NABARD could ring-fence proceeds for climate smart agriculture, solar irrigation and regenerative farming, a partial sovereign guarantee and dual listing attracting ESG mandated institutional investors.

Distribution matters as much as structure. A unified digital AgriFinance platform, built on the Open Network for Digital Commerce and integrated with Agristack, could serve as the marketplace, letting farmers access composite packages of credit, insurance, advisory and market linkage through one interface while banks, non-banking financial companies, agritech firms and insurers transact on the same rails. The 10,000 FPO initiative announced in the Union Budget 2020-21 provides the backbone for cluster based deployment, each cluster anchored by impact equity, priority sector tagged working capital and grant funded technical assistance, with the collective cash flows of the FPO as the primary repayment source.

Parametric weather insurance completes the design. Linking payouts to predefined rainfall or temperature thresholds settles claims far faster than conventional crop insurance, and blended structures can keep premiums affordable through demand side subsidy while drawing global reinsurance capital, as Kenya and Mexico's CADENA programme demonstrate.

Conclusion

The story of Indian agriculture has long been one of resilience against structural disadvantage: farmers have absorbed monsoon failures, price collapses, credit deserts and market exclusion with little beyond their own

ingenuity and community solidarity. That endurance is not an argument for the status quo but a case for doing better by the people who feed a nation of 1.4 billion.

Blended models refuse the false choice between commercial sustainability and social inclusion. Layered intelligently, public, private and philanthropic capital can make viable what the market alone would never finance: irrigation for a marginal farmer in Vidarbha, cold storage for an FPO in Bihar, solar pumps for a tribal cultivator in Jharkhand, a climate adaptive cropping system for a dryland farmer in Rajasthan. These are not acts of charity but investments in the productive capacity of the world's largest agricultural nation.

The moment is unusually favourable. India has record agricultural output, digital public infrastructure the developing world admires, a growing cadre of agritech innovators and a government that has steadily expanded the financial architecture of the rural economy. What remains is the will to connect these strands into a coherent national Blended Agricultural Finance Strategy aligning the Ministry of Agriculture, NABARD, the Reserve Bank of India, SEBI, commercial banks and private investors. For Indian banks this is no moment for passivity: priority sector mandates, ESG imperatives, digital infrastructure and a transforming rural economy together present a rare opportunity to build agricultural franchises that are sustainable, profitable and consequential. Capital sown with purpose and patience can yield a harvest of rural prosperity that no single revolution, scheme or technology has delivered on its own. The time to plant is now.



Runoff Management in Dryland Agriculture: Converting Every Raindrop into Sustainable Crop Production



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Introduction

Dryland agriculture is the backbone of Indian farming. Nearly 52–55 percent of the country's cultivated area depends solely on rainfall, contributing significantly to food grain, oilseed, pulse, cotton, and livestock production. Regions such as Vidarbha, Marathwada, Rajasthan, Karnataka, Telangana, Madhya Pradesh, and parts of Gujarat are characterized by rainfed or dryland farming systems where agricultural productivity is closely linked with rainfall availability and its efficient utilization. The major challenge in dryland agriculture is not always the scarcity of rainfall but rather its variability and inefficient utilization. In many dryland regions, annual rainfall may range from 700 to 1200 mm, which is theoretically sufficient to support profitable crop production. However, uneven distribution, prolonged dry spells, high-intensity storms, and inadequate water conservation measures often result in moisture stress and low crop productivity.

A substantial portion of seasonal rainfall is lost as surface runoff. Water that could otherwise infiltrate into the soil, recharge groundwater, or support crop growth flows away from fields and watersheds. Consequently, dryland agriculture suffers from soil erosion, declining soil fertility, reduced groundwater recharge, and increased vulnerability to drought. Therefore, the future sustainability of dryland agriculture depends on the scientific management of rainfall through effective runoff management practices. The philosophy of modern dryland farming is simple yet powerful:

"Conserve rainwater where it falls and utilize it where it is needed."

Understanding Runoff in Dryland Ecosystems

Runoff refers to the portion of rainfall that flows over the land surface instead of infiltrating into the soil. When rainfall occurs, it undergoes three major pathways:

- Infiltration into the soil profile
- Evaporation and transpiration losses
- Surface runoff

Under ideal conditions, a large portion of rainfall should infiltrate into the soil and become available to plants. However, when rainfall intensity exceeds the infiltration capacity of soil, excess water begins flowing downslope as runoff. In dryland regions, runoff generation is influenced by:

- High-intensity rainfall events
- Soil crusting
- Low organic matter content
- Steep slopes
- Degraded land surfaces
- Poor vegetative cover
- Continuous cultivation without conservation measures

The paradox of dryland agriculture is that farmers often experience drought despite receiving substantial seasonal rainfall. This occurs because much of the rainwater is lost through runoff before it can be stored in the soil profile.

Importance of Runoff Management in Dryland Agriculture

Water is the most limiting factor in dryland farming. Therefore, maximizing the productive use of rainfall becomes the primary objective. Effective runoff management helps:

Improve Soil Moisture Storage: The root zone acts as a natural reservoir for crops. Every millimetre of water infiltrated into the soil contributes directly to crop growth. Increased infiltration extends moisture availability during dry spells and improves crop survival.

Reduce Soil Erosion: Runoff is the principal cause of soil erosion in rainfed areas. The flowing water detaches and transports fertile topsoil, organic matter, and nutrients. Studies indicate that the formation of one centimetre of fertile topsoil may require hundreds of years. Therefore, preventing soil loss is equivalent to protecting future agricultural productivity.

Enhance Groundwater Recharge: When runoff is slowed and stored through various conservation structures, more water infiltrates into deeper soil layers and replenishes groundwater reserves.

Increase Crop Productivity: Improved soil moisture availability directly enhances germination, root development, nutrient uptake, and grain formation, resulting in higher and more stable yields.

Build Climate Resilience: Runoff management serves as an effective adaptation strategy against climate variability by reducing drought risk and improving water security.

Causes of Excessive Runoff in Dryland Regions

Several factors contribute to excessive runoff generation.

Rainfall Characteristics: High-intensity storms produce runoff rapidly because rainfall exceeds infiltration capacity.

Soil Properties: Soils with poor structure, compaction, or crust formation exhibit lower infiltration rates and generate more runoff.

Land Slope: As slope increases, runoff velocity also increases, reducing opportunities for infiltration.

Vegetative Cover: Bare soils are more susceptible to runoff and erosion. Vegetation acts as a protective barrier that slows water movement and improves infiltration.

Land Use Practices: Improper tillage, excessive grazing, residue removal, and deforestation accelerate runoff generation.

In-Situ Moisture Conservation: The First Line of Défense

The most economical and effective approach in dryland agriculture is to conserve rainfall within the field itself.

Broad Bed and Furrow (BBF) System: The Broad Bed and Furrow system is particularly suitable for Vertisols of Vidarbha. Benefits include:

- Improved drainage during heavy rainfall
- Reduced waterlogging
- Enhanced infiltration
- Better root growth
- Increased crop yields

The technology has shown remarkable success in soybean, cotton, pigeonpea, and other rainfed crops.

Conservation Furrows: Furrows constructed at suitable intervals act as temporary water storage channels that slow runoff and increase infiltration.

Contour Farming: Cultivation and sowing operations performed across the slope reduce runoff velocity and increase rainwater retention.

Ridge and Furrow System: This method improves rainwater distribution and minimizes runoff losses while providing favorable conditions for crop establishment.

Conservation Agriculture and Runoff Management

Conservation agriculture represents a paradigm shift in dryland farming.

The three fundamental principles include:

1. Minimum soil disturbance
2. Permanent soil cover
3. Crop diversification

Retention of crop residues on the soil surface provides multiple benefits:

- Reduced runoff generation
- Lower soil erosion

- Improved infiltration
- Increased soil organic carbon
- Better moisture conservation
- Enhanced biological activity

Crop residues absorb the impact of raindrops and prevent soil surface sealing, thereby improving water entry into the soil.

Bunding and Mechanical Measures: Bunding remains a cornerstone of dryland soil and water conservation.

Contour Bunding: Constructed along contour lines to intercept runoff and promote infiltration.

Graded Bunding: Used in higher rainfall areas to safely dispose of excess runoff while minimizing erosion.

Field Bunds: Help retain rainwater within agricultural fields and improve moisture storage.

These structures reduce runoff velocity and encourage groundwater recharge.

Runoff Harvesting: Transforming a Problem into an Opportunity

Traditionally, runoff has been viewed as a loss. Modern dryland agriculture treats runoff as a valuable resource. Runoff harvesting involves collecting excess rainwater and storing it for future use.

Farm Ponds: Farm ponds have emerged as one of the most successful runoff harvesting technologies. Stored runoff water can be utilized for:

- Protective irrigation
- Supplemental irrigation
- Vegetable cultivation
- Orchard management
- Livestock needs

Even one or two life-saving irrigations during critical crop stages can significantly increase yields.

Watershed-Based Runoff Management

Dryland agriculture requires management beyond individual fields. Watershed approaches integrate runoff management at landscape scale through structures such as:

Check Dams: Store runoff and enhance groundwater recharge.

Gabion Structures: Reduce flow velocity and control gully erosion.

Cement Nala Bunds: Provide long-term water storage and groundwater recharge benefits.

Percolation Tanks: Facilitate infiltration and aquifer replenishment.

Collectively, these structures improve water availability across entire watersheds.

Integrated Model for Sustainable Dryland Farming

The future of dryland agriculture lies in integrated resource management. A highly effective model consists of:

Farm Pond + Solar Pump + Drip Irrigation

In this system:

- Runoff is harvested in a farm pond.
- Solar energy powers water lifting.
- Drip irrigation delivers water efficiently to crops.

Advantages include:

- Higher water-use efficiency
- Reduced energy costs
- Increased crop productivity
- Improved profitability
- Enhanced climate resilience

This integrated model represents the transition from rainfed farming to climate-smart agriculture.

Runoff Management under Climate Change

Climate models predict:

- Increased rainfall variability
- More frequent extreme rainfall events

- Longer dry spells
- Greater drought risk

These changes will likely increase runoff generation and soil erosion. Consequently, runoff management will become increasingly important in sustaining dryland agriculture. Future strategies should focus on:

- Watershed-based planning
- Rainwater harvesting
- Groundwater recharge
- Conservation agriculture
- Precision irrigation
- Integrated farming systems

Economic Benefits of Runoff Management

Effective runoff management provides tangible economic returns through:

- Increased crop yields
- Reduced crop failure risk
- Improved fertilizer-use efficiency
- Enhanced groundwater availability
- Greater cropping intensity
- Increased farm income

Numerous watershed development programs across India have demonstrated significant improvements in productivity and rural livelihoods through scientific runoff management.

Conclusion

Dryland agriculture is often perceived as vulnerable. However, its productivity can be substantially enhanced through efficient management of rainfall resources. Runoff is not merely excess water flowing away from fields; it represents lost opportunities for crop production, groundwater recharge, and soil conservation. The future of sustainable dryland agriculture lies in maximizing the productivity of every raindrop through a combination of in-situ moisture conservation, runoff harvesting, catchment management, conservation agriculture, and efficient irrigation technologies. As climate variability intensifies, the importance of runoff management will continue to grow. By converting runoff into a productive resource, farmers can improve water security, enhance soil health, increase crop productivity, and build resilient agricultural systems. Ultimately, the success of dryland agriculture depends not on the amount of rainfall received, but on how effectively each drop is conserved, stored, and utilized.

"Every drop conserved today is an investment in tomorrow's food security."



Tiny Technology, Big Impact: How Nanoencapsulation is Transforming Food



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Abstract

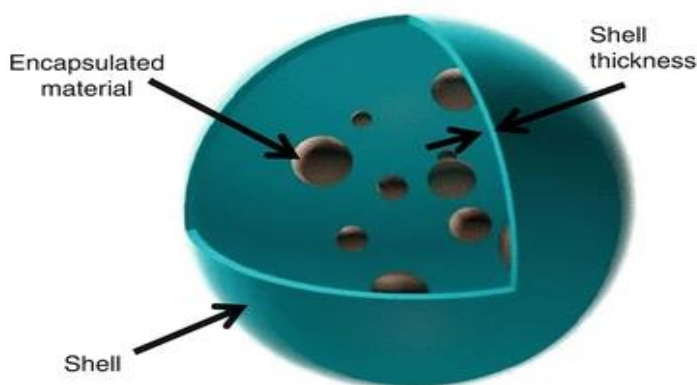
In recent years, the growing awareness among consumers about food quality and health has driven demand for functional foods enriched with bioactive compounds. However, many of these compounds are chemically unstable, poorly water-soluble, and highly susceptible to degradation during processing, storage, and digestion. Nanoencapsulation has emerged as one of the most promising technologies in food science, offering a means to protect bioactive ingredients from adverse environmental conditions, enhance their bioavailability, and deliver them in a controlled and targeted manner within the body. This article presents a comprehensive overview of nanoencapsulation in food, covering the nature of bioactive compounds and their limitations, the major types of nanocarriers and preparation techniques, applications in food safety and packaging, and the challenges and future directions of this technology. The discussion is grounded in recent scientific literature to provide a clear, evidence-based account of how nanotechnology is reshaping the modern food industry.

1. Introduction

Modern consumers are no longer satisfied with the basic nutritional value of food and instead prefer foods that do not only satisfy their primary needs but also include health effect promoters besides the nutrients, and that can replace synthetic additives by natural bioactive compounds which may prevent illnesses (Martins et al., 2023). This shift in consumer behavior has catalyzed a growing demand for functional foods and nutraceuticals, products that not only provide essential nutrients but also contribute to the prevention of diseases and the promotion of health (Hao et al., 2026). Nanotechnology has emerged as a key enabling tool in this context, as it has gained rapid popularity in many fields, including food science, where the labile bioactive is enclosed in a shield that protects it from harmful environmental factors and also allows for targeted delivery to specific areas (Chowdhury et al., 2024).

Nanotechnology is generally described as the arrangement and making of structures at the atomic and molecular scale, achieving particle sizes in the nano range of 1 to 100 nm (Kamble et al., 2025). In the food industry, nanotechnology is applied to improve food texture, flavor, taste, consistency, nutrient bioavailability, and shelf life using nanostructures, and it also presents well-known benefits in the fields of nutraceuticals, food microbiology, and nutrient delivery by improving nutrient absorption in the gastrointestinal tract

(Martins et al., 2023). Nanoencapsulation has been widely recognized as one of the most favorable technologies because it inhibits the degradation of bioactive compounds during the various phases of food processing, intestinal digestion, and absorption, and empowers their retention and discharge in a well-ordered way that improves their bio-distribution at the target site of the organ (Kamble et al., 2025). Nanoencapsulation is an area in constant innovation, and many recent studies have proposed new formulations or new encapsulation systems for the preservation of bioactive compounds with improved functionalities (Martins et al., 2023).



(https://link.springer.com/rwe/10.1007/978-90-481-9751-4_50)

The nanoencapsulation process includes putting solid, liquid, or gaseous components in small receptacles known as capsules, which can be manufactured in nano sizes of less than 100 nm, employing a variety of bio-based materials for the capsule's membrane creation, such as polysaccharides, gums, proteins, lipids, and blends of these (Taouzin et al., 2023). Nanoencapsulation in food products offers several benefits, namely enhancing bioactive compounds' stability and solubility, preventing deterioration during manufacturing, transport, and storage, masking unpleasant tastes, obtaining higher activity levels of the nanoencapsulated ingredients, and controlling release (Taouzin et al., 2023). The nanosized material enhances gastrointestinal absorption and ensures bioavailability, and the nanosized bioactive substances can enter the cell without disturbing the cell membrane and blood-brain barrier, further improving bioavailability (Kamble et al., 2025). This article provides an integrated review of nanoencapsulation technology and its transformative role in modern food science.

2. Bioactive Compounds and Their Challenges in Food

Bioactive components are naturally present in plants, animals, and algae, and their molecular structure determines their distinct physicochemical properties such as solubility and physicochemical stability (Kamble et al., 2025). Many bioactive compounds are antioxidants, polyphenols, flavonoids, flavors, bioactive peptides, and essential fatty acids, and they are considered helpful nutraceuticals with medicinal properties against oxidative stress, diabetes, cardiovascular diseases, cancer, and aging (Kamble et al., 2025). Food-derived bioactive compounds represent a varied range of molecules including lipid-soluble and water-soluble molecules, as well as micro and macromolecules, among which are vitamins, minerals, flavonoids, phenolic acids, alkaloids, carotenoids, peptides, and fatty acids (Taouzin et al., 2023).

Despite their valuable health properties, the physical and chemical stability of bioactive compounds is dramatically affected by harsh environmental influences during processing and storage, and is altered by physiological conditions within the body during digestion and absorption (Taouzin et al., 2023). Most bioactive compounds have poor solubility due to their hydrophobic nature, making them unavailable in cellular processes (Kamble et al., 2025). The bioactive compounds are commonly unstable in the food matrix as they are liable to heat, light, oxygen, UV radiation, water activity, and self-oxidation, and their instability and low water solubility influence their bioavailability, limiting food's health benefits (Kamble et al., 2025).

The translational gap between the *in vitro* efficacy and the *in vivo* performance of many bioactive compounds remains a major bottleneck in the development of efficacious nutraceutical products (Hao et al., 2026). Numerous bioactive compounds derived from natural sources, such as curcumin, resveratrol, omega-3 polyunsaturated fatty acids, various vitamins, and polyphenolic compounds, have been extensively demonstrated to exert potent antioxidant, anti-inflammatory, and other biofunctional activities in controlled experimental settings; nevertheless, these effects are often markedly attenuated following oral administration due to their poor stability and limited bioavailability under physiological conditions (Hao et al., 2026). Even if a fraction of the active ingredient reaches the small intestine intact, its absorption is often severely restricted due to unfavorable molecular size, poor intestinal permeability, and extensive hepatic first-pass metabolism (Hao et al., 2026). These combined limitations highlight the pressing need for protective delivery strategies such as nanoencapsulation to ensure that bioactive compounds retain their intended functionality when incorporated into food products.

3. Nanocarrier Systems and Preparation Methods

A wide range of nanocarrier systems have been developed to encapsulate food bioactive compounds, each with distinct structural properties suited to different applications. The principal types of nanocarriers for bioactive compounds include association colloids, nanoemulsions, nanoliposomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers, bio-polymeric nanoparticles, and nanofibers (Kamble et al., 2025). Nanoencapsulation deals with several types of materials on the atomic, molecular, and supramolecular scale, normally from 1 to 100 nm; nevertheless, some nanocapsules may present sizes up to 600 nm (Martins et al., 2023).

Among the lipid-based nanocarrier systems, liposomes are spherical closed vesicular structures that represent one of the earliest nanoencapsulation vehicles adopted in food science; they can encapsulate both hydrophilic and lipophilic compounds, thereby protecting sensitive ingredients from degradation (Hao et al., 2026). Nanoliposomes, which are smaller liposomes, have hydrophilic and lipophilic areas that can entrap

compounds in lipid bilayers with various lipotropic properties, and can encapsulate unstable substances such as vitamins, antioxidants, and antibacterial agents (Taouzin et al., 2023). Solid lipid nanoparticles are colloidal dispersions made up of particles having a lipid core that has hardened and is covered in an emulsifier molecule layer, and are structurally comparable to traditional emulsions with the exception that the droplets are entirely crystalline rather than liquid, providing a more rigid and protective environment for encapsulated nutrients (Taouzin et al., 2023). The introduction of nanostructured lipid carriers in the early 2000s as a second-generation lipid nanocarrier incorporated a blend of solid and liquid lipids, creating an imperfect crystalline structure in the nanoparticle core that leaves extra molecular space, allowing higher payloads of bioactive compounds to be stably encapsulated (Hao et al., 2026).

Polymeric nanocarriers are thought to be incredibly ideal for encasing and delivering bioactive chemicals, and currently natural-based nano-carriers such as starch, chitosan, casein, albumin, and whey protein are most frequently employed (Chowdhury et al., 2024). Chitosan is a naturally occurring polycationic linear polysaccharide produced from chitin, and its amino groups and hydroxyl functional groups enable chemical alterations that make it highly versatile as an encapsulating material (Taouzin et al., 2023). The preparation of nanocarriers is achieved through high and low-energy based methods, such as solvent evaporation, microfluidization, ultrasonication, ball milling, and high-pressure processing for the production of nanosized bioactive compounds (Kamble et al., 2025). Recently emerged nanoencapsulation technologies, including electrospraying, nanofluidics, complex coacervation, electrospinning, and polymerization, have further expanded the toolkit available to food scientists for preparing nanoscale delivery systems (Chowdhury et al., 2024). For food applications, the encapsulating materials must be generally recognized as safe, and the type and characteristics of the active compound, the carrier material, and the particle size are important factors in choosing the most appropriate encapsulation method (Martins et al., 2023).

4. Enhancing Bioavailability and Controlled Release Through Nanoencapsulation

One of the most significant benefits of nanoencapsulation is its capacity to dramatically improve the bioavailability of encapsulated bioactive compounds. Nanoencapsulation can shield bioactives from light, heat, oxidation, and pH extremes, and it also improves oral bioavailability through enhanced solubility, controlled release, mucoadhesion, endocytosis-mediated uptake, and lymphatic transport that bypasses first-pass metabolism (Hao et al., 2026). It improves the solubility of lipophilic compounds in an aqueous solution and enables their prolonged absorption through the controlled release of consumed substances that prevent sudden reactions and diminish their side effects on human wellbeing (Kamble et al., 2025). The main challenge related to the supply of functional components is stability to various conditions such as heat, pH, light, moisture, oxygen, and gastrointestinal conditions, and nanoencapsulation masks their unpleasant taste and color while addressing these stability concerns (Kamble et al., 2025).

Nanoencapsulation serves at the same time to target cells, tissues, or organs and to control the release and delivery of bioactive molecules, and it also serves to protect the bioactive compound from several reactions that can modify the molecule or alter its bioactivity including temperature, acidity, hydrolysis, and oxidation due to light exposure (Martins et al., 2023). The advantages of this technology include allowing targeting of all the bioactive beneficial characteristics of the compounds to specific targets, controlling the release of the bioactive components, allowing the concentration of the compound to be decreased while preserving it in hostile mediums, preventing interactions between the bioactive molecules and other food ingredients, and presenting high solubility and dispersibility (Martins et al., 2023). The functions of nanoencapsulation also include reducing the practical size and creating a restricted distribution of particles, increasing the surface area, improving the delivery of bioactive molecules, increasing the bioavailability of encapsulated compounds, increasing physical stability and extending shelf life, increasing precision targeting and promoting passage through fenestrated cells, and improving intracellular absorption (Martins et al., 2023).

The nanoscale dimension and high surface-area-to-volume ratio of nanocarriers facilitate enhanced intestinal uptake via multiple mechanisms, and in some cases may even enable partial circumvention of hepatic first-pass metabolism, advantages that have been shown to dramatically improve the oral bioavailability of encapsulated compounds, thereby restoring and amplifying their physiological effects in vivo (Hao et al., 2026).

Nanoencapsulation of natural products can thus be considered the most suitable nanotechnology to improve stability, solubility, and bioavailability, and the nanostructure can be incorporated into food during production, processing, packaging, and security (Taouzin et al., 2023).

5. Applications of Nanoencapsulation in Food Safety and Packaging

Beyond improving nutrient delivery, nanoencapsulation has found important and expanding applications in the areas of food safety and packaging. Nanotechnology plays a crucial role in active packaging by introducing nanomaterials that provide antimicrobial, oxygen-scavenging, moisture-control, and smart sensing properties, and bioactive packaging material not only helps preventing spoilage but also hinders microbial proliferation (Kamble et al., 2025). In food packaging, nanoencapsulation has improved materials by enhancing their mechanical strength and by producing antimicrobial films and nanosensors to detect pathogens or specific compounds such as indicators of disease conditions, which are important tools to enlighten consumers about food safety issues (Martins et al., 2023).

Antimicrobial compounds like curcumin, essential oils, lactoferrins, and anthocyanin can be encapsulated by nanoemulsion or composite nanoparticles to be used as coating solutions, edible films, and smart packaging, and they not only extend the shelf life of the products but also add functional value to the product (Kamble et al., 2025). Nanomaterials can respond with other substances, showing association with the contaminant functional group and producing effects like color change, alarming signals, or pH shifts, and they also have the ability to trace impurities to their main source (Kamble et al., 2025). The adhesion of specific nanoparticles has been attributed to antibacterial and antifungal properties, and an electronic nose made from a silicon-based substrate coated with a nano metal oxide that changes resistance when exposed to volatile compounds is one example of a food safety intervention based on nanotechnology (Kamble et al., 2025).

The use of micro and nanocapsules in food is a trend used mainly in the cereal, bakery, dairy, and beverage industries, as well as in packaging and coating (Martins et al., 2023). The nanoencapsulation of bioactive compounds has brought large improvements to the food, nutraceutical, pharmaceutical, and agriculture industries, as this technology allows the protection of bioactive compounds applied to different matrices and the control of their release (Martins et al., 2023). Nanocapsules may be included in food during production, processing, packaging, and security, and recent reviews have highlighted the potential use of nanoencapsulation of natural compounds in specific areas such as improving food shelf life, as food additives, as antimicrobials, and as antioxidants (Taouzin et al., 2023). Key nanoencapsulated nutraceuticals are now used in functional beverages, dairy products, dietary supplements, and other foods, illustrating the growing commercial applications of food nanotechnology (Hao et al., 2026).

6. Challenges, Safety Considerations, and Future Perspectives

Despite its considerable promise, nanoencapsulation in food is not without challenges. Numerous natural polymers including proteins, carbohydrates, and lipids have been used to shield bioactive compounds; they are non-toxic, biodegradable, and economical, but before utilization, characterization plays a critical role (Kamble et al., 2025). Several methods such as UV-Vis spectrophotometry, Fourier transform infrared spectroscopy, zeta potential measurement, chromatographic techniques, nuclear magnetic resonance spectroscopy, particle size analysis, and rheology are used to characterize the nanoparticles to test their toxicity and potential health risks (Kamble et al., 2025). The nanosize may increase the excess absorption of bioactive compounds, which might cause harmful health effects due to undesirable accumulation and diminished excretion, and therefore there is a need to select the appropriate nanoencapsulation strategy specific to the bioactive compounds (Kamble et al., 2025).

Regarding the regulatory implications of nanostructures in the food and medical industries, no formal law is established internationally, and the majority of nations currently lack precise standards for assessing the danger of encapsulated nano-products (Taouzin et al., 2023). Safety and health, as well as regulatory rules, should be considered during the production, processing, active packaging, and consumption of nano-processed food items (Taouzin et al., 2023). The challenges related to manufacturing scale-up, safety and toxicology, regulatory oversight, and consumer acceptance of nano-enabled nutraceuticals remain active areas of concern requiring further research and policy development (Hao et al., 2026). Difficulties in achieving uniform particle size,

stability, and controlled release across different food processing and storage conditions also impede practical implementation, and overcoming these challenges necessitates progress in developing cost-effective, biocompatible nanocarriers, comprehensive safety assessments, and well-defined regulatory standards (Kamble et al., 2025).

The prospects for the nanoencapsulation of bioactive compounds highlight the need for their worldwide regulation to facilitate their safe use and marketing, and various studies reporting the beneficial effects of nanostructured bioactive compounds support this trend and offer a promising future direction for research (Taouzinet et al., 2023). Future research avenues include the optimization of nanocarrier systems, tackling regulatory challenges, and investigating the long-term health and environmental effects (Kamble et al., 2025). Emerging trends such as co-encapsulation of synergistic ingredients and precision nutrition approaches are also gaining prominence, and by integrating advances in nanotechnology with nutritional science, nanoencapsulation is poised to significantly amplify the health benefits of functional foods and nutraceutical products in the coming years, paving the way for more effective functional diets and improved public health (Hao et al., 2026). The elaboration of bio capsules with high-value compounds from agro-industrial by-products is furthermore sustainable for the natural ecosystem and economically interesting from a circular economy perspective, adding a dimension of environmental sustainability to the growing promise of nanoencapsulation technology (Martins et al., 2023).

7. Conclusion

Nanoencapsulation represents a groundbreaking convergence of nanotechnology and food science that is steadily transforming how bioactive compounds are protected, delivered, and utilized in food systems. By engineering nanoscale carriers capable of shielding sensitive nutrients from environmental degradation, improving their water dispersibility, and enabling their controlled and targeted release within the human body, this technology addresses long-standing limitations in functional food development. From liposomes and nanoemulsions to polymeric nanoparticles and active packaging materials, the diversity of nanoencapsulation strategies reflects the broad scope of its applications. While challenges relating to safety assessment, regulatory frameworks, consumer acceptance, and industrial scalability remain to be fully resolved, the continued advancement of nanocarrier design and characterization is steadily narrowing these gaps. As scientific understanding deepens and regulatory clarity improves, nanoencapsulation is positioned to become a defining tool in the development of next-generation functional foods that are not only nutritionally enriched but also precisely designed to benefit human health.

References

- Chowdhury, S., Kar, K., & Mazumder, R. (2024). Exploration of different strategies of nanoencapsulation of bioactive compounds and their ensuing approaches. *Future Journal of Pharmaceutical Sciences*, 10, 72. <https://doi.org/10.1186/s43094-024-00644-y>
- Hao, M., Tan, X., Liu, K., & Xin, N. (2026). Nanoencapsulation of nutraceuticals: Enhancing stability and bioavailability in functional foods. *Frontiers in Nutrition*, 12, 1746176. <https://doi.org/10.3389/fnut.2025.1746176>
- Kamble, M. G., Singh, A., Singh, S. V., Kamble, M. G., Sagar, N. A., & Rani, N. (2025). Nanotechnology for encapsulation of bioactive components: A review. *Discover Food*, 5, 116. <https://doi.org/10.1007/s44187-025-00386-7>
- Martins, V. F. R., Pintado, M. E., Morais, R. M. S. C., & Morais, A. M. M. B. (2023). Valorisation of micro/nanoencapsulated bioactive compounds from plant sources for food applications towards sustainability. *Foods*, 12(1), 32. <https://doi.org/10.3390/foods12010032>
- Taouzinet, L., Djaoudene, O., Fatmi, S., Bouiche, C., Amrane-Abider, M., Bougherra, H., Rezgui, F., & Madani, K. (2023). Trends of nanoencapsulation strategy for natural compounds in the food industry. *Processes*, 11(5), 1459. <https://doi.org/10.3390/pr11051459>

Major Weed Flora of Makhana in the Koshi Region of Bihar



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Introduction

Makhana (*Euryale ferox* Salisb.), popularly known as fox nut or gorgon nut, is an important aquatic food crop and a traditional livelihood component of the wetlands and waterlogged areas of Bihar. The Koshi region, with its abundance of ponds, wetlands and low-lying areas, offers considerable potential for makhana cultivation and has witnessed increasing interest in both traditional pond-based and field-based production systems. Makhana is valued for its nutritional properties, attractive market price and potential to generate higher returns from waterlogged lands that are otherwise difficult to utilize for conventional crops. However, successful makhana production is not free from production constraints, and weed infestation is one of the important but often overlooked problems. A variety of floating, submerged and emergent aquatic weeds grow alongside makhana and compete with young plants for light, nutrients, space and other resources. The problem is particularly serious during the early establishment stage, when makhana plants are small and have limited competitive ability. Important weeds such as water hyacinth (*Eichhornia crassipes*), *Monochoria* spp., *Ceratophyllum demersum*, *Nymphaea* spp., *Nelumbo nucifera*, *Jussiaea/Ludwigia* spp., *Marsilea* spp. and *Scirpus* spp. are commonly associated with makhana-growing environments of north Bihar. If these weeds are not identified and managed at the right time, they can hinder crop establishment, reduce the effective growing space and create difficulties during crop management and harvesting. Therefore, proper identification of major weeds and timely, eco-friendly weed management are essential for improving the productivity and profitability of makhana cultivation in the Koshi region.

Major Weeds of Makhana in the Koshi Region

The weed flora associated with makhana varies according to water depth, soil type, nutrient availability, previous land use and the method of cultivation. In the Koshi region, particularly in ponds, shallow-water fields and waterlogged areas, several floating, submerged and emergent weeds are commonly observed. Some weeds grow rapidly during the early crop stage and can seriously interfere with makhana establishment. The important weeds are described below.

1. Water hyacinth (*Eichhornia crassipes*)

The most troublesome floating weed. Water hyacinth is one of the most aggressive aquatic weeds found in ponds and water bodies of Bihar.

It has:

- broad green leaves,
- swollen leaf stalks,
- fibrous roots hanging in water, and
- rapid vegetative multiplication.

It can quickly form a dense floating mat over the water surface.

A dense water-hyacinth population:

- blocks sunlight,
- occupies valuable water surface,
- competes with young makhana plants,
- interferes with water movement, and

- creates serious difficulties during crop management and harvesting.

Water hyacinth has also been highlighted as a major crop-protection concern in recent reviews of makhana production in Bihar.

2. *Monochoria* (*Monochoria* spp.)

An emergent weed of shallow water. *Monochoria* species are commonly associated with shallow-water agricultural ecosystems. They generally have soft green leaves and arise from the water or wet soil. Their growth can be particularly troublesome where makhana is cultivated under shallow-water conditions. *Monochoria* competes strongly with young makhana plants for nutrients and space. Dense populations can reduce the area available for healthy makhana establishment.

3. *Ceratophyllum* (*Ceratophyllum demersum*)

The submerged competitor. Unlike water hyacinth, *Ceratophyllum* grows under water. It has slender, branched stems with narrow leaves arranged around the stem. Because it remains submerged, farmers may not notice it until its population becomes large.

Large populations can:

- occupy the underwater space,
- compete for nutrients,
- interfere with young makhana plants, and
- make pond management more difficult.
- *Ceratophyllum demersum* was among the important macrophyte weeds recorded in makhana fields of Katihar.

4. Water lilies (*Nymphaea* spp.)

Beautiful flowers, but unwanted competition. Water lilies may look attractive, but excessive growth can create problems in makhana ponds. They produce floating leaves that occupy the same water surface that makhana needs.

When present in large numbers, they compete for:

- sunlight,
- space and
- nutrients.

Nymphaea species were recorded among the associated macrophytes in makhana production systems in north Bihar.

5. *Lotus* (*Nelumbo nucifera*)

A strong competitor for water surface. Lotus is another aquatic plant that can occur in makhana ponds. It has large leaves and strong underground structures. Once established, it can occupy considerable space. Because both lotus and makhana are aquatic plants requiring surface space, excessive lotus growth can interfere with makhana establishment and expansion. *Nelumbo nucifera* was also identified among the important macrophytes associated with makhana in Katihar.

6. *Jussiaea* / *Ludwigia* (*Jussiaea* spp.)

A weed of wet and shallow-water conditions. Species of *Jussiaea* (now often treated under *Ludwigia* in modern botanical classification) are associated with wet habitats and shallow-water cultivation. Recent observations from Bihar have identified *Jussiaea* among the weeds emerging in makhana fields, particularly under changing cultivation conditions. These weeds can compete strongly with young makhana when they establish before the crop canopy develops.

7. *Marsilea* (*Marsilea* spp.)

A small but persistent aquatic weed. *Marsilea* is commonly found in wet and shallow-water environments. It has characteristic clover-like leaves and can spread across moist soil or shallow water. It may become particularly important in field-based makhana cultivation, where water depth is comparatively low. Recent research from Bihar has reported *Marsilea* among weeds associated with makhana cultivation.

8. *Scirpus* (*Scirpus* spp.)

A sedge-like weed of wet areas. *Scirpus* species are associated with marshy and shallow-water habitats. They can establish a long pond margins and in shallow sections. These weeds can be especially troublesome in field-based systems where water depth varies across the plot. Recent observations from Bihar have included *Scirpus* among weeds associated with makhana.

9. Other weeds: The hidden competition

Apart from the major weeds mentioned above, makhana ponds can contain several other aquatic and semi-aquatic weeds.

The weed population varies according to:

- pond depth,
- soil type,
- water quality,
- nutrient status,
- previous cropping history,
- water source,
- method of makhana establishment, and
- surrounding vegetation.

Therefore, every makhana pond may not have the same weed flora. The first few weeks after makhana establishment are particularly important. At this time, the crop has not developed its full floating-leaf canopy. Research on makhana associated weeds indicates that weed infestation is particularly rapid during the initial growth phase, while weed pressure generally decreases after about 30–40 days of transplantation, as makhana develops luxuriant vegetative growth.

How can farmers recognize a weed problem?

Farmers should regularly inspect the pond and look for:

- **Floating weed patches-** Especially water hyacinth and other floating plants.
- **Emergent weeds-** Plants growing above the water surface in shallow areas.
- **Submerged weeds-** Green vegetation visible below the water surface.
- **Excessive aquatic plants-** Dense lotus or water-lily growth occupying the surface.
- **Weed patches around young makhana plants-** These are particularly important because they can directly interfere with crop establishment.

Weed management strategy for Koshi-region farmers

The best approach is **integrated weed management**, rather than depending on one method.

- **Before planting-** clean the pond, remove existing weeds, particularly perennial weeds and water hyacinth. Clean the pond margins and nearby channels as far as practical.
- **At crop establishment-** protect young makhana plants healthy seedlings and proper establishment help the crop compete with weeds.
- **Early crop growth-** control weeds before they become large manual removal and simple mechanical methods can be used, particularly in smaller ponds.
- **During 20–40 days after establishment-** monitor regularly remove newly emerging weed patches before they spread.
- **After canopy development-** spot control is enough in many situations once makhana leaves cover a large part of the water surface, many weeds naturally become less competitive.

Makhana–Fish: An opportunity for biological weed management

The Koshi region has considerable potential for integrated **makhana–fish farming**. Fish integration can provide an additional source of income and may also contribute to the suppression of some aquatic weeds. Recent research from Darbhanga has reported farmer innovations involving combinations of fish with makhana, with potential benefits for weed control. However, fish should not be considered a universal solution for all weeds. The effectiveness depends on fish species, stocking density, weed type and pond conditions. Therefore, location-

specific research is needed to identify the best **makhana + fish + weed-management combination** for the Koshi region.

Makhana is an aquatic food crop. Therefore, herbicide use in makhana ponds requires much greater caution than herbicide use in conventional field crops. Farmers should not use a herbicide merely because it controls the same weed in rice or another crop. For the Koshi region, there is a strong need for research on selective, crop-safe and environmentally compatible weed-management technologies rather than indiscriminate herbicide use.

Weed identification chart

Major weed	Where it grows	Main problem
Water hyacinth (<i>Eichhornia crassipes</i>)	Floating	Rapid spread and dense surface mat
Monochoria spp.	Shallow water/emergent	Competition with young makhana
Ceratophyllum demersum	Submerged	Competition below water
Nymphaea spp.	Floating leaves	Occupies water surface
Nelumbo nucifera	Emergent/floating	Strong competition for space
Jussiaea/Ludwigia spp.	Wet/shallow areas	Rapid growth around young crop
Marsilea spp.	Shallow water/wet soil	Spreads in open spaces
Scirpus spp.	Marshy/shallow areas	Persistent growth in shallow zones

Makhana is a valuable crop of the Koshi landscape, but its productivity depends greatly on how well the crop is established and protected during the early growth period. Weeds should not be allowed to dominate the pond before makhana gets established.

The most effective strategy is simple:

Clean → Monitor → Remove Early → Protect Young Plants → Encourage Canopy

Instead of trying to eradicate every aquatic plant throughout the season, farmers should concentrate their efforts on major weeds during the critical establishment period. The Koshi region has enormous potential for makhana-based farming systems. However, weed management remains an important research and extension challenge.

Future work should focus on:

- district-wise identification of makhana weeds;
- seasonal weed surveys;
- determining the critical period of weed competition;
- development of low-cost aquatic weeders
- evaluation of fish-based biological weed control;
- safe weed-management options for natural farming;
- development of weed identification guides in local languages; and
- development of an Integrated Weed Management package specifically for the Koshi region.

Such efforts can reduce labour requirements, improve crop establishment and contribute to higher and more sustainable makhana productivity.

References

- Sodi, M. & Kumar, S. (2020). Association of makhana (*Euryale ferox* Salisb.) with macrophyte weeds in Katihar district of Bihar, India. *Scholars Journal of Agriculture and Veterinary Sciences*, 7(11): 231–239.
- Manohar, B. & Sushmita (2019). Gorgon nut and its associated weeds. *Journal of Pharmacognosy and Phytochemistry*, 8(6): 315–318.
- Sinha, C.B.K. & Jha, V. (2025). Impacts of climate change on cultivation of makhana (*Euryale ferox* Salisb.) and biocontrol of associated weeds—a case study of Darbhanga district in Bihar, India. *International Journal of Plant and Environment*, 11(2): 388–394.
- Kumar, A. (2026). Present status, prospects and future scope of makhana in Bihar. *International Journal of Innovative Horticulture*, 14(2): 187–191.

Major Insect-Pests of Mungbean in the Kosi Region of Bihar



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Abstract

Mungbean or green gram (*Vigna radiata* L. Wilczek) is an important short-duration pulse crop cultivated during summer seasons in Kosi region of Bihar. The Kosi region of Bihar, comprising predominantly the districts of Saharsa, Supaul and Madhepura, has considerable potential for mungbean cultivation because of its fertile alluvial soils, warm climate and availability of rice-fallow and summer production systems. However, insect pests are among the major biological constraints limiting mungbean productivity. The crop is attacked by a diverse insect-pest complex from seedling establishment to pod maturation. Important pests include whitefly (*Bemisia tabaci*), Thrips, Bihar hairy caterpillar (*Spilosoma obliqua*) and pod borer (*Helicoverpa armigera*). Among these, whitefly is particularly important because, besides causing direct sap-feeding injury, it acts as a vector of mungbean yellow mosaic virus. The occurrence and severity of individual pests in the Kosi region are influenced by season, temperature, rainfall, humidity, crop stage, sowing time, cropping system and surrounding vegetation. Integrated pest management (IPM), involving timely sowing, field sanitation, balanced fertilization, resistant varieties, monitoring, conservation of natural enemies, botanical pesticides and need-based application of registered insecticides, is essential for sustainable mungbean production in the region.

Keywords: Mungbean, green gram, *Vigna radiata*, insect pests, Kosi region, Bihar, whitefly, thrips, pod borer

1. Introduction

Mungbean (*Vigna radiata* L. Wilczek) is one of the most important short-duration pulse crops grown in India. It is valued for its high-quality protein, digestibility and ability to fit into intensive cropping systems. Because of its relatively short duration, mungbean can be successfully incorporated into rice-based cropping systems.

In Bihar, mungbean has considerable importance as a pulse crop, particularly because it can provide an additional source of income and dietary protein while contributing to soil fertility through biological nitrogen fixation. The Kosi region, represented principally by Saharsa, Supaul and Madhepura, is characterized by alluvial soils, variable water availability and a rice-dominated cropping system. These conditions provide opportunities for mungbean cultivation, but the crop is exposed to several insect pests. For the Kosi region, understanding pest succession and adopting timely pest management is particularly important because mungbean is often grown during warm and humid periods that can favour rapid multiplication of several insect pests.

2. Major Insect Pests of Mungbean

2.1 Whitefly (*Bemisia tabaci*)

Whitefly is one of the most important insect pests of mungbean. Both nymphs and adults suck sap from leaves, resulting in loss of plant vigour, yellowing and premature deterioration of foliage. The importance of whitefly in mungbean is greater because it acts as a vector of mungbean yellow mosaic virus (MYMV). Consequently, even a relatively low population of whitefly can become economically important when the crop is exposed to virus infection.

According to ICAR-IIPR observations, whitefly may appear as early as 15–21 days after sowing and can remain present throughout the crop season. In summer mungbean, its activity may peak during the middle portion of the crop period.



2.2 Thrips

Thrips are particularly important during the flowering stage of mungbean. Flower thrips feed on flowers, buds and tender tissues, which may result in flower shedding, poor pod setting and reduced seed production. ICAR-IIPR reports flower thrips as an important pest during the flowering and pod-development stages. In summer mungbean, thrips activity may continue from flower initiation until pod maturation.



2.3 Bihar Hairy Caterpillar (*Spilosoma obliqua* Walker)



The Bihar hairy caterpillar is an important defoliating insect in several pulse and field crops. Young larvae may feed gregariously, while older larvae consume larger portions of leaves. Severe infestation can result in substantial defoliation and reduction in photosynthetic area.

2.4 Gram Pod Borer (*Helicoverpa armigera* Hübner)

The gram pod borer can attack mungbean during flowering and pod formation. Young larvae feed on flowers and tender tissues, whereas older larvae bore into pods and consume developing seeds. The pest is capable of causing direct quantitative and qualitative losses.

The pod borer complex, including *Helicoverpa* and *Maruca*, is considered an important pest problem in mungbean production.

3. Influence of Weather and Cropping System in the Kosi Region

The Kosi region has a humid subtropical agricultural environment with substantial seasonal variation in rainfall and temperature. Such conditions can strongly influence insect multiplication and movement.

Mungbean grown as a summer crop may experience different pest complexes. Warm and relatively dry periods can favour several sucking pests, while humid conditions and dense crop canopies may influence the development and survival of different insect species.

4. Importance of Pest Monitoring

Regular pest surveillance is particularly important for mungbean because of its short crop duration. Delayed detection can result in rapid pest multiplication and substantial yield loss.

A simple monitoring programme for Kosi farmers may include:

- Weekly inspection of 10–20 randomly selected plants at different locations in the field.
- Counting whiteflies on leaves.
- Examination of flowers for thrips.
- Inspection of flowers and pods for *Helicoverpa* damage.
- Recording weather conditions along with pest observations.
- Use of sticky and pheromone traps as monitoring tools.

Such observations can also generate valuable local data on pest succession and weather–pest relationships in Saharsa, Supaul and Madhepura.

5. Conclusion

Mungbean has considerable potential for diversification and intensification of pulse production in the Kosi region of Bihar. However, insect pests can adversely affect crop establishment, vegetative growth, flowering, pod development and final seed yield. Whitefly, thrips, defoliating caterpillars and gram pod borer constitute an important pest complex.

Among these, whitefly deserves special attention because of its role as a vector of mungbean yellow mosaic virus. Flower thrips and pod borers are particularly important during reproductive growth.

The most appropriate approach for Kosi-region mungbean production is an integrated pest management strategy based on regular surveillance, timely sowing, field sanitation, balanced crop nutrition, resistant or tolerant varieties, conservation of natural enemies, botanical and biological interventions, and need-based use of registered insecticides. Region-specific studies on pest dynamics and weather relationships will further improve pest forecasting and management recommendations for mungbean cultivation in Saharsa, Supaul, Madhepura and adjoining areas.

References

- ICAR-Indian Institute of Pulses Research. *Pulses Research: Crop Protection—Mungbean and Urdbean*. ICAR-IIPR, Kanpur.
- ICAR-Indian Institute of Pulses Research. *AICRP on Kharif Pulses: Crop Protection Recommendations*. ICAR-IIPR.
- Lal, S.S. (1985). A review of insect pests of mungbean and their control in India. *Tropical Pest Management*, 31(2), 105–114.
- Kooner, B.S., Malhi, B.S. & Cheema, H.K. (2004). Insect pest management of mungbean. pp. 214–235.

Panickar, B. et al. (2018). Impact of integrated management approaches on insect pests of mungbean. *Indian Journal of Plant Protection*, 46(1).

Swaminathan, R. et al. (2012). Biotic constraints and insect-pest complex associated with mungbean production. The major insect pests include stem fly, thrips, aphids, whitefly, pod borer complex, pod bugs and bruchids.

Singh, A.D.V. et al. (2024). Insect pests complex of mung bean. *International Journal of Advanced Biochemistry Research*, 8(9S), 1000–1003.



Carbon Trading in Indian Agriculture: A New Frontier for Sustainable Development and Climate Mitigation



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Imagine a farmer in Karnal, Haryana standing at the edge of his wheat field after the rabi harvest. He's not burning the stubble now. He performs zero tillage, micro-irrigation and waters his paddy in cycles rather than floods. For years sustainability lobbyists had convinced him this was the thing to do. Now, for the first time, the rest of the world is ready to pay him for it – in the form of carbon credits. India is the second largest producer of basic food crops and third highest emitter of greenhouse emissions in the world.



To deliver on Prime Minister Modi's promise of net carbon neutrality by 2070, the agriculture sector, still the engine of livelihoods for almost half the people, needs to shift from a net emitter to a net absorber of GHGs. According to an estimate, the agriculture sector alone has the potential to reduce India's yearly emissions by as much as 84% from 2019 to 2070 if the carbon markets are adequately tapped (Khurana et al., 2024).

The Promise and the Reality

The premise is simple. Companies that emit CO₂ can either reduce their own emissions or pay other organizations – including farmers – who can show they have lowered or avoided emissions. The currency of exchange is the carbon credit, which is equal to one tonne of sequestered or avoided CO₂-e. McKinsey research indicates the global market for carbon credits might grow by more than 15 times by 2030. And India's farms, with its large land mass and millions of farmers, are ideally placed to take a good share of that expansion. India said it had more than 50 active agricultural carbon projects that resulted in the reduction of about 37 million tonnes of CO₂-equivalent emissions annually.

But the surprising fact is that 99% of the farmers did not get any financial benefit. A 2024 survey of 841 farmers from seven villages in Haryana and Madhya Pradesh who participated in carbon farming schemes found that carbon farmers were primarily large-holders and non-marginalized castes, indicating systematic exclusion. Only 4 per cent of the participants were women. Some 28% had already abandoned the carbon-friendly practices they were originally educated in, raising serious issues about the permanence of the reported emissions reductions (Cariappa & Krishna, 2024).

From Paddy Fields to Carbon Credits

Top voluntary-market methodologies, like Verra's VM0042, recognize practices including conservation agriculture, zero or reduced tillage, cropping-residue management, direct seeding of rice, intercropping, biochar application, alternate wetting and drying in paddy, micro-irrigation, and tree planting (Cariappa et al., 2024; Singh et al., 2024). The math's is easy. A farmer who follows such techniques can accrue from one to four carbon credits per acre. This comes to approximately ₹780 per credit at present Indian market prices, with large corporate customers paying up to ₹2,000 per credit for bulk purchases (Singh et al., 2024). Farmers may cut water use by 40% and reduce methane emissions from flooded paddy fields by a striking 50% by using Alternate Wetting and Drying – a double reward for both farmer income and the climate (Singh et al., 2024). Studies in Bihar and Punjab indicate that Conservation Agriculture can increase farmers' revenues of carbon credits by USD 18 per hectare and USD 30 per hectare respectively. For an average Punjab farmer, an additional ₹11,000 every wheat season is possible, with certain exceptions due to methodology. This is already higher than the ₹33 million allocated to Punjab under the Government of India's Crop Residue Management Scheme for 2022–23, highlighting the potential of carbon markets as an incentive mechanism (Cariappa et al., 2024).

India's Policy Push

The administration is getting wise to this potential. India has launched the Framework for Voluntary Carbon Market in Agriculture and is also developing compliance and voluntary carbon markets (Cariappa, 2025). On 29 January 2024 in New Delhi, Shri Arjun Munda, Union Minister of Agriculture & Farmers' Welfare and Tribal Affairs announced the Framework for Voluntary Carbon Market in Agriculture Sector and Accreditation Protocol of Agroforestry Nurseries (Press Information Bureau, 2024). The initiative seeks to give small and medium farmers access to carbon credits and promote the adoption of environmentally responsible farming techniques. The government notified the Carbon Credit Trading Scheme in December 2023 for implementation of the carbon trading mechanism (Press Information Bureau, 2023). One of the sectors chosen under the offset method of carbon trading is Agriculture sector. The Energy Conservation Amendment Act, 2022 lays down the regulatory framework for the Indian Carbon Market. The CCTS will begin trading in carbon credits in 2026. NABARD has set up a Carbon Fund of Rs. 300 Crore to promote early investments in projects with potential to earn high quality carbon credits (NABARD, 2023). The fund will incentivize business sector participation and support Farmer Producer Organizations and cooperatives as viable project developers.

Why the Promise Isn't Reaching the Farmer

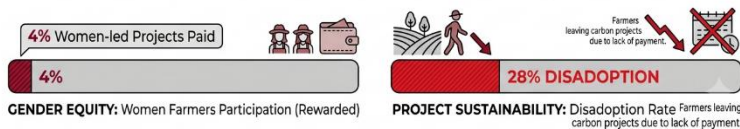
But a harsh reality check shows profound shortcomings. The 2024 analysis found that while several practices genuinely clear the additionality hurdle -- that is, the reductions wouldn't have happened regardless -- others just predated the initiatives, raising questions about whether each and every credit really reflects new climate action. For example, farmers have been practicing cover cropping for the last 9 years, laser land levelling for 6 years and minimum tillage for 4 years – all before the carbon initiatives began. The situation is further complicated by the fact that Verra, the largest certifier of carbon credits globally, has recently turned down four Indian carbon-farming projects due to methodological difficulties (Cariappa, 2025). Verra stated that the project documents were of poor quality and contained incorrect or incomplete information, reasons for not registering 4 projects. The risk is considerable of creating low-quality credits if they are not properly implemented. When the market is swamped with questionable offsets, the value of real offsets decreases, discouraging corporate buyers and eventually harming the farmers who did the proper job on the ground. When asked about the reasons for stopping the project activities, a high proportion of the disadopters reported that the main reason was the absence of monetary advantages. In addition, 27% cited yield penalties and 16% cited lack of proper knowledge on carbon farming as reasons for disadoption.

Can This Be Fixed?

'Carbon Core' enterprises – companies wholly focused on carbon credits – were more successful at spreading regenerative farming methods than subsidiaries or offshoots of larger companies. This is a high continuation rate, considering the intricacy of Carbon Core projects and the fact that 99% of the farmers have not yet received any monetary advantages. To increase inclusion, policy interventions must use differential pricing to encourage the participation of smallholder farmers and marginalized caste groups in carbon farming projects. Socially more

INFOGRAPHIC: 99% Farmers Received NO Payment

99% FARMERS RECEIVED NO PAYMENT
From Carbon Credit Projects.


REALITY SERIES

for greater credibility and efficacy. Carbon trading is not a panacea for Indian agriculture. But it is one of the most potent policy levers the country has to reconcile two priorities that have traditionally tugged in opposite directions: feeding 1.4 billion people, and conserving the climate they live in. The same technology that allows a corporate buyer to offset emissions might be used to support a small farmer in Bihar to move from flood irrigation to AWD—saving water, cutting methane, and putting money in her pocket—if it is designed inclusively, validated thoroughly, and paid regularly. This is the frontier. The next decade will decide if it is India’s most equitable growth tale — or simply another climate promise that didn’t see the pitch.

References

- Cariappa, A. G. (2025). Framework for voluntary carbon market in agriculture. *Down To Earth*.
- Cariappa, A. G., Konath, N., Sapkota, T., & Krishna, V. V. (2024). Conservation agriculture, VM0042, and ₹/hectare potential. *Scientific Reports*, 14(1), Article 9193. <https://doi.org/10.1038/s41598-024-59262-6>
- Cariappa, A. G., & Krishna, V. V. (2024). Carbon farming in India: Are the existing projects inclusive, additional, and permanent? *Climate Policy*, 25(5), 756–771. <https://doi.org/10.1080/14693062.2024.2416497>
- Energy Conservation Amendment Act, 2022, No. 20, Acts of Parliament, 2022 (India).
- Khurana, A., Kajale, D., Cariappa, A. G., & Krishna, V. V. (2024). Shaping India's climate future: A perspective on harnessing carbon credits from agriculture. *Outlook on Agriculture*, 53(2), 113–130. <https://doi.org/10.1177/00307270241240778>
- NABARD. (2023). *Carbon fund of Rs. 300 crore*. National Bank for Agriculture and Rural Development.
- Press Information Bureau. (2023, December). *Carbon Credit Trading Scheme notification*. Government of India.
- Press Information Bureau. (2024, January 29). *Launch of framework for voluntary carbon market in agriculture sector and accreditation protocol of agroforestry nurseries*. Government of India. <https://pib.gov.in/PressReleasePage.aspx?PRID=2000331>
- Singh, A., Kiran, R., & Mohan, D. (2024). Cap-and-trade mechanics and ₹780–₹2,000 credit rates. *Down To Earth*.

inclusive projects should be given greater prices. “Project developers need to do a good job in communication and provide regular training to support the uptake and continuity of regenerative farming practices.” Mechanisms must be devised for timely payments to farmers and to reduce economic disadoption. Robust systems must be put in place to guarantee initiatives meet the concepts of additionality and permanence,

DORB in Livestock Feed: Quality, Safety and Responsible Use



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Abstract

De-Oiled Rice Bran (DORB) is an important agro-industrial feed ingredient produced after oil is extracted from rice bran. Its value lies in the nutrients that remain available after processing, but its practical usefulness depends on much more than crude protein. Fibre, sand silica, acid-insoluble ash, moisture, total ash, physical condition, storage and formulation context all influence the quality decision. This article explains how farmers, feed buyers and feed manufacturers can evaluate DORB responsibly, avoid common procurement mistakes and use the material as part of a balanced ration. The emphasis is on buyer education, batch transparency and qualified nutritional supervision rather than on any single supplier or guaranteed animal response.

Introduction: from rice-milling by-product to feed ingredient

Rice milling creates several useful fractions, including rice bran. When crude rice bran oil is extracted, the remaining solid material is known as De-Oiled Rice Bran, commonly abbreviated as DORB. It can contribute protein, energy, phosphorus, B-complex vitamins, vitamin E and fibre to animal-feed systems. Because rice is processed in large quantities, DORB also represents an opportunity to convert an agro-industrial by-product into a useful component of the livestock economy.

However, calling DORB a feed ingredient does not mean that every batch has the same value. Processing conditions, raw-material freshness, cleaning, oil extraction, blending, transport and storage can all alter the final material. Two lots may appear similar in colour or carry similar crude-protein numbers while differing in fibre, mineral contamination, moisture or digestibility. Responsible use therefore begins with a shift in mindset: DORB should be evaluated as a quality-controlled ingredient, not as an undifferentiated filler purchased only on rate.

Why crude protein is only the beginning

Crude protein is usually the first number a buyer notices because it appears to offer a simple comparison. It is important, but it is not a complete measure of feeding value. The test estimates protein from nitrogen; it does not by itself prove how much of that nitrogen will be digested and used by the animal. Protein may also be affected by processing damage, poor storage or non-protein nitrogen that makes the number look stronger than the underlying nutrition.

The more reliable approach is to read a batch report as a pattern. A practical review should consider crude protein together with fibre, sand silica, acid-insoluble ash (AIA), moisture, total ash, residual oil, energy estimates, aflatoxin where relevant, and physical observations such as smell, colour, texture and free flow. If one attractive number is contradicted by several warning signs, the buyer should pause and investigate rather than approve the lot automatically.

Fibre: nutrition and procurement information in one parameter

Some fibre is naturally present in rice-bran-derived ingredients. The concern is excessive or poorly digestible fibre, especially when it indicates husk, sawdust or other non-nutritive material. In poultry and fish diets, excess fibre can dilute usable energy and reduce the predictability of feed conversion. Ruminants can tolerate more fibre because of rumen fermentation, but lignified or silica-heavy material still adds bulk without equivalent nutritional value.

As a buyer-awareness reference, premium DORB is often discussed around 9-11 percent fibre, while values above approximately 13 percent deserve closer investigation. These are practical checkpoints, not a substitute for the species-specific specification agreed between a buyer, supplier and nutritionist. Fibre should never be read in

isolation; its meaning becomes clearer when compared with sand silica, AIA, moisture and the material's physical condition.

Sand silica and ash: identifying non-nutritive load

Sand and silica add weight but do not add useful nutrition. High sand silica can result from soil, dust, rice husk, sawdust or inadequate cleaning. Acid-insoluble ash is useful because it helps identify mineral matter that remains undissolved in acid. Total ash, on the other hand, measures the inorganic residue after a sample is burned and may include both natural minerals and contamination. The interpretation must therefore consider the combination rather than treating every ash value as proof of adulteration.

A commonly used quality-awareness checkpoint is sand silica below 3 percent for a premium batch. A value substantially above that level should trigger a request for clarification, representative sampling and confirmatory testing. The commercial issue is straightforward: a buyer paying feed price for non-nutritive material is paying for weight rather than useful nutrition. In fish farming, excess mineral material may also contribute to undesirable pond loading; in poultry, it can reduce effective nutrient density; in cattle, it can lower ration efficiency even when higher fibre is tolerated.

Moisture and storage: quality after the laboratory

DORB is an organic, moisture-absorbing material. A sound batch can deteriorate after dispatch if it is placed directly on a damp floor, pressed against a wet wall, stacked without air movement or left uninspected during humid weather. Clumping, local heating, a musty smell, rancidity, fungal growth and mycotoxin risk can develop in pockets within a stack. The outside of a bag may look normal while the inner or lower bags are already affected. Moisture below 11 percent is a useful quality and storage checkpoint, while lower moisture may provide a safer starting point for longer storage when warehouse conditions are appropriate. Buyers should use pallets or a moisture-resistant base, leave space from walls, maintain inspection lanes, protect bags from leaks, keep stacks ventilated and follow first-in, first-out rotation. Torn or wet bags should be isolated immediately, and surrounding stock should be inspected rather than simply mixed together.

Adulteration: why an informed buyer matter

Adulteration is not only a laboratory problem; it is a supply-chain and animal-health problem. Rice husk, sawdust, sand, silica-rich material, dolomite, marble powder, salt or inferior by-products may be introduced to increase weight, alter apparent protein or hide poor processing. Urea and other non-protein nitrogen sources are particularly concerning when a buyer relies on crude protein alone. They can raise a nitrogen-based reading without providing the balanced protein and energy contribution required in a poultry or aquaculture ration.

The buyer's protection is a combination of physical and documentary checks. Request a batch-specific report rather than a generic certificate. Match the report to the lot or truck. Sample from multiple bags and stack positions, mix the portions properly, retain a sealed counter-sample and record the lot number. Inspect smell, colour, texture, flow, clumping and unusual dust. When the pattern is inconsistent, seek independent testing or qualified technical advice before using the material.

Species and formulation context

DORB does not have one universal inclusion rule. Poultry diets are sensitive to energy density and fibre. Fish diets require attention to digestibility, feed conversion and pond-water consequences. Dairy and other ruminant diets use the rumen differently, but still require attention to balance, mineral supply and the quality of accompanying ingredients. The same batch may therefore be acceptable for one formulation only after a nutritionist has considered the animal species, age, production stage, health status, local ingredients and the complete ration.

DORB should not be treated as a one-for-one replacement for every protein or energy ingredient. Its practical role is to contribute to a balanced formula at a suitable inclusion level, with quality parameters and animal response monitored. Final inclusion and any change in ration should be approved by a qualified animal nutritionist or veterinarian responsible for the feeding programme.

A responsible DORB purchasing checklist

Ask for the current, batch-specific laboratory report.

Read protein with fibre, sand silica, AIA, moisture and ash rather than alone.

Compare the report with the physical lot and the purchase specification.

Sample multiple bags and retain a sealed reference sample.

Check for fresh odour, uniform colour, free flow, clumps, heating and unusual dust.

Store on pallets, away from walls, with airflow and first-in, first-out rotation.

Escalate suspected contamination or spoilage to an independent laboratory and qualified adviser.

Conclusion

DORB can support livestock-feed economics and resource efficiency when its quality is understood and its use is disciplined. The right question is not simply, “What is the protein percentage?” It is, “Does this batch show a consistent pattern of usable nutrition, low non-nutritive load, controlled moisture, sound storage and suitability for the intended ration?” Better answers come from transparent reports, representative samples, careful warehouses and qualified formulation decisions. Quality awareness protects the farmer first and helps the feed industry use an important rice-based ingredient with greater confidence.



Legumes for Climate-Resilient and Sustainable Agriculture in India



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Abstract

Climate change threatens food & nutrition security in India due to threats namely soil degradation, dry conditions, hot weather, erratic rainfall causing widespread risks to crop production. Use of Legumes, which is a climate smart technology because of their built-in N -fixing, reduce cost of fertilization, curb GHG emissions, enriched soils, sequester C in the soil, retain water, improve crop output, give cheaper supply of protein, benefit farmers etc; but they can not gain importance because of cheap seed quality issues, climate/pest threat, absence of market infrastructure and market access technologies etc.

Keywords: Climate-resilient agriculture, Biological nitrogen fixation, Carbon sequestration, Crop diversification.

Introduction

The agricultural sector forms the mainstay of the Indian economy, providing sustenance and ensuring food and nutritional security. The adverse effects of climate change on agriculture include the impact on the productivity of crops due to increasing temperature, irregular rainfall, drought and flooding. The green revolution increased the food security of the country but resulted in soil degradation and depletion of ground water.

Mechanistic Foundations of Legume-Driven Ecosystem Resilience

Legumes ability to condition and restore agricultural ecosystems relies on a diverse ensemble of biological and biochemical processes. They not only can be used as a replace crop to increase sustainability but also they could use as a “bio agents” to restore water, soil and microclimatic dynamics of their environment.

Biological Nitrogen Fixation (BNF) Dynamics

The most important factor in the evolution of the legumes is its mutualistic association to the diazotrophs such as the bacterial genera of Rhizobium, Bradyrhizobium, Sinorhizobium and Mesorhizobium. The reduction of nitrogen happens in the roots called root nodules. The mechanism mainly occurs by means of the nitrogenase enzyme complexes (made of 2 subunits of nitrogen and 1 subunit of reductase) that are responsible for cleaving the extremely resistant triple bond that forms between the 2 N-atoms in the N₂ gas (air) and create NH₃, a form which plants can fix: $N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16P_i$

Rhizosphere Modification and Nutrient Solubilization

Rhizosphere improvement legumes create positive effects to soil micro-environment by means of releasing to protons, hydroxides, or organic compounds like citric acid, malic acid, oxaloacetic acid and fumaric acid. They result in the soil pH shift towards acid which improves the soil thereby freeing of the bound phosphorous through their reactions with calcium, iron and aluminium ion.

Soil Physical Architecture and Carbon Sequestration

Legumes by producing large, deep taproots that will break up compaction in the soil, increase water permeability of the soil, and limit erosion caused by heavy rain. Legume roots release sticky, soil-binding substances and the structure will be the strengthened by beneficial fungal partners. Over time due to rapid decomposition of legume residues organic matter content of the soil increases thereby improving long term soil fertility.

Agro-ecological Benefits Associated with Legumes

The inclusion of legumes in the conventional cereal based cropping systems such as rice – wheat rotation is a system of sustainable cultivation and climate-friendly farming system for India. Because legumes are naturally effective in disrupting pest and disease cycles and suppress weeds by the nature of their of non-host traits and leaf

architecture therefore the use of synthetic agricultural chemicals may be eliminated. Legumes' short growing season, as well as its tolerance to range of climatic conditions, can stabilize farm systems against hydro-metrological shocks and reduce the possibility of complete harvest failure and loss of livelihoods for the farmer. In addition to agronomic benefits, legumes perform intensive ecological functions for sustainability .Their capacity for BNF of 50-250 kg/ha per year considerably reduce the dependence on synthetic nitrogenous fertilizers that a farming system needs. Such self sufficiency reduces the green house gas emissions from production of nitrogenous fertilizers(nitrous oxides), decreases the fossil fuel consumption needed for the synthesis of such fertilizers and limits the accumulation of excess nitrogen which prevents the loss of ground water and eutrophication of surface water. By increasing the cover crop species present within agro-ecosystems legumes contribute further by supplying food and habitats for beneficial pollinators, predators and decomposers and exudation that enhances a range of beneficial microbial processes and beneficial fungi.

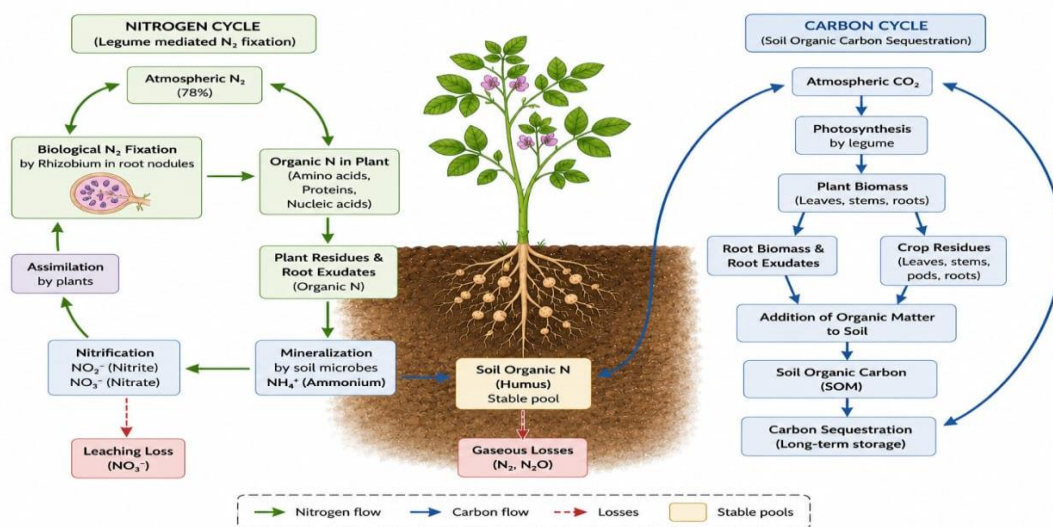


Figure 1: Biogeochemical cycle of legume-mediated nitrogen fixation and soil organic carbon sequestration.

Physiological and Morphological Adaptations to Climate Extremes

Stress Type	Target Crop Species	Adaptive Mechanism / Physiological Pathway	Resilience Dividend
Acute Moisture Deficit (Drought)	Chickpea (<i>Cicer arietinum</i>), Pigeon Pea (<i>Cajanus cajan</i>)	Deep taproots access deeper soil moisture, while osmotic adjustment improves drought tolerance.	Prevents cellular dehydration; maintains turgor and metabolic function during dry spells.
Thermal / Heat Stress	Mung Bean (<i>Vigna radiata</i>), Cowpea (<i>Vigna unguiculata</i>)	Heat shock proteins and antioxidants protect cells from harmful reactive oxygen species.	Prevents oxidative cellular damage and maintains chlorophyll stability under high heat.
Biotic Stresses (Pests & Pathogens)	Lentil (<i>Lens culinaris</i>), Black Gram (<i>Vigna mungo</i>)	Elicitation of phytoalexins and pathogenesis-related (PR) proteins; synthesis of structural polyphenols to reinforce cell walls against invading vectors.	Naturally disrupts pest life cycles; lowers dependency on synthetic chemical pesticides.
Soil Salinity & Alkalinity	Cluster Bean (<i>Cyamopsis tetragonoloba</i>)	Legumes exclude sodium and retain potassium, improving tolerance to saline soil conditions.	Sustains cellular ionic balance; enables economic yields in degraded, salt-affected terrains.

Table 1: Matrix of Key Leguminous Adaptations to Abiotic and Biotic Climatic Stresses

Structural Bottlenecks and Scientific Interventions

However, these obvious advantages, there is a failure to lead to an overall increase in the land area used for growing legumes in India in proportion to our nutritional demands and ecological balance. The expansion in production is constrained by interlinking structural and genetic bottlenecks as well as marketing constraints.

Production Bottlenecks and Challenges

- Pulses are largely cultivated under sub-optimal conditions of shallow and less fertile soils.
- Unavailability of climate tolerant and sensitive varieties of seeds results in lack of productivity.
- Pulses susceptible to pest and diseases result in major damage to produce.
- Ill procurement procedure and unsteady prices make pulse cultivation unattractive to cultivators.

Advanced Breeding and Biotechnological Pathways

Biotechnology aids in overcoming climatic, environmental and biotic constraints with MAS(Marker Assisted selection), Genomics and CRISPR /Cas9 technologies. Researchers develop varieties that are drought tolerant, insects and diseases, and improved root systems.

Policy Frameworks and National Initiatives

Only through innovative approaches under robust national policies, full potential of legumes could be unleashed. More pulse production, good distribution, procurement of seeds, better market linkages and assured public private partnership in paying for ecosystem services will lead the sustainable Agriculture in India.

Policy Synergy Opportunity

Pulses included in TPDS, PM POSHAN and ICDS can lead to improved nutritional outcomes, sustained farmers' demand, development of pulse cultivation and seed systems, development of Indian value chains.

Conclusion and Future Horizons

Legumes through soil improvement, efficient utilization of resources, diversification of cropping system, reducing its carbon foot print by virtue of their ability of biological nitrogen fixation, carbon sequestration and its inherent climate resilient and drought tolerance capacity constitutes an inextricable component of India's sustainable and climate smart agriculture to accomplish sustainable intensification under changing climate scenarios. In the days to come, climate smart and climate adoptable varieties supported with efficient nutrient management, digitisation of agriculture, conservative agriculture practice, and favourable policy backup will be contributing for enhancement of its importance further. Prioritizing research, making access for genuine seeds available, development of climate change adapted value chain and investing on farmer's extension through providing extended services are equally important to make legumes an enablers of a food-secure, nutrient security and eco-friendly future.

References

- Swaminathan, M. S. (2010). From Green to Evergreen Revolution: Indian Agriculture: Performance and Challenges. Academic Foundation.
- Singh, N. P., & Pratap, A. (2016). Food Legumes for Nutritional Security and Sustainable Agriculture. Indian Journal of Genetics and Plant Breeding, 76(4), 381-395.
- Directorate of Pulses Development (2023). Status Paper on Pulse Production in India. Ministry of Agriculture & Farmers Welfare, Government of India.
- Varshney, R. K., et al. (2019). Pearl millet genome sequence provides a resource to improve agronomic traits in arid environments. Nature Biotechnology, 35(10), 969-976.

Progressive Farmers, Promising Farms, Prosperous Nation Aug. 15 Special



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As the country completes 79 years of freedom, agriculture sector remains the bedrock of India's growth story all through the last eight decades. The transformation of the sector from shortages and imports to surplus and exports is unparalleled and marvelous. Agriculture in India defied Malthusian theory. As per the third Advance Estimates released by the ministry of Agriculture and Farmers' welfare, total food grain production for the year 2025-26 is estimated at a record breaking 376.56 million tonnes. It is India's highest production so far; it is also more than 40% than it was one decade ago in 2014-15. Similarly the horticulture production in the country has risen to 377.78 million tonnes exceeding the food grains production. The surplus today has been as a result of various pro-farming policies, programmes and various interventions over last seven decades. The green revolution of 1960s led to phenomenal growth in production of food grains. India's dairy, poultry, and fisheries sectors have seen remarkable growth. Similarly, the White Revolution, starting in the 1970s, boosted milk production from 20 mt to 239 mt by 2023-24. The country is also witnessing a surge in production of fisheries leading to blue revolution. Due to the Blue Revolution fish production in the country has increased to 197.75 lakh tonnes in 2025-26 with sea food exports hitting an all time high of over 73,890 crores. The egg production in the country has now reached 149.11 billion and country now ranks second in world in total egg production. India also ranks first in milk production recording a production of 247.87 million tonnes of milk in the year 2024-2. The country has the largest area under cultivation. It is now the largest producer of pulses, spices, milk, tea, cashew, jute, banana, jackfruit and many other commodities (FAO). It stands second in production of fruits and vegetables, wheat, rice, cotton and oilseeds. India has the largest cotton cultivation area all over the world after China and the USA and it is the prime agriculture commodity or fiber crop worldwide. India is the third highest potato producing country and the second largest producer of Pulses in the world. The country also has the largest livestock population. Farms are now progressive, farmers are promising and nation is on the way to be a prosperous one.

Before proceeding ahead, let me go to some decades back. After a long and tumultuous struggle that lasted near two decades, the Britishers were forced to declare India as an independent country on Aug. 15, 1947. The day marked the end of foreign dominance and beginning of a new era of self governance and democracy in India. As the country celebrates its 79th Independence Day on August 15, it is also a day to pay rich tributes to the countless freedom fighters, revolutionaries and nationalists who sacrificed their lives for independence of the country. The journey of last more than seven decades has been unique with country progressing by leaps and bounds to become the fifth largest economy in the world at present and posing to become third largest economy in the next few years. Every sector of the economy has witnessed revolutionary strides and the world has felt and observed the positive impacts of this entire phenomenon. The agriculture sector after attaining independence suffered from numerous challenges that include feeding the increasing population, low productivity and stagnation, creating adequate employment opportunities for the surplus labour besides ensuring timely availability of inputs to the farming community. Agriculture sector also suffered because of outdated technology, crude practices and huge dependence on timely rainfall. It was referred to as the 'begging bowl' with major portion of our food requirements being met from imports from other countries. Farmers of that era were a static entity even reluctant to go for any change in their crude and unscientific cultivation practices. Overhauling the agriculture sector was not possible without ensuring that the relevant technology reached out to farming community well in time as well as motivating the farming community to adopt the new technologies. In all these years of country's journey post independence, the agriculture sector has been the country's strength in its contribution in Gross Domestic Product (GDP) of the country, in providing employment to the population and as a source of livelihood for the vast majority of rural populace.

India from a 'begging bowl' thus changed to a 'bread basket' and the fortune changed by what is known as 'Green revolution'. The period corresponding to 1967-78 witnessed huge upsurge in food grains production especially in states of Punjab Haryana and Uttar Pradesh. Green revolution spread to millions of third world countries also. Reports reveal that the absolute number of poors came down from 1.15 billion in 1975 to 825 million in 1995. All this happened despite a 60 per cent growth in population. Since the Green revolution of 1960s, India has never looked back. It is also here pertinent to mention that the country's prevalence of undernourished population dropped from 13% in 2022-24 to 12% in 2022-24 contributing to a global decline reducing the count of hungry individuals by roughly 30 million.

Despite remarkable achievements in the agriculture sector, there has been another side of this achievement. We have not yet been self sufficient in Pulses and Oilseeds. The negative impact and threat posed to our environment by climate change and large scale indiscriminate use of chemical fertilizers and plant protection chemicals to increase the yields are now clearly visible. The ground water has been rendered poisonous and contaminated with harmful chemicals. Such is the infestation that vast stretches of land extending up to kilometers is now not fit for any drinking water. Soils have been degraded, turned barren and a large number of biodiversity has been lost. Biodiversity is on the decline. Yields of crops are not increasing and large scale nutritional insecurity is manifested through children, pregnant and lactating mothers and adolescent girls.

The sector needs to embrace technologies which do not interfere with the environment, practices which are sustainable, and farming techniques like diversification and Integrated Farming System Models. At the same time it is also necessary that high value crops be promoted. Although we have attained food security for all, by nutritional security is a concern for all of us. To address nutritional security, a host of initiatives have been started. Biofortification and climate resilient varieties are being developed. From a chemical intensive green revolution, we have now to move towards an evergreen revolution based on the principles of natural farming, sustainability, local resource use efficiency, economic viability, social compatibility and profitability. Natural Farming is being promoted all across the country as environmental friendly approach. In the next two years one crore farmers would be roped in to practice natural farming. The food processing in the country is at present very low. The food processing sector can be utilized to enhance income opportunities for the rural population, facilitate job creation, minimize food wastage, improve the availability of nutritious foods by enhancing the processing of fruits and vegetables, and augment the proportion of value-added products.

The government of India has also come up with many pro-farmer schemes and programmes which include Primeminister Kisan Samman Nidhi (PMKISAN), Primeminister Krishi Sinchai Yojana (PMKSY), Soil Health Card (SHC), Primeminister Fasal Bima Yojana (PMFBY), and Primeminister Kisan Mandhan Yojana. To attract and retain Youth in agriculture, Entrepreneurship development schemes like Agri-Startups and skill development are being promoted with handholding and financial support to the youth who are interested in setting up agriculture or allied ventures. All these programmes have started showing results. Many youths have left their high earning jobs and started their own startups in agriculture and creating job opportunities for others also. Farmers particularly farm women feel more empowered, youths are now more skilled and the once static farming community is now a dynamic and vibrant one with collective approaches like Farmer Producer Organizations (FPOs).

The country has now set the goal of being a Developed Nation i. e *Viksit Bharat* by 2047. By 2047, India aims to become a developed nation. A recent article of Hon'ble Minister of Agriculture and Farmers' Welfare, GoI reported that for India to become a developed nation by 2047, its economy must grow at 7.8% annually with a projected population of 1.6 billion and half of that will be in urban areas. This shift will double overall food demand with demand for fruits, vegetables and animal based products expected to triple, while cereal demand remains stable leading to surpluses.

However rising urbanization and industrialisation will shrink agricultural land and average land holdings will come down from one hectare to 0.6 ha. This will further pressure on water and agro-chemicals risking resource degradation. The climate crisis poses an even greater threat endangering sustainable agriculture

Viksit Bharat is a vision for India to become a developed nation focusing on economic growth, social inclusion and environmental sustainability. The goal of *Viksit Bharat* is impossible to attain without giving due

importance to agriculture. Agriculture is critical for India's development as it still engages about 45.8% of working population. If the dream of *Viksit Bharat* has to be realized and fulfilled by 2047, agriculture sector has to be developed to its full potential. Primeminister of the country Sh. Narendra Modi during his 2025 Independence day address has already laid out an ambitious blueprint for a *Viksit Bharat* by 2047 with *Atmanirbharta* at its core. The transformation to *Viksit Bharat@2047* is possible only by strengthening our agriculture sector, our small and marginal farmers who made up 85% of Indian agrarian population and are central to rural livelihoods and food & nutritional security. The transformation would move India to a high-tech, climate-resilient and sustainable powerhouse and ensure food security to long-term farmer prosperity.



From Brewery Waste to Fish Feed: Turning a By-product into an Aquaculture Resource



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Abstract

The growing aquaculture sector requires affordable, nutritionally balanced and environmentally sustainable feed ingredients. At the same time, the brewing industry generates large quantities of organic by-products, particularly brewer's spent grain (BSG) and brewer's spent yeast (BSY). These materials contain valuable nutrients such as proteins, carbohydrates, fibre, lipids, minerals, vitamins and bioactive compounds, making them potential resources for aquafeed production. BSG is particularly abundant and can partially replace conventional protein ingredients, while BSY is a protein-rich by-product with additional antioxidant and immunostimulatory properties. Studies in different fish species indicate that moderate inclusion of brewery by-products can maintain growth performance and feed utilization, although their effectiveness depends on fish species, inclusion level and processing method. Processing techniques such as fermentation and enzyme treatment can further improve the nutritional value and digestibility of BSG. The utilization of brewery by-products in aquafeeds offers a promising waste-to-feed approach that can reduce waste disposal, diversify feed resources, lower dependence on conventional protein sources and contribute to the development of a circular and sustainable aquaculture industry.

Keywords:

Brewery by-products, brewer's spent grain, brewer's spent yeast, aquafeed, alternative protein, waste valorization; sustainable aquaculture, circular economy

Introduction

Beer is a fermented beverage produced through a series of processes such as malting, milling, mashing, wort separation, boiling, fermentation, maturation and packaging. The process converts grain starch into fermentable sugars, which are then fermented by yeast to produce beer. These large-scale operations generate substantial quantities of organic by-products and waste materials (Rachwał et al., 2020). The large-scale production of beer generates considerable quantities of organic by-products, mainly brewer's spent grain (BSG), hot trub and brewer's spent yeast. Among these, BSG is the most abundant brewery by-product, generated after the mashing process when the liquid wort is separated from the residual grain (Rachwał et al., 2020). The increasing generation of these by-products creates challenges related to their storage, disposal and environmental management. However, rather than considering them simply as waste, their nutrient content and other valuable components provide opportunities for waste valorization, where industrial by-products are converted into useful value-added products.

Aquaculture is one sector where such by-products can potentially be utilized effectively. Feed represents a major component of aquaculture production costs, while the growing demand for fish and the expansion of aquaculture are increasing the need for nutritionally adequate, affordable and sustainable feed ingredients. Conventional protein sources such as fishmeal and soybean meal are widely used, but concerns related to cost, resource availability and environmental sustainability have encouraged researchers to investigate alternative feed ingredients. In this context, agro-industrial by-products such as brewery waste are receiving increasing attention

as potential ingredients for aquafeeds. These by-products lower feed costs, reduce the global aquaculture carbon footprint, and supply essential proteins and nutrients (Zerai et al., 2008).

Brewer's spent grain contains protein, fibre, lipids, minerals and other bioactive compounds, making it a potentially useful ingredient in animal and fish nutrition. Brewer's spent yeast is also considered a valuable protein-rich by-product with potential applications in aquafeed production. However, the direct use of BSG can be limited by its high fibre content, variable nutritional composition, lower digestibility of certain nutrients and poor storage stability in its fresh form. Processing methods such as drying, grinding, enzymatic treatment and fermentation may help improve its nutritional quality and suitability for inclusion in fish diets (Karlsen and Skov, 2022). These by-products lower feed costs, reduce the global aquaculture carbon footprint, and supply essential proteins and nutrients (Zerai et al., 2008).

Therefore, the utilization of brewery by-products in aquaculture represents a promising "waste-to-feed" approach, in which an industrial by-product is converted into a useful resource for fish production. Such utilization can simultaneously contribute to waste reduction, nutrient recovery, feed diversification and sustainable aquaculture, while providing opportunities to reduce dependence on conventional feed ingredients.

Brewery by-products and their nutritional potential

Beer production generates two major by-products: brewer's spent grain and residual brewer's yeast (Mathias et al., 2014). These by-products differ in their moisture, ash and chemical composition, depending on the raw materials used and the conditions of the brewing process. However, they generally contain valuable nutrients such as carbohydrates, proteins, fibre, vitamins, minerals and phenolic compounds, making them potentially useful for food and feed applications (Santos et al., 2003; Olajire, 2012). Their high moisture content is an important characteristic, as a considerable proportion of the water used during brewing remains associated with these residues (Santos et al., 2003).

Brewer's spent grain (BSG)

It is the most abundant by-product of the brewing industry, accounting for approximately 85% of the total residues generated during beer production (Aliyu & Bala, 2011). BSG is formed in the mashing process and removed before the boiling step of the brewing process. This solid residue from wort production is composed of barley grain husks (Kerby & Vriesekoop, 2017). It contains approximately 15–27% protein on a dry matter basis, along with valuable antioxidant compounds such as polyphenols and phenolic acids. Research has indicated that BSG can potentially replace up to 50% of conventional protein sources in aquafeeds without adversely affecting fish growth performance (Geremia et. al., 2026). Brewer's spent grain (BSG) is a lignocellulosic by-product containing considerable amounts of fibre (30–70%), lipids, vitamins and minerals. Its fibre fraction includes approximately 12–28% lignin, 12–25% cellulose and around 28% non-cellulosic polysaccharides, with arabinoxylans being the predominant component (Mussatto & Roberto, 2005; Lynch et al., 2016).

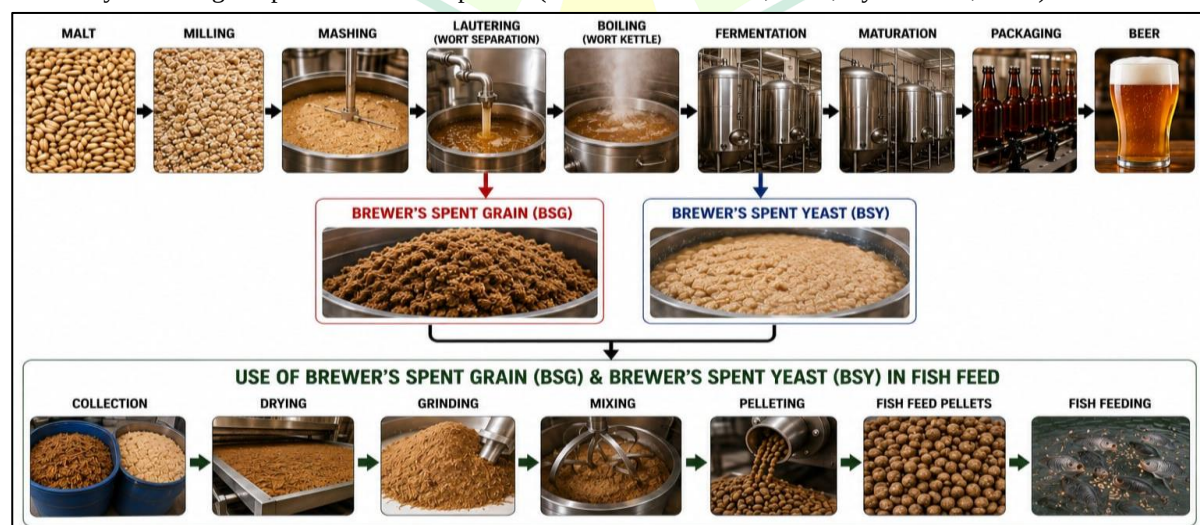


Fig. 1: Generation of brewery by-products during beer production and use in fish feed

Brewer's Spent Yeast (BSY)

Brewer's spent yeast (BSY) is the second major by-product of the brewing industry, contributing up to approximately 15% of the total brewery by-products (Huige, 2006; Kerby & Vriesekoop, 2017). It is mainly recovered after fermentation and maturation, when excess *Saccharomyces cerevisiae* yeast is removed from the beer (Olajire, 2012). BSY contains valuable nutrients, including approximately 49% protein, 40% carbohydrates, 7% minerals and vitamins, and 4% lipids. However, it has a high moisture content of about 74–86%, with dry matter generally ranging from 10–16% (Mathias et al., 2015). In addition, BSY is a source of B-group vitamins and polyphenolic compounds, increasing its potential for food and feed applications (Podpora et al., 2016).

Nutritional Benefits

High Protein Content: Brewer's spent yeast contains up to 49% crude protein and functions as a valuable single-cell protein source.

Immune Support: Yeast components act as immunostimulants and antioxidants, improving fish gut health and disease resistance.

Cost Reduction: Replaces traditional ingredients to make commercial aquafeed cheaper and more sustainable.

Limitations and Challenges

High Fiber and Lignocellulose: Brewer's spent grains contain high fiber levels, which can limit energy digestibility in certain fish species if included at too high of a rate.

Amino Acid Imbalance: High replacement levels may lack sufficient methionine, requiring synthetic amino acid supplementation.

Species Specificity: Carnivorous and omnivorous fish handle inclusion differently; optimal inclusion ranges typically fall between 10% and 30% of the total diet.

Use of brewery by-products in fish feed

Brewer's spent grain (BSG) has been investigated as an alternative ingredient in fish feeds, mainly as a partial replacement for fishmeal, soybean meal and other plant protein sources. Studies in species such as Nile tilapia, striped catfish, rainbow trout and gilthead seabream have shown that moderate BSG inclusion can maintain growth and feed efficiency (Estévez et al., 2022). However, higher inclusion levels may reduce growth performance, as observed in Pacific white shrimp when 70% of fishmeal was replaced with BSG (He et al., 2020). Processing methods such as fermentation, enzyme treatment and microwave processing may improve the nutritional value and feed utilization of BSG (Martínez-Antequera et al., 2025). Thus, BSG shows potential as a partial and sustainable replacement for conventional protein sources in aquafeeds (Geremia et al., 2026).

Brewer's spent yeast (BSY) is a protein-rich brewery by-product with valuable nutritional and functional properties, including antioxidant and immunostimulatory effects. Its nutrients can be efficiently utilized by fish, making it a promising alternative protein source in aquafeeds. The suitable inclusion level varies with fish feeding habits, with reported optimal levels of approximately 10–31.5% for carnivorous fish and 19–31.6% for omnivorous fish. BSY can potentially replace 30–50% of fishmeal in carnivorous fish and 35–80.8% in omnivorous fish diets. Its wider use could reduce global fishmeal consumption by about 13.94% (0.369 million tonnes), lower the carbon footprint by approximately 1.79 million tonnes CO₂-equivalent, and improve the fish-in-fish-out ratio from 0.82:1 to 0.71:1, thereby supporting a more sustainable circular bioeconomy in aquaculture (Gokulakrishnan et al., 2023).

References

- Aliyu, S., & Bala, M. (2011). Brewer's spent grain: A review of its potentials and applications. *African Journal of Biotechnology*, 10, 324–331.
- Estévez, A., Padrell, L., Iñarra, B., Orive, M., & San Martín, D. (2022). Brewery by-products (yeast and spent grain) as protein sources in rainbow trout (*Oncorhynchus mykiss*) feeds. *Frontiers in Marine Science*, 9, 862020. <https://doi.org/10.3389/fmars.2022.862020>
- Geremia, E., Buonocore, E., Venditti, P., Adamos, I., Paolacci, S., Agnisola, C., & Napolitano, G. (2026). Potential opportunities and challenges of utilizing brewer's spent grain in sustainable fish feeding within the circular economy. *Frontiers in Physiology*, 17, 1766656.

- Gokulakrishnan, M., Kumar, R., Ferosekhan, S., Siddaiah, G. M., Nanda, S., Pillai, B. R., & Swain, S. K. (2023). Bio-utilization of brewery waste (brewer's spent yeast) in global aquafeed production and its efficiency in replacing fishmeal: From a sustainability viewpoint. *Aquaculture*, 565, 739161.
- He, Y., Galagarza, O. A., Wang, H., Taylor, Z. W., Ferguson, C. S., Ogejo, J. A., et al. (2020). Protein-rich product recovered from brewer's spent grain can partially replace fishmeal in diets of Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture Research*, 51, 3284–3296. <https://doi.org/10.1111/are.14664>
- Huige, N. (2006). Brewery by-products and effluents. In F. G. Priest & G. G. Stewart (Eds.), *Handbook of brewing* (2nd ed., pp. 656–707). Taylor & Francis Group.
- Karlsen, F., & Skov, P. V. (2022). Review—Potentials and limitations of utilising brewer's spent grain as a protein source in aquaculture feeds. *Journal of Cleaner Production*, 357, 131986. <https://doi.org/10.1016/j.jclepro.2022.131986>
- Kerby, C., & Vriesekoop, F. (2017). An overview of the utilisation of brewery by-products as generated by British craft breweries. *Beverages*, 3, 24. <https://doi.org/10.3390/beverages3020024>
- Lynch, F., Santana-Sánchez, A., Jämsä, M., Sivonen, K., Aro, E.-M., & Allahverdiyeva, Y. (2015). Screening native isolates of cyanobacteria and a green alga for integrated wastewater treatment, biomass accumulation and neutral lipid production. *Algal Research*, 11, 411–420. <https://doi.org/10.1016/j.algal.2015.05.015>
- Martínez-Antequera, F. P., Simó-Mirabet, P., Heras, V., Román, M., Mancera, J. M., Martos-Sitcha, J. A., et al. (2025). Effect of two different pretreatments of brewers spent grain used as feed ingredient on nutritional, immunological, and metabolical parameters in gilthead seabream (*Sparus aurata*). *Biology*, 14, 585. <https://doi.org/10.3390/biology14060585>
- Mathias, T. R. D. S., de Mello, P. P. M., & Servulo, E. F. C. (2014). Solid wastes in brewing process: A review. *Journal of Brewing and Distilling*, 5, 1–9. <https://doi.org/10.5897/JBD2014.0043>
- Mathias, T. R. S., Alexandre, V. M. F., Cammarota, M. C., Mello, P. P. M., & Sérvulo, E. F. C. (2015). Characterization and determination of brewer's solid wastes composition. *Journal of the Institute of Brewing*, 121, 400–404. <https://doi.org/10.1002/jib.229>
- Mussatto, S. I., & Roberto, I. C. (2005). Acid hydrolysis and fermentation of brewer's spent grain to produce xylitol. *Journal of the Science of Food and Agriculture*, 85, 2453–2460. <https://doi.org/10.1002/jsfa.2276>
- Olajire, A. A. (2012). The brewing industry and environmental challenges. *Journal of Cleaner Production*, 30, 1–21.
- Podpora, B., Swiderski, F., Sadowska, A., Rakovska, R., & Wasiak-Zys, G. (2016). Spent brewer's yeast extracts as a new component of functional food. *Czech Journal of Food Sciences*, 34, 554–563. <https://doi.org/10.17221/419/2015-CJFS>
- Rachwał, K., Waško, A., Gustaw, K., & Polak-Berecka, M. (2020). Utilization of brewery wastes in food industry. *PeerJ*, 8, e9427.
- Santos, M., Jiménez, J. J., Bartolomé, B., Gómez-Cordovés, C., & del Nozal, M. J. (2003). Variability of brewers' spent grain within a brewery. *Food Chemistry*, 80, 17–21. [https://doi.org/10.1016/S0308-8146\(02\)00229-7](https://doi.org/10.1016/S0308-8146(02)00229-7)
- Zerai, D. B., Fitzsimmons, K. M., Collier, R. J., & Duff, G. C. (2008). Evaluation of brewer's waste as partial replacement of fish meal protein in Nile tilapia, *Oreochromis niloticus*, diets. *Journal of the World Aquaculture Society*, 39, 556–564. <https://doi.org/10.1111/j.1749-7345.2008.00186.x>

Automation in Agriculture: From Manual Farming to Smart Crop Management



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Abstract

Agriculture is rapidly changing from labour-intensive farming to technology-driven production. Automation, supported by sensors, the Internet of Things (IoT), artificial intelligence (AI), drones, robotics, and smart irrigation, is helping farmers monitor crops, manage resources, and make timely decisions. This article highlights the evolution from manual farming and mechanization to smart and increasingly autonomous agriculture. It also discusses major technologies, benefits, challenges, and opportunities for making automation accessible to small farmers.

Keywords: Agricultural automation, smart farming, IoT, artificial intelligence, precision agriculture, robotics, smart irrigation

Introduction

For generations, farming has depended on human labour, experience, and careful observation. Farmers traditionally decide when to irrigate, fertilize, control pests, and harvest based on field conditions and experience. However, rising labour costs, labour shortages, water scarcity, climate variability, and increasing production demands are encouraging farmers to adopt new technologies (FAO, 2022).

Today, agriculture is increasingly shifting towards smart and automated farming, where digital technologies work alongside farmers. Sensors can monitor field conditions, drones can assess crops, and AI can analyse data to support timely decision-making. Rather than replacing farmers, automation aims to make farming more precise, efficient, productive, and sustainable.

From Manual Farming to Mechanization

The first major transformation in agriculture came with mechanization. Traditional farming relied heavily on human and animal power for ploughing, sowing, harvesting, and transportation. Tractors, harvesters, seed drills, and irrigation pumps increased the speed and scale of farm operations while reducing physical labour (Sims *et al.*, 2016).

However, conventional mechanization mainly focused on doing farm operations faster. Modern automation goes further by allowing machines to respond to differences in soil, crops, weather, and resource requirements. This has created a pathway from mechanized farming towards precision and smart agriculture (Jiang *et al.*, 2020).



Fig. 1: Transformation from Traditional Farming to Smart Agricultural Management

The Rise of Smart Agriculture

The next stage of agricultural development is associated with Precision Agriculture, Digital Agriculture, and Agriculture 4.0. These approaches combine IoT, AI, robotics, remote sensing, cloud computing, and automated machinery to improve farm monitoring and decision-making (Fountas *et al.*, 2020; Klerkx *et al.*, 2019).

The basic process is simple: Collect data → Analyse → Make decisions → Automate action → Monitor results. For example, instead of irrigating a crop according to a fixed schedule, a soil-moisture sensor can identify when the soil becomes dry and automatically activate irrigation. This represents a shift from calendar-based farming to condition-based farming.

Key Technologies Driving Agricultural Automation

1. Internet of Things (IoT)

IoT connects sensors, machines, controllers, and communication systems. Sensors can monitor soil moisture, temperature, humidity, pH, rainfall, and other conditions. This information can be accessed through mobile applications or cloud platforms for real-time farm management (Tzounis *et al.*, 2017).

2. Smart Sensors

Sensors provide continuous information about soil, crops, and environmental conditions. When combined with IoT and data analytics, they help farmers identify changes in crop and field conditions and take timely action.

3. Artificial Intelligence

AI and machine learning can analyse large amounts of agricultural data. They are increasingly used for **disease detection, yield prediction, weed identification, crop monitoring, and irrigation management** (Kamilaris and Prenafeta-Boldú, 2018).

For example, an AI system can analyse a photograph of a leaf and identify symptoms that may indicate a plant disease.

4. Drones and Remote Sensing

Agricultural drones equipped with cameras and multispectral or thermal sensors can monitor large fields quickly. They can help identify crop stress, nutrient deficiencies, pest and disease problems, and variations in crop growth (Tsouros *et al.*, 2019).

5. Automated Irrigation

Smart irrigation systems combine soil-moisture sensors, pumps, valves, weather information, and automated controllers. Water can therefore be supplied according to actual crop requirements rather than a fixed schedule, helping improve water-use efficiency (Adeyemi *et al.*, 2017).

6. Automated Fertilization

Automated fertigation combines irrigation and fertilizer application. Parameters such as pH, electrical conductivity, water flow, and nutrient concentration can be monitored to deliver nutrients more accurately, particularly in protected cultivation.

7. Agricultural Robotics

Agricultural robots are being developed for planting, weeding, harvesting, crop monitoring, and targeted spraying. By performing repetitive and labour-intensive activities, robots can reduce drudgery and improve operational precision (Bechar and Vigneault, 2016).

Smart Greenhouses and Protected Cultivation

Automation is particularly useful in greenhouse and protected cultivation. Sensors can continuously monitor temperature, humidity, light intensity, carbon dioxide, and growing-media moisture.

Based on this information, automated systems can control ventilation, cooling, irrigation, fertigation, shading, and lighting. The greenhouse therefore becomes more than a protective structure it becomes an intelligent production environment (Maraveas, 2023).

Automation in Crop Protection

Crop protection is another important area of automation. Traditional pest and disease management often depends on regular field inspection and uniform pesticide application. Smart systems can combine cameras, drones, sensors, weather data, and AI to identify weeds, pests, and diseases at an early stage. Automated sprayers and

robots can then support targeted treatment, potentially reducing unnecessary chemical application (Mesías-Ruiz *et al.*, 2023).

Data-Driven Crop Management

Data is at the heart of smart farming. Traditional farming mainly depends on experience and observation, while smart farming combines farmer knowledge with continuous information from sensors, weather stations, remote sensing, and connected devices (Wolfert *et al.*, 2017).

A typical system follows: Sensors → Data Collection → Analysis → Decision → Automated Action → Monitoring

For example, when a soil-moisture sensor detects low moisture, the system can automatically activate a pump and irrigation valve. After irrigation, the sensor checks the moisture level again. This closed-loop system connects monitoring, decision-making, and action (Zhai *et al.*, 2020).

Benefits of Agricultural Automation

- **Reduced labour:** Automates repetitive and labour-intensive activities (FAO, 2022).
- **Improved precision:** Enables accurate application of water, fertilizers, and crop-protection inputs (Gebbers and Adamchuk, 2010).
- **Better resource efficiency:** Helps reduce unnecessary use of water, fertilizers, and energy (Walter *et al.*, 2017).
- **Early problem detection:** Sensors, drones, and AI can identify crop stress, pests, and diseases at an early stage (Kamilaris and Prenafeta-Boldú, 2018).
- **Improved productivity:** Timely and precise operations can support better crop performance.
- **Reduced drudgery:** Machines can reduce physically demanding farm activities.
- **Better decision-making:** Real-time data helps farmers make faster and more informed decisions.

Challenges in Adopting Automation

Despite its benefits, agricultural automation also faces several challenges.

- **High investment cost:** Advanced machinery, sensors, drones, and software can be expensive.
- **Limited digital skills:** Farmers may require training to operate and interpret digital systems.
- **Poor connectivity:** Limited internet, electricity, and rural infrastructure can restrict adoption.
- **Maintenance:** Automated equipment requires regular servicing and technical support.
- **Data security:** Data ownership, privacy, and cybersecurity are emerging concerns.
- **Uncertain returns:** Farmers may hesitate to invest when economic benefits are unclear (FAO, 2022; Klerkx *et al.*, 2019).

Making Automation Accessible to Small Farmers

Automation should not be limited to large commercial farms. Small farmers can begin with affordable and modular technologies, such as soil-moisture sensors, automated irrigation controllers, and mobile-based monitoring systems.

Farmer Producer Organizations, cooperatives, custom-hiring centres, universities, startups, and government agencies can support adoption through shared equipment, training, demonstrations, and service-based models. Technologies should be selected according to local farming conditions, farm size, affordability, and actual farmer needs.

The Future: From Smart Farming to Autonomous Farming

The future of agriculture is likely to involve greater integration of AI, robotics, IoT, drones, satellite data, sensors, and autonomous machinery. Future systems may identify individual plants, detect weeds, monitor crop health, and perform targeted operations with limited human intervention (Saiz-Rubio and Rovira-Más, 2020).

However, farming is unlikely to become completely human-free. Farmers will continue to provide experience, judgement, strategic planning, and risk management. The future is therefore more likely to be farmer-centred automation, where technology handles repetitive and data-intensive tasks while farmers remain in control of important decisions.

Conclusion

Agricultural automation represents a major transition from manual and mechanized farming to smart, precise, and data-driven agriculture. Technologies such as IoT, sensors, AI, drones, automated irrigation, smart greenhouses, and robotics can improve productivity, resource efficiency, crop monitoring, and working conditions.

However, high costs, limited skills, inadequate infrastructure, and maintenance challenges must be addressed, particularly for small farmers. Affordable technologies, training, shared services, and supportive policies can make automation more accessible. Ultimately, the future of agriculture is not about replacing farmers with machines, but about combining farmer knowledge with intelligent technology to create more productive, sustainable, and resilient farming systems.

References

- Adeyemi, O., Grove, I., Peets, S., and Norton, T. (2017). Advanced monitoring and management systems for improving sustainability in precision irrigation. *Sustainability*, 9(3), 353.
- Bechar, A., and Vigneault, C. (2016). Agricultural robots for field operations: Concepts and components. *Biosystems Engineering*, 149, 94–111.
- FAO. (2022). *The State of Food and Agriculture 2022: Leveraging Agricultural Automation for Transforming Agrifood Systems*. FAO, Rome.
- Fountas, S., Espejo-García, B., Kasimati, A., Mylonas, N., and Darra, N. (2020). The future of digital agriculture: Technologies and opportunities. *IT Professional*, 22(1), 24–30.
- Gebbers, R., and Adamchuk, V. I. (2010). Precision agriculture and food security. *Science*, 327(5967), 828–831.
- Kamilaris, A., and Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70–90.
- Klerkx, L., Jakku, E., and Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and Agriculture 4.0. *NJAS – Wageningen Journal of Life Sciences*, 90–91, 100315.
- Maraveas, C. (2023). Incorporating artificial intelligence technology in smart greenhouses: Current state of the art. *Applied Sciences*, 13(1), 14.
- Mesías-Ruiz, G. A., et al. (2023). Boosting precision crop protection towards Agriculture 5.0 via machine learning and emerging technologies. *Frontiers in Plant Science*, 14, 1143326.
- Saiz-Rubio, V., and Rovira-Más, F. (2020). From smart farming towards Agriculture 5.0: A review on crop data management. *Agronomy*, 10(2), 207.
- Sims, B. G., Hilmi, M., and Kienzle, J. (2016). *Agricultural Mechanization: A Key Input for Sub-Saharan African Smallholders*. FAO.
- Tzounis, A., Katsoulas, N., Bartzanas, T., and Kittas, C. (2017). Internet of Things in agriculture, recent advances and future challenges. *Biosystems Engineering*, 164, 31–48.
- Tsouros, D. C., Bibi, S., and Sarigiannidis, P. G. (2019). A review on UAV-based applications for precision agriculture. *Information*, 10(11), 349.
- Walter, A., Finger, R., Huber, R., and Buchmann, N. (2017). Smart farming is key to developing sustainable agriculture. *PNAS*, 114(24), 6148–6150.
- Wolfert, S., Ge, L., Verdouw, C., and Bogaardt, M. J. (2017). Big data in smart farming – A review. *Agricultural Systems*, 153, 69–80.
- Zhai, Z., Martínez, J. F., Beltran, V., and Martínez, N. L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. *Computers and Electronics in Agriculture*, 170, 105256.

Healing the Planet, Growing Wealth: The Carbon Farming Revolution in Medicinal & Aromatic Plants (MAPs)



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Introduction

The world faces a mounting challenge: agriculture accounts for nearly 25% of global greenhouse gas emissions, while simultaneously millions of rural farmers struggle with poverty and declining incomes (Singh et al. 2026). Carbon Farming is a whole farm approach to optimizing carbon capture on working landscapes by implementing practices that are known to improve the rate at which CO₂ is removed from the atmosphere and stored in plant material and/or soil organic matter.

Carbon farming, a revolutionary approach that combines climate mitigation with agricultural productivity is transforming the economics of farming while healing the planet. When applied to medicinal and aromatic plants (MAPs), this innovation creates a powerful triple win: sequestering atmospheric carbon, restoring degraded soils, and generating substantial wealth for some of the world's most vulnerable farming communities. Carbon farming in MAPs offers something rare: a solution that works with nature rather than against it, that simultaneously addresses climate change, biodiversity loss, and rural poverty. This article explores how the integration of carbon farming principles into medicinal and aromatic plant cultivation is reshaping agriculture, generating wealth, and offering hope for a sustainable future (Rattan Lal, 2015).

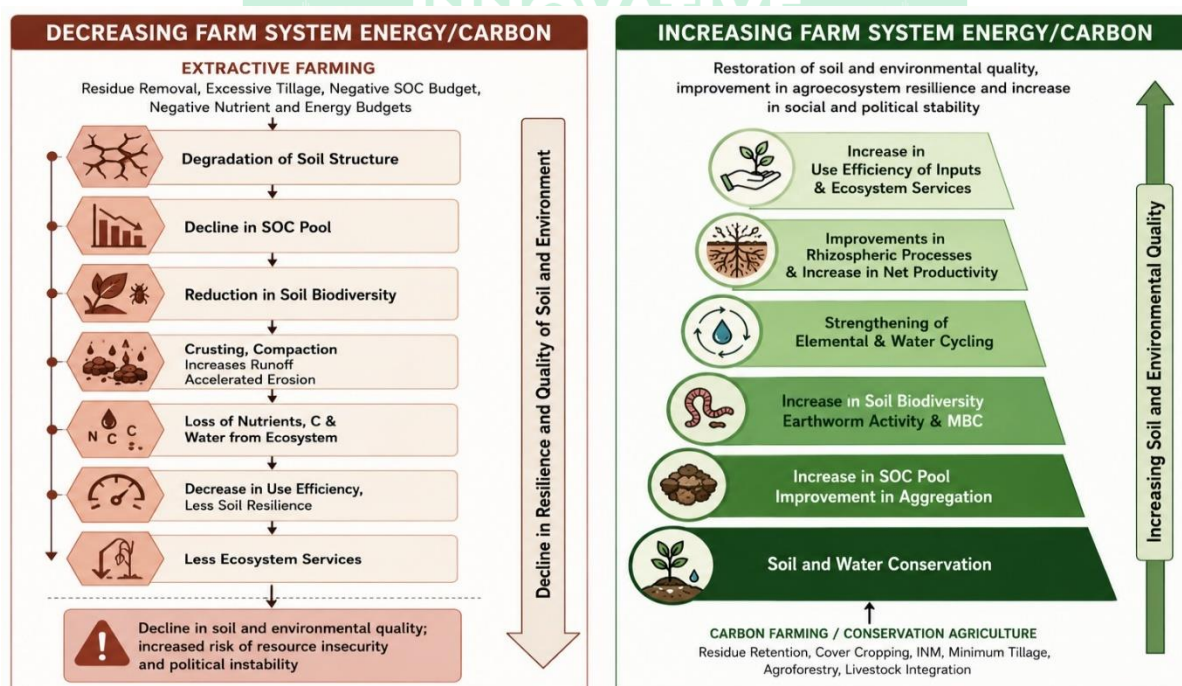


Fig. 1. Increasing and Decreasing of Farm System Energy (Adapted from Rattan Lal 2015)

Carbon farming practices

Carbon farming practices are management practices that are known to sequester carbon and/or reduce GHG emissions. At least thirty-five of these practices are identified by the Natural Resource Conservation Service (NRCS) as conservation practices that improve soil health and sequester carbon while producing important co-benefits, including: increased soil water holding capacity, hydrological function, biodiversity, and resilience.

Table: 1. Practices of Carbon Farming identified by NRCS (Natural Resource Conservation Service)

1	Cover Crop	18	Prescribed Grazing
2	Conservation Crop Rotation	19	Fence (for managed grazing)
3	Residue and Tillage Management -No Till	20	Watering Facility (grazing systems)
4	Residue and Tillage Management- Reduced Till	21	Nutrient Management
5	Residue and Tillage Management - Mulch Till	22	Compost Facility
6	Strip cropping	23	Waste Recycling (organic amendments)
7	Contour Farming	24	Mulching
8	Field Border	25	Irrigation Water Management
9	Filter Strip	26	Tree/Shrub Establishment
10	Grassed Waterway	27	Windbreak/Shelterbelt Establishment
11	Riparian Forest Buffer	28	Hedgerow Planting
12	Riparian Herbaceous Buffer	29	Alley Cropping
13	Critical Area Planting	30	Silvopasture
14	Conservation Cover	31	Forest Farming
15	Forage and Biomass Planting	32	Forest Stand Improvement
16	Range Planting	33	Upland Wildlife Habitat Management
17	Pasture and Hay Planting	34	Wildlife Habitat Planting
35	Wetland Restoration		

Medicinal and Aromatic Plants: A Lucrative Carbon Farming Opportunity

While carbon farming has proven effective across many agricultural systems, medicinal and aromatic plants represent a unique and exceptionally promising opportunity. MAPs are among the highest-value agricultural commodities globally. The world trade in botanicals exceeds US \$32.702 billion annually, with Asian botanical trade accounting for US \$14.505 billion (Riaz et al. 2021) India alone is the second-largest exporter of MAPs with an 8.75% share in Asian trade.

Several factors make MAPs particularly suited for carbon farming:

- 1. High Market Value:** Species like *Withania somnifera* (Ashwagandha), *Ocimum sanctum* (Tulsi), and saffron command premium prices, often ranging from €1,500 to €66,200 per hectare (Macaluso et al. 2024). This economic potential makes the transition to carbon-farming practices economically attractive for farmers, unlike many conventional crops where margins are thin.
- 2. Compatibility with Intercropping:** MAPs integrate exceptionally well with diversified cropping systems. Research demonstrates that intercropping medicinal and aromatic plants with cereals, legumes, and vegetables enhances overall farm productivity while improving essential oil yields and composition (Aćimović et al. 2025). These diverse systems simultaneously maximize carbon sequestration through greater biomass production and microbial activity.
- 3. Adaptability to Agroforestry Systems:** Agroforestry—the deliberate integration of trees, crops, and livestock—represents one of carbon farming's most powerful tools. Studies indicate that even a modest increase in agroforestry coverage (up to 30%) could sequester between 12 to 19 peta-grams of carbon dioxide, with high potential in regions like South America, sub-Saharan Africa, and Southeast Asia (Shuaib et al. 2025). When MAPs are incorporated into agroforestry systems, the carbon sequestration potential multiplies, while trees provide shade, microclimatic regulation, and additional income streams from timber and non-timber forest products.
- 4. Soil Health Enhancement:** The cultivation of medicinal plants specifically requires and promotes superior soil health. Research shows that farms integrating medicinal plants achieve higher species richness, improved biodiversity indices, and enhanced soil health compared to control systems (Kholiya, et al. 2025). This creates a positive feedback loop where healthier soils support higher-quality medicinal plants with superior phytochemical commanding even higher market prices.

Furthermore, medicinal plant cultivation provides income diversification and economic stability that protects farmers from climate variability. When monsoons fail or temperatures fluctuate, diverse MAP cultivation

provides a buffer that pure commodity crops cannot (Mofokeng et al. 2022). This resilience is increasingly critical in a climate-uncertain world.

Table. 2. Carbon accumulation of Various MAPs crop

Crop or practice	Reported carbon result	Interpretation	Reference
Vetiver (<i>Chrysopogon zizanioides</i>)	15.24 t C ha ⁻¹ yr ⁻¹ in shoot and root biomass	Very high biomass-carbon accumulation, particularly useful on degraded land.	Singh et al. 2014
Lemongrass (<i>Cymbopogon flexuosus</i>)	5.38 t C ha ⁻¹ yr ⁻¹ in biomass	Suitable for low-input restoration and aromatic-oil production	Singh et al. 2014
Palmarosa (<i>Cymbopogon martinii</i>)	6.14 t C ha ⁻¹ yr ⁻¹ in biomass	Combines carbon accumulation with essential-oil production	Singh et al. 2014
Aromatic-grass soil carbon	Lemongrass 3.08, palmarosa 2.79, vetiver 5.75 t C ha ⁻¹	Indicates that roots and residue management can build soil carbon in addition to standing biomass.	Yadav et al. 2023
Conservation agriculture generally	Around 0.2–0.5 t C ha ⁻¹ yr ⁻¹ in many dryland or temperate conditions	A realistic planning range for soil-carbon gains from reduced disturbance, cover and residue retention; actual rates depend strongly on climate and	(FAO, 2001)
Global cropland soil-carbon potential	Approximately 0.56–1.15 t C ha ⁻¹ yr ⁻¹ under a substantial increase in soil organic carbon in the 0–30 cm layer	Represents a broad technical potential, not a guaranteed MAP-farm result.	Zomer et al. 2017
Distillation-waste mulch	4.73–7.88 t C ha ⁻¹ reported at about 2.5–5 t residue ha ⁻¹	Shows the value of returning aromatic-crop residues to soil rather than burning or dumping them.	Yadav et al. 2023
Distillation-waste vermicompost	About 0.585 t C ha ⁻¹ in one reported application	Can also improve nutrient cycling and crop productivity.	Yadav et al. 2023
Distillation-waste biochar	Approximately 50–70% of biochar carbon estimated to remain stored for 100 years, depending on biochar properties	Biochar offers more persistent storage than fresh mulch, but results depend on feedstock, pyrolysis and soil	Yadav et al. 2023
Geranium under Egyptian conditions	–375 kg CO ₂ -eq per feddan per season in one 2026 LCA; 1 feddan = 0.42 ha	The reported system was a net sink within the study boundary, although much of the carbon in harvested biomass is temporary rather than permanent.	Hamed et al. 2026
Violet under Egyptian conditions	+15,972 kg CO ₂ -eq per feddan annually	Solvent extraction accounted for 97.3% of reported emissions, demonstrating the importance of low-carbon processing.	Hamed et al. 2026

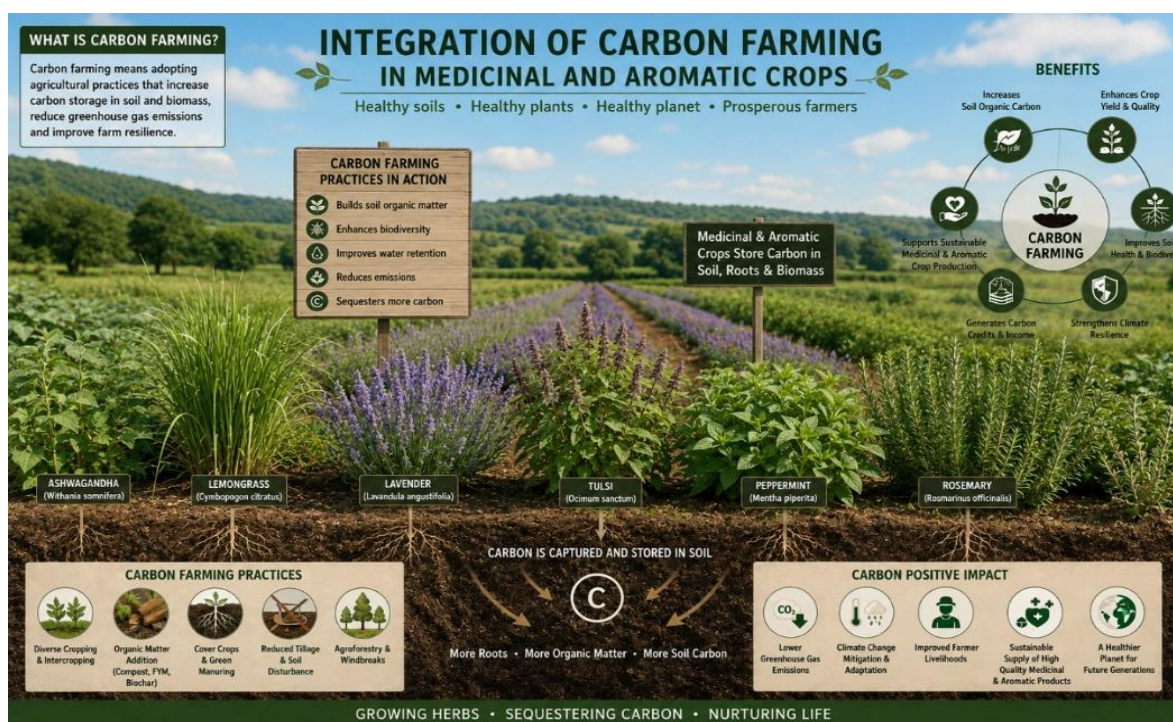


Fig. 2 Integration of Carbon Farming in MAPs Crop (Adapted from Mofokeng et al. 2022)

Recommended field practices in MAPs:

1. Perennial and deep-rooted MAPs

Prioritize perennial, high-biomass species on marginal or degraded land where agronomically appropriate:

- Vetiver for erosion control, mine-affected soils, saline or contaminated sites.
- Lemongrass and palmarosa for aromatic production with relatively low input requirements.
- Geranium, mint, basil, patchouli and other MAPs in rotations or agroforestry systems where market and soil conditions are suitable.

Aromatic grasses can restore degraded land because their dense root systems protect soil, add below-ground carbon and improve aggregation. A review based on 38,600 ha of degraded land in India estimated biomass carbon sequestration of roughly 0.208–0.588 million tonnes C and soil-carbon sequestration of about 0.108–0.222 million tonnes C across the assessed crop scenarios. (Yadav et al. 2023)

2. Minimum soil disturbance

Use minimum tillage or no-tillage where planting method, weed pressure and crop establishment permit it. Reduced disturbance:

- Lowers tractor fuel use.
- Reduces erosion and loss of soil organic matter.
- Protects soil aggregates and fungal networks.
- Helps retain root-derived carbon.

FAO recommends combining minimum disturbance with permanent soil cover and crop diversification; carbon accumulation is usually greatest during the first 5–20 years, then slows as the soil approaches a new equilibrium. (FAO, 2001)

3. Permanent soil cover

Maintain at least 30% organic soil cover using crop residues, living cover crops, green manure or mulch. In MAP fields, suitable options may include:

- Legume cover crops during establishment or between rows.
- Residues from mint, lemongrass, palmarosa or other non-diseased crops.
- Straw, leaves or locally available composted organic material.

- Mulch on sloping land and around perennial plants.

Do not burn residues. Burning rapidly returns much of the carbon to the atmosphere and removes nutrients that could otherwise support soil organic matter. (Marcelino et al. 2023)

4. Intercropping and agroforestry

Combine MAPs with nitrogen-fixing crops, trees or compatible food crops where competition for light, water and nutrients is manageable. Intercropping can increase total biomass input, reduce erosion and diversify farmer income. Evidence from MAP systems reports increased soil organic carbon in combinations involving crops such as *Aloe vera*, *Artemisia pallens*, *Piper longum* and *Bacopa monnieri*, although results vary by species and management. (Golijan & Marković 2018) Agroforestry is especially relevant for shade-tolerant medicinal plants such as turmeric, ginger, long pepper and some understory herbs. Tree roots and litter add a longer-lived carbon pool, while MAPs provide shorter-term income.

5. Organic amendments and biochar

Use composted manure, vermicompost and processed distillation residues based on soil-test requirements. Distillation residues are carbon-rich: reported solid residues contain approximately 36–40% carbon. (Yadav et al. 2023)

Recommended hierarchy:

1. Return clean, disease-free residue as mulch where decomposition and phytotoxicity are acceptable.
2. Compost or vermicompost residue to stabilize nutrients and reduce waste.
3. Convert a suitable fraction into biochar using controlled pyrolysis.
4. Apply biochar together with nutrient sources when soil tests show a need.

Biochar should not be applied automatically. Check its pH, electrical conductivity, contaminants, maturity and carbon stability. FAO notes that biochar performance varies by feedstock and soil, and that excessive alkalinity or poor-quality material can create agronomic problems. (FAO, 2001)

6. Water, nutrients and energy

Efficient irrigation

Use drip or micro-irrigation, soil-moisture scheduling and rainwater harvesting where feasible. Efficient irrigation reduces pumping emissions and may improve water productivity without lowering oil or biomass yield. Avoid excessive irrigation because it can increase energy use, nutrient leaching and, in poorly aerated soils, nitrous-oxide emissions. Irrigation should be matched to crop growth stage, soil moisture and weather conditions. (Marcelino et al. 2023)

7. Nitrogen management

Use integrated soil-fertility management:

- Base fertilizer rates on soil and plant testing.
- Apply nitrogen in split doses synchronized with crop demand.
- Combine compost or vermicompost with reduced mineral fertilizer rather than applying both indiscriminately.
- Use legumes or green manures where compatible.
- Avoid excess nitrogen, which increases production emissions, nitrate losses and nitrous oxide.

8. Low-carbon drying and distillation

Processing can eliminate the carbon benefit of field production if it relies on inefficient fossil-fuel systems. Priorities include:

- Solar drying or well-designed solar-assisted dryers.
- Biomass boilers using genuinely sustainable residues rather than forest wood.
- Solar thermal steam generation for essential-oil distillation.
- Biogas heat from anaerobic digestion of suitable organic waste.
- Heat recovery from stills and insulated distillation equipment.
- Short transport distances between field and distillation unit.
- Moisture reduction before transport, where this does not compromise oil quality.

The 2026 geranium–violet LCA illustrates this contrast: geranium was reported as a small net sink, while violet became a large net source because solvent extraction generated most of its emissions. The study model solar thermal or biogas heat as options capable of reducing violet’s extraction emissions by approximately 50–100%. (Hamed et al. 2026)

Conclusion

Carbon farming in aromatic and medicinal plants is a potent way to rebuild ecosystems and generate new revenue. MAPs farmers may enhance soil health, fortify climate resilience, and boost their earnings by integrating sustainable production, carbon sequestration, biodiversity conservation, and fair value chains. This revolution demonstrates that when agriculture is managed by innovation, traditional knowledge, and conscientious stewardship, both income growth and environmental healing can coexist.

References

- Riaz, U., Iqbal, S., Sohail, M. I., Samreen, T., Ashraf, M., Akmal, F., ... & Akhter, R. M. (2021). A comprehensive review on emerging importance and economical potential of medicinal and aromatic plants (MAPs) in current scenario.
- Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), 5875-5895.
- Singh, R., Kumar, P., Kumari, P., Singh, P., Basu, S., Kumar, V., ... & Jha, S. (2026). Carbon Sequestration Potential of Agronomic Practices in Agricultural Soil: A Review. *International Journal of Environment and Climate Change*, 16(4), 839-858.
- Macaluso, D., Licciardo, F., & Carbone, K. (2024). Farming of medicinal and aromatic plants in Italy: structural features and economic results. *Agriculture*, 14(1), 151.
- Aćimović, M., Navarro Rocha, J., Ibraliu, A., Červenski, J., Sikora, V., Winter, S., ... & Salamon, I. (2025). Intercropping medicinal and aromatic plants with other crops: Insights from a review of sustainable farming practices. *Agronomy*, 15(12), 2692.
- Shuaib, M. B., Sauwa, M. M., Adigwe, F. A., Afolabi, A. E., & Musah, M. (2025). Agroforestry and soil carbon sequestration: Interlinkages with soil health and climate change mitigation. *International Journal of Sustainable Agricultural Research*, 12(4), 241-251.
- Kholiya, D., Uttam, L.D., Rajan, P., Sharma, S., Manjeet, Jain, G., Bhandari, A., Kaur, D.P., (2025) Integrating Medicinal Plant Cultivation into Agroforestry Systems for Biodiversity and Income Generation. *Journal of Neonatal Surgery*, 14 (22s), 944-953.
- Mofokeng, M. M., Du Plooy, C. P., Araya, H. T., Amoo, S. O., Mokgehle, S. N., Pofu, K. M., & Mashela, P. W. (2022). Medicinal plant cultivation for sustainable use and commercialisation of high-value crops. *South African Journal of Science*, 118(7-8), 1-7.
- Hamed, S.A., Abo-Karima, M.K., Ali, G., Elmessery, W.M., Elwakeel, A.E., Ahmed, A.F., Al-Harbi, M.S., Abouelatta, A.M., (2026) Medicinal and aromatic plants as climate-smart crops: case studies on Pelargonium graveolens and Viola odorata under Egyptian conditions. *Sci Rep*. Mar 4;16(1):12159. doi: 10.1038/s41598-026-43039-0. PMID: 41781466; PMCID: PMC13076789.
- Yadav, D., Yadav, A., Singh, M. et al. Cultivation of aromatic plant for nature-based sustainable solutions for the management of degraded/marginal lands: techno-economics and carbon dynamic. *Carbon Res*. 2, 27 (2023). <https://doi.org/10.1007/s44246-023-00055-3>
- Zomer, R.J., Bossio, D.A., Sommer, R. et al. Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Sci Rep* 7, 15554 (2017). <https://doi.org/10.1038/s41598-017-15794-8>
- Singh, M., Guleria, N., Prakasa Rao, E.V.S. et al. Efficient C sequestration and benefits of medicinal vetiver cropping in tropical regions. *Agron. Sustain. Dev.* 34, 603–607 (2014). <https://doi.org/10.1007/s13593-013-0184-3>
- Marcelino, S., Hamdane, S., Gaspar, P. D., & Paço, A. (2023). Sustainable Agricultural Practices for the Production of Medicinal and Aromatic Plants: Evidence and Recommendations. *Sustainability*, 15(19), 14095. <https://doi.org/10.3390/su151914095>
- Golijan Pantović, J., & Marković, D. (2018). The benefits of organic production of medicinal and aromatic plants in intercropping system. *Acta Agriculturae Serbica*, 23(45), 61-76.

Black Soldier Fly Larvae Meal as a Sustainable Alternative to Fishmeal in Aquaculture



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Abstract

Black soldier fly (BSF) larvae (*Hermetia illucens*) are gaining attention as a sustainable alternative protein source for aquaculture feed. The increasing cost and limited availability of fishmeal and fish oil have created a need for alternative feed ingredients. This paper reviews the nutritional value, life cycle, and potential use of BSF larvae in fish and shellfish diets. BSF larvae contain high levels of protein, lipids, amino acids, calcium, and phosphorus, and can be produced using organic wastes such as food waste, animal manure, and agricultural by-products. Studies have shown that BSF meal can partially or, in some fish species, substantially replace fishmeal without negatively affecting growth, feed utilization, or survival. In shrimp, moderate inclusion levels of BSF meal have also shown positive effects on growth and body nutrient composition. Therefore, BSF larvae have strong potential as a cost-effective and environmentally friendly feed ingredient for sustainable aquaculture while also contributing to organic waste management and resource recycling.

Keywords: Black soldier fly, aquaculture

Introduction

Aquaculture has been growing rapidly worldwide and plays an important role in meeting the increasing demand for food (FAO 2018). However, the availability of fishmeal and fish oil, which are commonly used in aquaculture feeds, is decreasing (Tschirner *et al.*, 2017). Their limited availability increases feed costs and may negatively affect wild fish populations, creating economic and environmental concerns for sustainable aquaculture (FAO 2016). To reduce the dependence on fishmeal and fish oil, researchers have investigated various plant- and animal-based protein sources, including soybean meal, bean meal, sunflower meal, slaughterhouse waste, agricultural by-products, Azolla, and black soldier fly (BSF) pre-pupae (Audu *et al.*, 2010; Goda *et al.*, 2007; Booth and Sheppard, 1984). However, plant-based ingredients may not provide sufficient essential nutrients for carnivorous fish and may therefore have limited nutritional value in their diets (Naylor *et al.*, 2000).

Insects are considered promising alternative protein sources for aquaculture because they contain high levels of protein, amino acids, fats, and minerals (Veldkamp *et al.*, 2012; Van Huis *et al.*, 2013; Bosch *et al.*, 2014). Several insect species, including black soldier fly (BSF) (*Hermetia illucens*), housefly (*Musca domestica*), and mealworm (*Tenebrio molitor*), can convert organic waste into valuable nutrients (Newton *et al.*, 2005; Li *et al.*, 2013). Among these insects, BSF larvae are considered particularly suitable for aquaculture feed because of their rapid growth, high feeding capacity, and ability to convert different organic wastes into nutrient-rich biomass (Kim *et al.*, 2011;). BSF larvae are easy to rear, require simple production systems, and are not considered major pests or disease vectors. They can also help reduce harmful bacteria in organic waste and may provide beneficial effects on fish health (Erickson *et al.*, 2004). BSF larvae can feed on a wide range of organic materials, including kitchen waste, animal manure, slaughterhouse by-products, and agricultural waste (Diener *et al.*, 2009). They are also nutritionally rich, containing approximately 40–45% protein, 30–35% fat, 11–15% ash, 4.8–5.1% calcium, and 0.6% phosphorus on a dry-matter basis, along with various amino acids and minerals (Yu and Chen, 2009). Several studies have successfully used BSF larvae as feed for fish such as rainbow trout, catfish, and tilapia, as well as for poultry and swine (Bondari and Sheppard, 1987; Yu and Chen, 2009).

Therefore, BSF larvae have considerable potential as a sustainable and cost-effective alternative protein source for aquaculture feed while also contributing to organic waste management and resource utilization.

Black Soldier Fly Larvae

The adult *H. illucens* is about 16 mm long and has a black body with blue-green metallic reflections on the thorax. In some individuals, the abdomen may have reddish markings. The second abdominal segment has translucent

patches. The fly has a broad head, well-developed eyes, and antennae that are about twice as long as the head. Its legs are black with whitish-colored feet (tarsi). The wings are transparent and membranous, and when the fly is at rest, they fold horizontally over the abdomen and overlap each other.



Life Cycle



Black soldier fly life cycle

about 25 mm in length and 0.22 g in weight. The larval stage generally lasts 18–36 days, depending on the type of food substrate and temperature. After the larval stage, the insect enters the pre-pupal stage, which lasts up to 7 days, followed by the pupal stage, which lasts about 1–2 weeks. Adult flies may live for 47–73 days when provided with water and sugar in captivity, while in the wild they feed mainly on nectar.

The Nutritional Profile of Black Soldier Fly

Black soldier fly (BSF) larvae are a rich source of nutrients, containing about 42.1% crude protein, while defatted BSF larvae can contain up to 56.9% crude protein (Makkar *et al.*, 2014). This protein content is similar to that of soybean meal and only slightly lower than that of fishmeal. Depending on the processing method, BSF protein meal may contain about 3.4–38.6% lipid on a dry-matter basis. BSF larvae also have a favorable amino acid profile compared with soybean meal, making them a potential alternative to fishmeal (Tran *et al.*, 2015). Before processing into protein meal, some of the oil may be removed from the larvae (Stamer, 2015). BSF larvae are also rich in minerals such as ash, calcium, and phosphorus, with nutrient levels varying according to their growth stage. For better storage, BSF larvae should be kept at around 10–16°C (50–60°F); at room temperature, they can generally be stored for several weeks.

Black Soldier Fly Larvae as the Feed for the Finfishes

Studies have shown that black soldier fly (BSF) larvae can be successfully used as a feed ingredient for different fish species. In Atlantic salmon (*Salmo salar*), replacing 25%, 50%, or even 100% of fishmeal with BSF meal resulted in good growth and feed utilization, with no major differences in the quality of the fish fillets. Blue tilapia

An adult female *H. illucens* can lay about 206–639 eggs at a time. The eggs are usually laid in cracks or on surfaces near decaying organic matter, such as manure or compost. The eggs hatch into larvae within 3–4 days. Newly hatched larvae are about 1 mm long and weigh approximately 0.1 g. As they grow, they can reach

fed chopped BSF larvae also showed good aroma and texture, and the product was well accepted by consumers (Bondari and Sheppard, 1981). In *Pangasius hypophthalmus*, complete replacement of fishmeal with BSF larvae meal has also been reported (Henry *et al.*, 2015). Similarly, feeding trials with BSF larvae meal in Bala shark (*Balantiocheilus melanopterus*) resulted in good growth, survival, and improved endurance. These findings indicate that BSF larvae can be a useful alternative protein source in fish diets.

Black Soldier Fly Larvae as the Feed for the Shellfishes

Pacific white shrimp (*Litopenaeus vannamei*) showed good weight gain, specific growth rate, and feed conversion ratio when less than 25% of the fishmeal was replaced with black soldier fly (BSF) meal. The use of BSF meal at levels below 29% and 15% also improved the protein and lipid content of the shrimp body, respectively. These results suggest that BSF meal can be a suitable alternative protein source for shrimp feed when used at appropriate inclusion levels.

Conclusion

Black soldier fly (BSF) larvae (*Hermetia illucens*) are a promising sustainable alternative to fishmeal and fish oil in aquaculture feeds. Their high protein, amino acid, lipid, and mineral content, combined with their ability to convert organic waste into valuable biomass, provides both nutritional and environmental benefits. Studies in fish and shrimp have shown that BSF meal can support good growth, feed efficiency, and survival when included at appropriate levels. Therefore, BSF larvae have strong potential to reduce dependence on conventional marine protein sources, lower feed costs, and promote sustainable aquaculture and organic waste utilization. Further research is needed to determine optimum inclusion levels for different aquatic species.

References

- Audu, B., Adamu, K., & Binga, S. (2010). The Effect of Substituting Fishmeal Diets with Varying Quantities of Ensiled Parboiled Beniseed (*Sesamum indicum*) and Raw African Locust Bean (*Parkia biglobosa*) on the Growth Responses and Food Utilization of the Nile Tilapia *Oreochromis niloticus**. *International Journal of Zoological Research*, 6(4), 334–339. <https://doi.org/10.3923/ijzr.2010.334.339>
- Booth, D. C., & Sheppard, C. (1984). Oviposition of the Black Soldier Fly, *Hermetia illucens* (Diptera: Stratiomyidae): Eggs, Masses, Timing, and Site Characteristics. *Environmental Entomology*, 13(2), 421–423. <https://doi.org/10.1093/ee/13.2.421>
- Bosch, G., Zhang, S., Oonincx, D. G. a. B., & Hendriks, W. H. (2014). Protein quality of insects as potential ingredients for dog and cat foods. *Journal of Nutritional Science*, 3, e29. <https://doi.org/10.1017/jns.2014.23>
- Diener, S., Zurbrugg, C., Gutiérrez, F.R., Nguyen, D.H., Morel, A., Koottatep, T., and Tockner, K. (2011). Black soldier fly larvae for organic waste treatment—prospects and constraints. *Proceedings of the WasteSafe*. 2: 13–15. <https://doi.org/10.1007/s12649-011-9079-1>
- Erickson, M.C., Islam, M., Sheppard, C., Liao, J., and Doyle, M.P. (2004). Reduction of *Escherichia coli* O157:H7 and *Salmonella enterica* serovar enteritidis in chicken manure by larvae of the black soldier fly. *Journal of Food Protection*. 67: 685–690. <https://doi.org/10.4315/0362-028X-67.4.685>
- FAO. La Situation Mondiale Des Pêches et de L'aquaculture 2018. Atteindre les Objectifs de Développement Durable; FAO: Rome, Italy, 2018; ISBN 978-92-5-130692-5.
- FAO. The State of World Fisheries and Aquaculture; FAO: Rome, Italy, 2016; ISBN 9789252091851.
- Goda, A. M., El-Haroun, E. R., & Chowdhury, M. a. K. (2007). Effect of totally or partially replacing fish meal by alternative protein sources on growth of African catfish *Clarias gariepinus* (Burchell, 1822) reared in concrete tanks. *Aquaculture Research*, 38(3), 279–287. <https://doi.org/10.1111/j.1365-2109.2007.01663.x>
- Henry, M., Gasco, L., Piccolo, G., Fountoulaki, E., 2015. Review on the use of insects in the diet of farmed fish: Past and future. *Anim Feed Sci Technol* 203, 1–22. DOI: <https://doi.org/10.1016/j.anifeedsci.2015.03.001>
- Jeyaprakashabari S. and Aanand S. (2021) Black Soldier Fly Larvae Meal in Fish Culture.
- Kim, W., Bae, S., Kim, A., Park, K., Lee, S., Choi, Y., Han, S., Park, Y., and Koh, Y. (2011). Characterization of the molecular features and expression patterns of two serine proteases in *Hermetia illucens* (Diptera: Stratiomyidae) larvae. *BMB Reports*. 44: 387. <https://doi.org/10.5483/BMBRep.2011.44.6.387>

- Li, L., Zhao, Z., and Liu, H. (2013). Feasibility of feeding yellow mealworm (*Tenebrio molitor* L.) in bioregenerative life support systems as a source of animal protein for humans. *Acta Astronautica*, 92: 103-109. <https://doi.org/10.1016/j.actaastro.2012.03.012>
- Makkar, H. P., Tran, G., Heuzé, V., & Ankers, P. (2014). State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology*, 197, 1–33. <https://doi.org/10.1016/j.anifeedsci.2014.07.008>
- Naylor, R. L., Goldburg, R. J., Primavera, J. H., Kautsky, N., Beveridge, M. C. M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., & Troell, M. (2000). Effect of aquaculture on world fish supplies. *Nature*, 405(6790), 1017–1024. <https://doi.org/10.1038/35016500>
- Newton, L., Sheppard, C., Watson, D.W., and Burtle, G. (2005). Using the black soldier fly, *Hermetia illucens*, as a value-added tool for the management of swine manure. Report for Mike Williams, Director of the Animal and Poultry Waste Management Centre, North Carolina State University, <http://tinyurl.com/mxam64v>
- Stamer, A. (2015). Insect proteins—a new source for animal feed. *EMBO Reports*, 16(6), 676–680. <https://doi.org/10.15252/embr.201540528>
- Tran, G., Heuzé, V. and Makkar, H.P.S., 2015. Insects in fish diets. *Animal Frontiers*, 5(2), pp.37-44.
- Tschirner, M.; Kloas, W. Increasing the Sustainability of Aquaculture Systems: Insects as Alternative Protein Source for Fish Diets. *GAIA Ecol. Perspect. Sci. Soc.* 2017, 26, 332–340.
- Van Huis, A., Van Itterbeeck, J., Klunder, H. C., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). Edible insects: future prospects for food and feed security. In *Socio-Environmental Systems Modeling* (Issue 171). <https://research.wur.nl/en/publications/edible-insects-future-prospects-for-food-and-feed-security>
- Veldkamp, T., Van Duinkerken, G., Van Huis, A., Lakemond, C., Ottevanger, E., Bosch, G., & Van Boekel, T. (2012). Insects as a sustainable feed ingredient in pig and poultry diets : a feasibility study = Insecten als duurzame diervoedergrondstof in varkens- en pluimveevoeders : een haalbaarheidsstudie. In *Socio-Environmental Systems Modeling*. <https://research.wur.nl/en/publications/insects-as-a-sustainable-feed-ingredient-in-pig-and-poultry-diets>
- Yu G-H, Chen, Y-H 2009: Research progression on the larvae and prepupae of black soldier fly *Hermetia illucens* used as animal feedstuff. *Chinese Bulletin of Entomology*, 46(1):41-45.

Soybean Story: A Global Superhero and its Soil Microbe Partners and sustainable practices for healthy soil



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1. The Power of a Single Bean: Why Soybean rules the world

The soybean (*Glycine max*) is far more than just a staple food of global trade: it is a biological marvel that anchors our modern food system. Its dominance is not accidental. The soybean has risen to become a “tropical giant” because it offers a unique combination of versatility and high-density notations that few other plants can’t match. Whether it is providing high quality protein for human diet and supplements, severing as the primary fuel for the worlds’ livestock or being utilized in aquaculture and biofuels, the soybean is central to human welfare.

What truly distinguishes soybean from other major global crops is its status as a “protein giant.” While many other crops provide energy in the form of starch or oil, the soybean provides a massive amount of both protein and oil, dominating entire protein category.

Nutritional Profile: Soybean vs. other Food Legumes

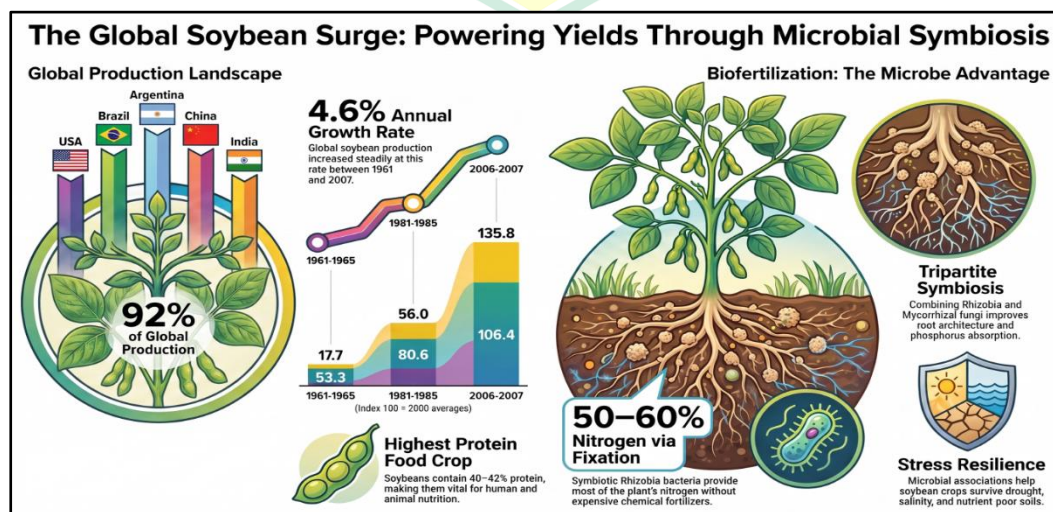
As a farmer, student and as an agriculture researcher, it is important to understand the tradeoffs between different crops. The following table illustrates why the soybean is the undisputed leader in protein content among food crops.

Crop	Protein Content	Oil Content	Primary Strength
Soybean	40–42%	18–22%	Highest protein of all food crops
Groundnut	Lower than Soybean	>22%	Leader in oil content among food legumes

The soybean is a “microbial superhero.” Among the world’s most cultivated crops like, maize, rice and wheat. The soybean is the only one capable of forming symbiotic partnership with both nitrogen fixing bacteria and specialized fungi. This double partnership is the secret to its global success.

USA, Brazil, Argentina, China and India just these five nations produce more than 92% of the world’s supply. In Brazil, technological advances have allowed the soybean to thrive in the Cerrado grasslands, proving that with the right science, this crop can transform vast landscapes into productive agriculture hubs.

To understand how a single bean can produce such high protein yields without exhausting the earth, we must look beneath the surface at the tiny biological engines living in its roots.



2. Nature's Nitrogen Factory: The secret life of Rhizobia

The soybean's success is fueled by a microscopic partnership happening in the soil. Soybean belongs to the legume family, which gives them the rare ability to team-up with "helpful bacteria" known as Rhizobia (specifically the species *Bradyrhizobium japonicum*). These bacteria live in small, round growths on the soybean roots called nodules. Inside these nodules, a process called Biological Nitrogen Fixation (BNF) takes place. This is a perfect winning partnership.

- **The bacteria's job:** they take atmospheric nitrogen gas (N_2) from the air, a resource that plants cannot access on their own—and convert it into a form the plant can use for growth.
- **The plant's job:** In exchange for the nitrogen, the soybean provides the bacteria with a safe home and energy in the form of carbohydrates produced through photosynthesis.

Why Biology Beats Chemicals

While farmers can add nitrogen to soil using chemical fertilizers, relying on Rhizobia is a more sustainable and scientifically sound choice.

- **Cost effectiveness:** Biological nitrogen is a significantly less expensive source of nutrients for farmers than purchasing industrial chemical N.
- **Environmental Protection:** Chemical nitrogen can run off into water sources or release greenhouse gases during production. BNF is a clean, natural process.
- **High Efficiency:** These tiny bacteria can naturally provide 50-60% of the soybean plant's total nitrogen needed.

While these bacteria provide the fuel for growth, another hidden partner helps the soybean explore the soil for other essential resources.

3. The Hidden Underground web: Arbuscular Mycorrhizal (AM) Fungi

While Rhizobia handle the nitrogen, a second group of microbes called Arbuscular Mycorrhizal (AM) fungi acts as a support system for the plant's roots. These fungi grow microscopic, hair-like threads called hyphae that extend far beyond the reach of the plant's own root system. This creates a "tripartite association," a three-way team consisting of the Plant, the Bacteria, and the Fungi. This is not a one-sided deal; the AM fungi receive up to 20% of the plant's photosynthetic carbon in exchange for their services.

- **The tripartite association: synergistic mechanisms**

Strategic investment is shifting towards the "Tripartite Association" (Soybean + Rhizobia + AM Fungi) often enhanced by plant growth promoting Rhizobacteria (PGPR). The value added by a consortium containing *Pseudomonas* (e.g., strain 54RB) and *Bacillus* (e.g., *B. thuringiensis* NEB17) is driven by specific biological mechanisms.

- **Combating Abiotic and Biotic Stresses**

When soybeans, Rhizobia, and AM fungi work together, the plant becomes far more resilient. This trio helps the soybean survive Abiotic Stresses (environmental factors like drought and poor soil quality) and Biotic stresses (living threats like pests and diseases). These fungi also produce glomalin, a substance often called "soil glue." Glomalin sticks soil particles together, creating a healthy soil structure that holds water better and prevents erosion. By managing these natural biological partnerships, we can find better ways to meet the massive challenges of the coming decades.

4. Feeding the future: sustainable farming and science

The demand for soybeans is growing, but we are currently facing the "2050 Challenge." Current data shows that soybean production is increasing by about 1.3% per year. However, agricultural scientists warn that this growth rate is not at the level essential for providing people with their food by 2050. To close this gap sustainably, we use Inoculants (also called Biofertilizers). These are products containing high-quality strains of helpful bacteria and fungi that farmers add to their seeds or soil. This "natural boost" improves yields while protecting the environment from excessive chemical use.

Sustainable Practices for Healthy Soil

- **No Tillage:** By not plowing the earth, farmers reduce soil erosion, save fuel, and keep more carbon in the ground, which supports microbial life.

- **Crop Rotation:** Alternating soybeans with crops like maize or wheat prevents the soil from becoming exhausted and helps maintain a diverse community of helpful soil microbes.
- **Biochar:** This specialized charcoal added to the soil can increase nutrient retention and provide a perfect habitat for beneficial bacteria to thrive.

5. Conclusion: Our Role in Soybean Revolution

The story of the soybean is a powerful reminder that food production is about much more than just seeds and tractors; it is about managing a complex, living ecosystem hidden beneath our feet. By protecting "nature's tiny helpers" the rhizobia and AM fungi we can support human welfare while ensuring the long term health of our planet.



When veterinary drugs become a food-safety threat: Understanding prohibited drugs and drug residues



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Abstract

Veterinary drugs are essential for maintaining animal health, preventing disease and supporting efficient livestock and poultry production. However, inappropriate use of veterinary medicines can result in residues of parent drugs, metabolites or degradation products in animal-derived foods such as meat, milk, eggs, honey and fish. When residues exceed permissible limits or involve substances prohibited for use in food-producing animals, they may pose significant food-safety and public-health risks. Major concerns associated with certain residues include toxicological, pharmacological, allergic, genotoxic and carcinogenic effects, as well as antimicrobial resistance (AMR). Important prohibited or restricted substances include chloramphenicol, nitrofurans, nitroimidazoles, clenbuterol, malachite green, colistin and other specified veterinary drugs. In India, the Food Safety and Standards Authority of India (FSSAI) regulates veterinary drug residues through the *Food Safety and Standards (Contaminants, Toxins and Residues) Regulations, 2011* and subsequent amendments. Adherence to prescribed withdrawal periods, responsible drug use and proper veterinary supervision are essential to prevent residues from entering the food chain. Residue monitoring involves rapid screening methods followed by confirmatory techniques such as HPLC, LC-MS/MS and GC-MS/MS. Since antimicrobial use in animals can contribute to the emergence and dissemination of resistant microorganisms, veterinary drug residues and AMR represent interconnected One Health concerns. Strengthening antimicrobial stewardship, farmer education, veterinary services, regulatory enforcement and residue surveillance is therefore essential to ensure food safety while protecting animal, human and environmental health.

Key words: Drugs, Antimicrobial resistance, Maximum residue limits, FSSAI, Pharmacological, Extraneous maximum residue limit (EMRL)

The health of humans is closely linked to the safety and quality of the food they consume. In modern livestock and poultry production, veterinary drugs are widely used for the prevention and treatment of diseases and, in some production systems, for improving animal productivity. These drugs include antibiotics, antiparasitic drugs, anti-inflammatory agents and other therapeutic substances. Following treatment, residues of these drugs or their metabolites may remain in animal-derived foods such as meat, milk, eggs, honey and edible organs. When these residues exceed permissible limits, they may pose risks to consumers and become an important food-safety and public-health concern.

The occurrence of veterinary drug residues is influenced by several factors, including the pharmacological properties and pharmacokinetics of the drug, dosage, route of administration, frequency and duration of treatment, animal species, age and physiological condition, and the method of processing or storage of animal products. One of the major causes of excessive residues is inappropriate use of veterinary medicines, particularly failure to observe the recommended withdrawal period.

Antimicrobial drugs have played a major role in improving animal health and productivity. However, their inappropriate and excessive use has contributed to the development and spread of antimicrobial resistance (AMR). Therefore, veterinary drug residues and antimicrobial resistance are closely connected issues within the One Health framework, as they involve animal health, human health, food safety and the environment.

Drug Residues

Veterinary drug residues refer to the parent drug or its metabolites and degradation products that remain in edible tissues or products of animals after administration of a veterinary medicinal product. Residues may occur in meat, liver, kidney, milk, eggs, honey and other products of animal origin.

More than 200 veterinary drug residues belonging to different pharmacological groups have been reported in food matrices. Important groups include:

- Antimicrobials/antibiotics – tetracyclines, sulfonamides, β -lactams, macrolides, aminoglycosides and quinolones.
- Antiparasitic drugs – anthelmintics and anticoccidial drugs.
- Anti-inflammatory drugs – particularly non-steroidal anti-inflammatory drugs.
- Hormonal and growth-promoting substances – used in some livestock production systems.
- Other therapeutic agents used for disease prevention and treatment.

Residues may enter food when drugs are administered at inappropriate doses, administered through an incorrect route, used for an unapproved indication, or when the recommended withdrawal period is not followed. The withdrawal period is the minimum time that must elapse between the last administration of a veterinary drug and the production of food for human consumption. It allows the drug concentration in edible tissues or products to decline to an acceptable level.

The safety of food containing veterinary drug residues is assessed using concepts such as the maximum residue limit (MRL), which is the highest concentration of a veterinary drug residue legally permitted in a particular food commodity when the drug has been used according to good veterinary practice.

Veterinary drug residues are important from a public-health perspective because humans may be repeatedly exposed to them through contaminated food. The effects depend on the type of drug, concentration of the residue, frequency and duration of exposure, and susceptibility of the individual.

Excessive or prolonged exposure to certain residues may result in:

- Allergic or hypersensitivity reactions, particularly with some antimicrobial drugs.
- Toxic effects resulting from exposure to pharmacologically active compounds.
- Development or selection of antimicrobial-resistant microorganisms.
- Disruption of normal intestinal microbial flora.
- Potential mutagenic, teratogenic or carcinogenic effects for certain substances.
- Economic losses associated with rejection or disposal of contaminated animal products.

Milk, meat and eggs are particularly important sources because they are consumed frequently and in large quantities. Therefore, even relatively low concentrations of residues may become important when exposure occurs repeatedly.

Antimicrobial resistance (AMR) occurs when microorganisms such as bacteria, parasites, fungi or viruses develop the ability to survive or grow in the presence of medicines that would normally inhibit or kill them. Antimicrobials are essential for the treatment and prevention of infectious diseases in livestock and poultry. However, excessive, unnecessary or inappropriate use can create selective pressure that favours resistant microorganisms. Resistant bacteria may persist in animals and their environment and can subsequently spread through several pathways.

Resistant microorganisms or resistance genes may reach humans through consumption of contaminated animal products, direct contact with infected or colonized animals, contaminated water and environmental exposure. Thus, antimicrobial use in food-producing animals can contribute to the wider AMR problem.

This makes AMR a One Health problem, requiring coordinated action involving veterinary medicine, human medicine, food production and environmental health. Measures such as antimicrobial stewardship, appropriate diagnosis, responsible prescribing, vaccination, improved farm hygiene, biosecurity and adherence to withdrawal periods can help reduce unnecessary antimicrobial use.

Detection of veterinary drug residues is an essential component of food-safety surveillance. Testing helps determine whether residues are present and whether their concentrations are within the permitted limits. Residue detection generally involves two major stages:

a. Screening methods- Screening tests are used to rapidly identify samples that may contain residues. They are generally inexpensive, rapid and suitable for testing large numbers of samples. Examples include:

- Microbial inhibition tests
- Enzyme-linked immunosorbent assays (ELISA)
- Receptor-based assays

- Rapid immunochromatographic tests

A positive screening result usually requires confirmation using a more specific analytical method.

b. Confirmatory methods- Confirmatory methods provide accurate identification and quantification of specific drugs or their metabolites. Common techniques include:

- High-performance liquid chromatography (HPLC)
- Liquid chromatography–mass spectrometry (LC-MS/MS)
- Gas chromatography–mass spectrometry (GC-MS/MS)
- Other validated chromatographic and mass-spectrometric techniques

Samples may be collected from meat, liver, kidney, milk, eggs, honey and other animal products. Appropriate sampling, extraction, purification and validation of analytical methods are important for obtaining reliable results. Residue-monitoring programmes should compare detected concentrations with established maximum residue limits (MRLs). Samples exceeding the applicable limit may indicate improper drug use, failure to observe withdrawal periods or other problems in veterinary drug management.

Veterinary medicines are indispensable for maintaining animal health, preventing disease and supporting efficient livestock and poultry production. However, their use must be balanced against the potential risks associated with drug residues and antimicrobial resistance.

The occurrence of residues is not necessarily an indication that veterinary medicines have been used incorrectly. When medicines are used according to approved dosage, route, duration and withdrawal period, residues are generally expected to decline to safe levels before the animal product enters the food chain. The major concern arises when drugs are used indiscriminately or when recommended withdrawal periods are ignored.

The problem is particularly challenging in developing countries because of limited residue-monitoring facilities, inadequate regulatory systems, unrestricted access to veterinary medicines, insufficient awareness among farmers and inappropriate prescribing or administration practices. Strengthening veterinary services, improving farmer education, enforcing regulations and establishing effective residue-monitoring programmes are therefore important strategies for protecting food safety.

Overall, veterinary drug residues, antimicrobial resistance and food safety are interconnected. A comprehensive approach based on responsible veterinary drug use, adherence to withdrawal periods, surveillance of residues, antimicrobial stewardship and One Health collaboration is essential for protecting animal health, human health and the environment.

Prohibited Drugs in Food-Producing Animals: From Farm to Fork

Veterinary medicines play an essential role in protecting animals from infectious and non-infectious diseases and maintaining their health and productivity. However, when certain medicines are used in food-producing animals inappropriately or when prohibited substances are used, their residues may remain in meat, milk, eggs, fish and other products entering the human food chain. This makes the responsible use of veterinary medicines an important issue not only for animal health, but also for food safety and public health.

A veterinary drug residue refers to the parent compound or its metabolites that remain in an edible animal product after administration of a veterinary medicine. The presence of a residue does not automatically mean that a food is unsafe. For approved medicines, regulatory authorities establish maximum residue limits (MRLs) and appropriate withdrawal periods to ensure that residues remain within acceptable levels. However, some substances are not permitted for use in food-producing animals because of their toxicological, pharmacological or antimicrobial-resistance concerns.

The prohibition of a veterinary drug is generally based on concerns that its use could pose an unacceptable risk to consumers or contribute to other public-health problems.

Some substances or their metabolites may have toxic, carcinogenic or genotoxic effects. Others may produce pharmacological effects when residues are consumed. In the case of antimicrobial drugs, inappropriate use can also contribute to the development and spread of antimicrobial resistance (AMR).

Therefore, the regulation of veterinary drugs follows an important principle: medicines used in animals intended for human consumption must be selected and administered responsibly so that animal treatment does not compromise food safety.

Veterinary Drugs Not Permitted Under Indian Food-Safety Regulations

The Food Safety and Standards Authority of India (FSSAI), under the *Food Safety and Standards (Contaminants, Toxins and Residues) Regulations, 2011* and subsequent amendments, specifies antimicrobials and other veterinary drugs that are not permitted to be used at any stage of production of meat and meat products, milk and milk products, poultry and eggs, aquaculture and its products.

The current FSSAI compendium available in 2026 lists the following substances or groups:

No.	Substance/group	Major food-safety concern
1	Carbadox	Toxicological concern associated with residues/metabolites
2	Chloramphenicol	Serious toxicological effects and concern over residues
3	Chlorpromazine	Pharmacological and toxicological concerns
4	Clenbuterol	Pharmacological effects in consumers
5	Colistin	Antimicrobial-resistance concern
6	Crystal violet	Toxicological and genotoxicity concerns
7	Glycopeptides	Importance of antimicrobial-resistance control
8	Malachite green	Toxicological concern and persistence of residues
9	Nitrofurans and their metabolites	Toxicological and genotoxic/carcinogenic concerns
10	Streptomycin and dihydrostreptomycin	Antimicrobial-resistance and residue concerns
11	Nitroimidazoles	Toxicological/genotoxicity concerns for relevant compounds
12	Steroids	Hormonal and food-safety concerns
13	Stilbenes	Hormonal/growth-promoting and toxicological concerns
14	Sulphamethoxazole	Antimicrobial-resistance and residue concerns

FSSAI also specifies an extraneous maximum residue limit (EMRL) of 0.001 mg/kg for the listed substances, with a specific lower EMRL of 0.0003 mg/kg for chloramphenicol. The existence of an EMRL should not be interpreted as permission to use these substances; the regulation separately states that their use is not permitted.

Some Important Examples

Chloramphenicol - Chloramphenicol is a broad-spectrum antimicrobial that was historically used in veterinary medicine. Its use in food-producing animals has been prohibited because of serious concerns associated with human exposure to residues. One of the important concerns is the potential for bone-marrow toxicity, including the rare but serious condition of aplastic anaemia. Because a safe residue level could not be established with sufficient confidence, chloramphenicol has become one of the best-known examples of a veterinary antimicrobial that should not be used in food-producing animals.

Nitrofurans - Nitrofurans are another important group of prohibited substances. Examples include furazolidone, nitrofurazone, furaltadone and nitrofurantoin. These drugs are metabolised in animals and can produce metabolites that may persist in edible tissues. Some of these metabolites have raised concerns regarding genotoxicity and carcinogenic potential. For this reason, residues of nitrofurans are an important target in food-safety monitoring.

Nitroimidazoles - Nitroimidazoles such as metronidazole, dimetridazole and ronidazole have been used for antimicrobial or antiprotozoal purposes. Their residues are regulated because of concerns regarding the toxicological properties of the parent compounds and/or their metabolites.

Clenbuterol - Clenbuterol is a β_2 -adrenergic agonist. Although pharmacologically active in animals, inappropriate use in food-producing animals can result in residues that may have physiological effects in humans. Consumption of contaminated animal products has been associated with symptoms such as palpitations, tremors, headache and changes in blood pressure. Therefore, its misuse presents a direct food-safety concern.

Malachite Green - Malachite green is primarily associated with aquaculture. It has historically been used as an antimicrobial and antiparasitic compound in fish production. However, concerns about its toxicological properties and persistence of residues have led to restrictions on its use in food-producing aquaculture.

Colistin - Colistin is different from some of the substances discussed above because its major concern is strongly connected to antimicrobial resistance. Colistin has been considered a critically important antimicrobial for human medicine because it can be used to treat infections caused by multidrug-resistant Gram-negative bacteria. The

emergence and spread of transferable resistance mechanisms, such as mcr genes, has increased concern about unnecessary or inappropriate use of colistin in animals. This shows why veterinary antimicrobial use cannot be viewed only as an animal-health issue. It is also a one health issue involving animals, humans and the environment.

How the drug residues reach humans:

The process from veterinary medicine to human exposure can be understood simply:

Drug administration → absorption and distribution in the animal → metabolism → residues in edible tissues or products → harvesting/slaughter/milking → food processing → human consumption

Residues may occur when prohibited substances are used, when approved drugs are administered incorrectly, or when the required withdrawal period is not observed. The withdrawal period is the time that must pass between the last administration of a veterinary medicine and the production of food from the treated animal. It allows the concentration of the drug or its residues to decline to an acceptable level. Failure to observe withdrawal periods can therefore turn an otherwise legitimate veterinary treatment into a food-safety problem.

What happens when residues enter the food chain?

The effects depend on the particular drug and the amount and duration of exposure. Potential consequences include:

- Toxic effects
- Allergic or hypersensitivity reactions
- Pharmacological effects
- Genotoxic or carcinogenic effects for certain compounds
- Selection and spread of antimicrobial-resistant microorganisms
- Disruption of treatment options for human infections

The consequences are therefore not limited to the person consuming a contaminated food product. Antimicrobial resistance can have wider effects across animal, human and environmental populations.

Antimicrobial resistance: Antimicrobial resistance is one of the strongest reasons why responsible veterinary drug use has become a global priority. When antimicrobials are used unnecessarily or inappropriately, susceptible microorganisms may be eliminated while resistant organisms survive and multiply. Resistance genes can subsequently spread between microorganisms and across different environments.

Thus, Animal antimicrobial use → selection of resistant microorganisms → spread of resistance → reduced effectiveness of antimicrobials → difficulty treating infections

Role of veterinarians

Veterinarians have a critical role in preventing veterinary drug residues from entering the food chain. This includes:

- Prescribing medicines only when justified
- Selecting appropriate drugs and doses
- Following approved routes of administration
- Maintaining treatment records
- Advising farmers about withdrawal periods
- Avoiding prohibited substances
- Promoting responsible antimicrobial use
- Educating farmers about the risks of drug misuse
- Supporting residue monitoring and surveillance

Farmers and animal owners also have an important responsibility to follow veterinary instructions and maintain appropriate records of treatment.

Indian regulatory framework

In India, food safety relating to veterinary drug residues is regulated through the Food Safety and Standards Authority of India (FSSAI) under the *Food Safety and Standards (Contaminants, Toxins and Residues) Regulations, 2011*, along with subsequent amendments.

FSSAI provides requirements concerning contaminants, toxins, veterinary drug residues and other substances in foods. The current FSSAI compendium should be consulted when determining the regulatory status of individual substances because the regulations are periodically amended. The official FSSAI regulations page and the amendment page should therefore be used as the primary regulatory references when preparing an article or educational material.

Conclusion

Veterinary medicines are indispensable for maintaining animal health and productivity, but their benefits come with a responsibility to protect the safety of food derived from treated animals.

The presence of prohibited veterinary drugs or excessive residues in meat, milk, eggs or fish can create risks ranging from direct toxicological effects to the broader problem of antimicrobial resistance. Preventing these risks requires cooperation among veterinarians, farmers, regulatory authorities, food producers and consumers.

References

- Mesfin, Y.M., Mitiku, B.A. and Tamrat Admasu, H. (2024), Veterinary Drug Residues in Food Products of Animal Origin and Their Public Health Consequences: A Review. *Vet Med Sci*, 10: e70049.
- Food Safety and Standards Authority of India (FSSAI). *Food Safety and Standards (Contaminants, Toxins and Residues) Regulations, 2011*, including subsequent amendments and the current consolidated compendium. Official FSSAI source.
- Ahmad, N., R. Joji, and M. Shahid. 2023. "Evolution and Implementation of One Health to Control the Dissemination of Antibiotic-Resistant Bacteria and Resistance Genes: A Review." *Frontiers in Cellular and Infection Microbiology* 12: 1065796.
- Atta, A. H., S. A. Atta, S. M. Nasr, and S. M. Mounair. 2022. "Current Perspective on Veterinary Drug and Chemical Residues in Food of Animal Origin." *Environmental Science and Pollution Research* 29: 15282–15302.
- Chen, J., G.-G. Ying, and W.-J. Deng. 2019. "Antibiotic Residues in Food: Extraction, Analysis, and Human Health Concerns." *Journal of Agricultural and Food Chemistry* 67: 7569–7586

Smart Poultry: Transforming Farming with AI



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Introduction

Poultry farming must produce meat and eggs efficiently while maintaining bird welfare, controlling disease, and reducing costs. Traditional farm inspection is often limited by flock size, labor availability, and the fast pace of changes in bird health or housing conditions. AI addresses these challenges by converting large streams of farm data into practical management insights. Precision poultry farming is the broader framework in which AI is applied. It integrates sensors, computer vision, microphones, and automated control systems to monitor birds and their environment continuously. Recent reviews argue that this approach can improve both production and sustainability when it is carefully adapted to local conditions.

Applications of AI

AI can help control the poultry house environment. Various sensors can measure temperature, humidity, ammonia and carbon dioxide level in the poultry house. When conditions become inappropriate, automatic ventilation fans, cooling systems or other equipment respond immediately which is very helpful and effective during extreme hot weather condition. Another important application is in precision feeding. AI can then help farmers to adjust feeding according to its age, body weight and production status as per the flock size. Automatic feeders, electronic weighing machine regularly monitor feed consumption and bird growth thereby reduce wastage of feed and improve feed efficiency.

For disease forecasting based on weather information, previous disease records and farm conditions, AI models using Random Forest, N beats can forecast the disease. through an early warning of increased risk of and take preventive measures.

Further to reduce the dependency on manpower most of the modern farms are also using automatic egg collection systems, smart feeders, automatic drinkers, electronic weighing machines, robotic cameras and manure-removal systems. These technologies reduce work load stress to the farmers and increase the efficiency for better management decisions.

Overall, AI acts as an additional tool for the poultry farmer as it can monitor the flock, analyses farm conditions, identify changes and based on analysis can provide suitable suggestion for optimization along with farmers experience can improve the production and productivity. Some of the equipment's used in poultry are enlisted below: -

Objective	Equipment's	Brand
Bird monitoring	AI camera, CCTV, computer vision	Fancom, SKOV, OPTI farm, PLF Agritech
Flock sound monitoring	Microphones, acoustic monitoring	Sound Talks, Fancom
Temperature & humidity	Digital temperature/RH sensors	SKOV, Fancom, Rotem
Ammonia monitoring	NH ₃ sensors	SKOV, Fancom, Dräger
CO ₂ monitoring	CO ₂ sensors	SKOV, Fancom, Rotem
Air speed/ventilation	Airflow sensors	SKOV, Fancom
Automatic ventilation	Fans, controllers, inlets	Big Dutchman, SKOV, Munters, Fancom
Cooling	Cooling pads, evaporative cooling systems	Munters, SKOV, Big Dutchman
Automatic feeding	Feeders, feed lines, sensors	Big Dutchman, Roxell, Chore-Time
Automatic drinking	Nipple drinker systems	Lubing, Plasson, Big Dutchman
Bird weighing	Automatic poultry weighing systems	Fancom, SKOV, Big Dutchman
Egg collection	Egg conveyors and automatic collection	Big Dutchman, Vencomatic, Moba
Egg grading/sorting	Machine vision and egg graders	Moba, Sanovo, Prinzen

Objective	Equipment's	Brand
Farm control	Central computer/controller and dashboard	SKOV, Fancom, Big Dutchman, Rotem
Weather monitoring	Weather station and environmental sensors	Davis Instruments, Campbell Scientific

Benefits

Better decision-making is the primary advantage of AI in poultry farming. Farmers can get ongoing, data-driven notifications regarding flock health, housing, feeding conditions rather than depending on sporadic visual inspection for better flock consistency, reduced mortality and timely intervention. With improved environmental condition, optimum feeding, early disease detection will reduce the wastage of feed, energy, medicine while improving the production and productivity and enhance the farmers income. AI-driven precision feeding systems tailor feed distribution to individual animal needs, improving both productivity and efficiency. Advances in breeding management leverage AI to analyses genetic data and optimize reproductive strategies (Jini *et al.*, 2025).

Challenges

Since AI is a relatively new technological innovation, its effective implementation requires specialized expertise and training to understand and operate the system. Moreover, the availability of the required equipment is limited and involves considerable cost. Further, the operation of AI-based systems, particularly those integrated with IoT, requires reliable internet connectivity and appropriate supporting infrastructure.

These issues can be especially difficult for smaller farms. Data quality is another concern. AI models are only as good as the data on which they are trained, and poultry farms vary widely in terms of breed, climate, housing design, and management practices. A model that works well in one setting may need retraining or validation before it can be used elsewhere. Interpretability also matters. Farmers are more likely to trust systems that provide clear and useful explanations for their recommendations. For this reason, current research increasingly emphasizes explainable AI and human oversight rather than complete automation.

Data security remains a significant concern, especially when dealing with sensitive information such as animal health records. Interoperability between AI platforms used by different stakeholders is also a major challenge, often resulting in inefficiencies and difficulties in data sharing and integration.

Future prospects

The future of AI in poultry production will likely involve more integrated systems that combine computer vision, audio analysis, IoT sensors, and predictive analytics. Such systems can provide a more comprehensive picture of flock welfare and production conditions than single-sensor tools, enabling more informed and timely decision-making.

Research also points toward the development of more locally adapted AI systems for specific production contexts. This is especially important in regions with varied climates and management practices, where general models may not perform well without further adaptation or validation. As these systems become more affordable and user-friendly, their adoption is likely to increase in both large- and medium-scale poultry operations.

Conclusion

AI is becoming a significant part of modern poultry husbandry because it improves monitoring, welfare assessment, precision feeding, environmental control, and forecasting. Its main strength lies in its ability to convert data into faster, more accurate, and informed management decisions. However, its successful implementation depends on factors such as cost, data quality, infrastructure, and careful integration with human expertise. Therefore, the future adoption of AI in poultry production will depend not only on technological advancements but also on making these systems affordable, reliable, user-friendly, and adaptable to different production conditions.

References

Jini, D., Srishailam, B., Kumar, J., Alone, R. A., Bam, J., & Wangchu, L. (2025). *Leveraging artificial intelligence (AI) for information dissemination and decision support in livestock husbandry*. International Journal of Advanced Biochemistry Research, 9(1S), 570–574. DOI: 10.33545/26174693.2025.v9.i1Sh.3565.

How Plant Diseases Start: The Hidden World Inside Plant Cells



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Introduction

Plants may appear healthy because of their leaves, flowers, and fruits, but their real strength lies underground. Roots absorb water and nutrients, anchor plants, store food, and interact with beneficial soil organisms. Since they remain hidden beneath the soil, studying them has always been difficult.

To overcome this challenge, scientists developed **Shovelomics**, a simple and rapid field-based technique for studying plant root systems. By excavating and analysing roots directly in the field, Shovelomics helps researchers identify crops with stronger, deeper, and more efficient roots. This technique is playing a vital role in developing drought-tolerant, high-yielding, and climate-resilient crops, making it an important tool for sustainable agriculture and future food security.

The Hidden World Beneath Our Feet

Roots are often called the “hidden half” of plants because they remain invisible while performing essential functions that determine plant health and productivity.

A strong root system acts as the foundation of a plant. Just as a building requires a strong foundation to remain stable, plants need healthy roots for proper growth and development.



Important Functions of Roots

1. Water Absorption:

Roots absorb water from the soil and transport it to different parts of the plant. Deep roots help plants access water stored in lower soil layers during drought conditions.

2. Nutrient Uptake:

Roots take up essential minerals such as nitrogen, phosphorus, and potassium, which are necessary for plant growth.

3. Plant Anchorage:

Roots hold plants firmly in the soil and protect them from falling due to strong winds or heavy rainfall.

4. Food Storage:

Many plants store carbohydrates and nutrients in their roots for future growth.

5. Soil Improvement:

Roots improve soil structure by creating channels that increase aeration and water movement.

What is Shovelomics?

Shovelomics is a rapid field-based technique used to study plant root systems. The term is derived from two words: “**Shovel**”, the tool used for digging roots, and “**Omics**”, which refers to the study of biological characteristics on a large scale.

Traditional root studies often required expensive laboratory equipment and were time-consuming. Shovelomics changed this by providing a simple, affordable, and practical method for analysing roots directly in the field.

In this technique, plants are carefully excavated using a shovel, and the root system is cleaned, photographed, and analysed. Scientists measure different root characteristics and compare plants to identify those with superior root systems.

Shovelomics was initially developed for studying maize root architecture but is now widely used in crops such as wheat, rice, sorghum, barley, soybean, chickpea, and other important agricultural plants.

Why Are Plant Roots Important for Agriculture?

Modern agriculture faces several challenges, including drought, soil degradation, and increasing demand for food. Improving root systems can help overcome many of these problems.

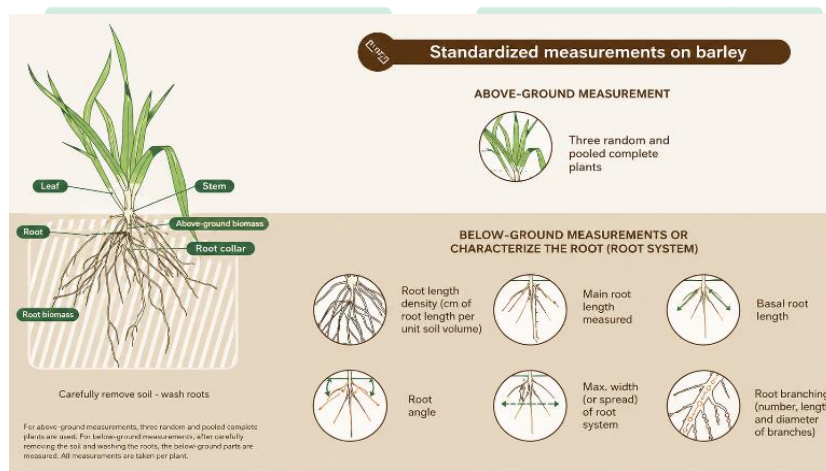
Plants with strong roots can:

- Absorb water efficiently.
- Survive longer periods of drought.
- Utilize nutrients more effectively.
- Produce stable yields under stressful conditions.
- Reduce dependence on excessive irrigation and fertilizers.

How Does Shovelomics Work?

Shovelomics follows a simple and systematic process to study plant roots under natural field conditions. Unlike traditional methods that require complex laboratory procedures, Shovelomics allows researchers to examine root systems quickly and efficiently.

The major steps involved are:



1. Selection of Plants

Healthy plants are selected from the field based on the research objective. Different crop varieties may be chosen to compare their root characteristics.

2. Root Excavation

A shovel is carefully used to dig around the plant. The root system is removed gently to avoid damage, especially near the root crown.

3. Root Cleaning

The collected roots are washed with water to remove soil particles and expose the complete root structure.

4. Root Imaging

Clean roots are photographed or scanned using digital imaging techniques. These images provide detailed information about root shape and structure.

5. Root Analysis

Computer software is used to analyse the images and measure different root traits. The collected data help scientists identify plants with better root performance.

Root Traits Measured in Shovelomics

Roots differ greatly among plant varieties. Some roots grow deeper, some spread widely, and others develop more branches. Shovelomics helps scientists measure these differences and select plants with desirable root characteristics.

1. Root Length

Root length determines how deeply plants can explore the soil. Longer roots help plants access water and nutrients from deeper soil layers.

2. Root Number

A greater number of roots increases the plant's ability to absorb water and minerals from the soil.

3. Root Angle

Root angle shows the direction of root growth. Deep-growing roots help plants survive drought by reaching underground water sources.

4. Root Diameter

The thickness of roots influences their strength, transport ability, and storage capacity.

5. Root Branching

Branched root systems explore more soil area and improve nutrient absorption.

6. Root Crown Architecture

The arrangement of roots near the base of the plant affects plant stability and overall root efficiency.

Applications of Shovelomics

Shovelomics has become an important technique in agricultural research and crop breeding. It helps scientists understand how root systems influence plant growth and productivity.

1. Crop Improvement

Plant breeders use Shovelomics to identify plants with superior root systems. These root traits can be introduced into new crop varieties with improved performance.

2. Drought Tolerance

Water scarcity is a major threat to agriculture. Crops with deeper and stronger roots can access water from deeper soil layers and survive dry conditions.

3. Nutrient Use Efficiency

Efficient root systems absorb nutrients more effectively, reducing the need for excessive fertilizer application.

4. Climate-Smart Agriculture

Shovelomics supports the development of crops that can withstand climate-related stresses such as drought, heat, and poor soil conditions.

5. Precision Agriculture

Information about root growth helps farmers improve irrigation, nutrient management, and crop production practices.

Benefits of Shovelomics

➤ Fast and Efficient

Large numbers of plants can be studied within a short time, helping researchers complete experiments faster.

➤ Low Cost

It requires simple tools such as a shovel, water, camera, and computer software, making it affordable.

➤ Field-Based Method

Roots are studied under natural growing conditions, providing realistic information about plant performance.

➤ **High-Throughput Screening**

Thousands of plants can be evaluated to identify the best-performing varieties.

➤ **Supports Sustainable Agriculture**

By helping develop crops with efficient root systems, Shovelomics reduces the need for excessive water and fertilizers.

➤ **Improves Food Security**

Stronger root systems contribute to stable crop production under changing environmental conditions.

From Research Fields to Farmers' Fields

The knowledge gained through Shovelomics is not limited to research laboratories. The information collected from root studies helps plant breeders develop improved crop varieties that can perform better under different environmental conditions.

Farmers benefit from crops developed through root-based research because these varieties can:

- Survive drought conditions more effectively.
- Absorb nutrients efficiently.
- Produce stable yields even under stress.
- Require less water and fertilizer.
- Improve farm productivity and profitability.

Real-World Success Stories

Shovelomics has contributed significantly to crop improvement programmes around the world. By studying root characteristics, scientists have identified plants with improved adaptability and productivity.

➤ **Maize**

In maize research, Shovelomics has helped identify plants with deeper and stronger root systems. These improved roots allow maize plants to access water from deeper soil layers and perform better during drought conditions.

➤ **Wheat**

Root studies in wheat have helped researchers understand traits related to nutrient uptake and water absorption. Selecting plants with efficient roots supports better yield stability.

➤ **Rice**

Rice researchers use root studies to identify varieties that can tolerate water stress and improve resource use efficiency.

Challenges in Root Study

Although Shovelomics has made root research easier, some challenges still exist.

- Digging roots carefully requires skill and patience.
- Deep roots may be difficult to recover completely.
- Soil conditions can affect root excavation.

Future Scope of Shovelomics

The future of Shovelomics is closely linked with advances in technology. Modern tools are making root studies faster, more accurate, and more useful for agriculture.

Future developments include:

➤ **Artificial Intelligence (AI)**

AI-based systems can analyse root images automatically and identify valuable root traits quickly.

➤ **Machine Learning**

Machine learning models can predict which root characteristics contribute to better crop performance.

➤ **Genomics**

Combining Shovelomics with genetic studies can help identify genes responsible for strong and efficient root systems.

➤ **Digital Agriculture**

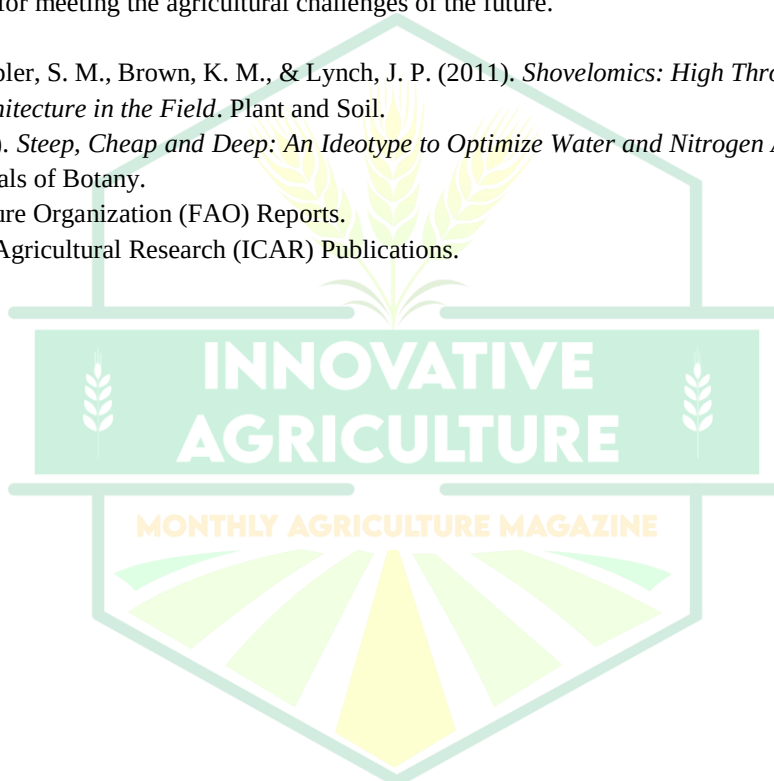
Root information can support smart farming practices by improving irrigation and nutrient management decisions.

Conclusion

Shovelomics has emerged as a simple, rapid, and cost-effective technique for studying the hidden half of plants—the root system—which plays a fundamental role in water and nutrient uptake, plant stability, food storage, and soil health. By enabling researchers to evaluate root traits directly under field conditions, it supports the identification and development of crop varieties with stronger, deeper, and more efficient root systems. These improved crops are better equipped to withstand drought, utilize nutrients efficiently, and maintain stable yields under changing climatic conditions. With the integration of advanced technologies such as artificial intelligence, machine learning, genomics, and digital agriculture, Shovelomics is expected to become even more powerful in future crop improvement programmes. Ultimately, this innovative approach contributes to sustainable agriculture, enhanced resource-use efficiency, increased farmer profitability, and global food security, making it an indispensable tool for meeting the agricultural challenges of the future.

References

- Trachsel, S., Kaeppler, S. M., Brown, K. M., & Lynch, J. P. (2011). *Shovelomics: High Throughput Phenotyping of Maize Root Architecture in the Field*. Plant and Soil.
- Lynch, J. P. (2013). *Steep, Cheap and Deep: An Ideotype to Optimize Water and Nitrogen Acquisition by Maize Root Systems*. Annals of Botany.
- Food and Agriculture Organization (FAO) Reports.
- Indian Council of Agricultural Research (ICAR) Publications.



Varietal Characteristics of Turmeric



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Turmeric (*Curcuma longa* L.), a triploid species ($2n = 3x = 63$) belonging to 'Zingiberaceae' family is a well-known indigenous spice crop. It is also known as the Golden Spice, Indian Saffron, Indian Solid Gold, Spice of Life, Haldi, etc. Turmeric is native to Southeast Asia and has been used for 4,000 years to treat a variety of ailments in Indian Vedic culture. Turmeric is valued for its deep yellow colour (0.2-8% curcumin) pungency (2.2-4.2% termerol) and aromatic flavour of volatile oil (1.5-5%). During Vedic period turmeric was referred as "Earthy herb of the Sun" with the orange-yellow rhizome regarded as the "Sacred spice".

Origin and distribution

The genus *Curcuma longa* has a wide spread occurrence in the tropics of South East Asia. Turmeric has been distributed in India, South-East Asian countries and North Australia. In India, turmeric is extensively cultivated in the states of Telangana, Andhra Pradesh, Odisha, West Bengal, Tamil Nadu, Assam, Maharashtra, Karnataka, Bihar and Kerala.

Botany

The plant is an herbaceous perennial, 60-90 m high, with a short stem and tufted leaf. There are 7 to 12 leaves and the leaf sheaths form the pseudo stem. At the base of pseudo stem, there is the primary bulb. The primary bulb bears many straight or slightly curved bulbs forming secondary branches called fingers. The secondary branches give rise to tertiary branches thus giving a clump appearance. The lamina is green above and pale green below and has a length of 30-40 cm along with width 8-12 cm. Inflorescence is a central spike of 10-15 cm length. 1-4 flowers are born in axil of the bract opening one at a time.

Related species

1. ***Curcuma amada***: It is commonly called as 'Mango ginger, since it possesses the odour of raw mango.
2. ***Curcuma aromatica***: It is commonly called as 'Kasthuri manjal'. Rhizome smells like camphor and inner side is creamy white.
3. ***Curcuma augustifolia***: It is commonly called as 'East Indian arrow root'
4. ***Curcuma zedoaria***: It is called as the 'duplicate kasthuri' or 'manja koova'. The edible rhizome of zedoary has a white interior and a fragrance reminiscent of mango
5. ***Curcuma caesia***: It is called as 'black zedoary', 'blue zedoary', 'kali haldi' or 'black turmeric'. It has bluish-black rhizomes. Rhizome has intense camphoraceous odour and medicinal properties. It is popular in West Bengal and Kasargod in Kerala.

Improved varieties

A number of cultivars are available in the country and are known mostly by the name of locality where they are cultivated. Some of the popular cultivars are Duggirala, Tekkurpet, Sugandham, Amalapuram, Erode local, Salem, Alleppey, Moovattupuzha and Lakdong. Improved varieties of turmeric released by different research organizations are also available.

I) Varieties released from Kerala Agriculture University

Kanthi (T1): It is developed through selection from Mydukur and released in 1996. Crop matures in 8-9 months and with yield of 8.9 tonnes of fresh rhizome/ha. Curcumin content is 7.18%. It has erect leaf with broad lamina, big mother rhizomes with medium bold fingers and closer internodes.

Sobha (T2): It is developed through selection from Menthala local and released in 1996. Crop matures in 240-270 days and with yield of 7.0 tonnes of fresh rhizome/ha. Curcumin content is 7.39% and oleoresin content is

19.95%. It has big mother rhizome with medium bold fingers and closer inter nodes. Inner core of rhizomes is dark orange.

Sona (T3): It is developed through germplasm selection and released in 1996. Crop matures in 240-270 days and with yield of 4.2 tonnes of fresh rhizome/ha. Curcumin content is 7.11%, oleoresin percentage is 18% and essential oil content is 4.40%. It has orange yellow rhizomes, medium, bold with no tertiary fingers. Variety is field tolerant to leaf blotch and best suited for central zones of Kerala.

Varna (T4): It is developed through germplasm selection and released in 1996. Crop matures in 240-270 days and with yield of 4.2 tonnes of fresh rhizome/ha. Curcumin content is 7.87%, oleoresin percentage is 13.88% and essential oil content is 4.56%. It has orange yellow rhizomes, medium, bold with no tertiary fingers. Variety is field tolerant to leaf blotch and best suited for central zones of Kerala.

II. Varieties released from ICAR-Indian Institute of Spices Research

IISR Prabha (T5): It is developed through Open pollinated progeny selection in 1996. Crop matures in 205 days with a yield of 37 tonnes of fresh rhizomes/ha. Curcumin percentage is 6.52%, oleoresin percentage is 15.0% and fibre content of 6.5%. A high yielding and good quality with reddish yellow coloured rhizome. Free from disease incidence in farmer's field. A value-added variety.

IISR Prathibha (T6): The variety is released by ICAR – IISR in the year 1996. Developed by Pedigree method (Open-pollinated progeny selection). It can be adaptable across all over India. The crop matures in 225 days with an average yield of 39.12 tonnes of fresh rhizomes/ha. Curcumin content is prominently higher (6.52%), Oleoresin (16.2%), and Essential oil (6.2%) making it suitable for industrial, culinary and medicinal purposes. It has plumpy and bold rhizomes with fibre content. Resistant to root knot nematode.

IISR Alleppey Supreme (T7): It is developed through Alleppey finger turmeric selection in 2004 and areas of adoption include Kerala (rainfed), Karnataka, Maharashtra and North Bengal. Crop matures in 210 days with a yield of 5.28 t/ha (dry) and potential yield of 19.94 t/ha (fresh). Curcumin percentage is 5.5% and oleoresin percentage is 16.0%. Variety is tolerant to leaf blotch.

IISR Suvarna (T8): It is developed through selection from the germplasm (PCT-8) collected from Assam and released in 1987. Crop matures in 200 days with a yield of 17.4 tonnes of fresh rhizomes/ha and potential yield of 43.5 tonnes of rhizomes/ha. Curcumin percentage is 4.0%, oleoresin percentage is 13.5% and essential oil of 7.0%. It is moderately tolerant to Rhizome rot (*Pythium graminicolum*) and Leaf blotch (*Taphrina maculans*). A high yielding, short duration turmeric with deep orange coloured rhizome with slender fingers.

IISR Suguna (T9): It is developed through selection from the germplasm (PCT-13) collected from Andhra Pradesh and released in 1991. Crop matures in 190 days with a yield of 29.3 tonnes of fresh rhizomes/ha and potential yield of 60.3 tonnes of rhizomes/ha. Curcumin percentage is 4.9%, oleoresin percentage is 13.5% and essential oil of 6.0%. It is moderately tolerant to Rhizome rot (*Pythium graminicolum*) and Leaf blotch (*Taphrina maculans*). A high yielding and good quality with reddish yellow coloured rhizome. Free from disease incidence in farmer's field. A value-added variety.

IISR Sudharsana (T10): It is developed through selection from the germplasm (PCT-14) collected from Singhat, Manipur and released in 1991. Crop matures in 190 days with a yield of 28.8 tonnes of fresh rhizomes/ha and potential yield of 54.9 tonnes of rhizomes/ha. Curcumin percentage is 7.9%, oleoresin percentage is 15.0% and essential oil of 7.0%. It is moderately tolerant to Rhizome rot (*Pythium graminicolum*) and Leaf blotch (*Taphrina maculans*). A high yielding high quality short duration turmeric with thick plumpy rhizomes. Field tolerant to rhizome rot.

IISR Kedaram (T11): It is developed through Alleppey finger turmeric selection in 2004 and areas of adoption include Kerala, Karnataka, Maharashtra and North Bengal. Crop matures in 180 days with a yield of 5.28 t/ha (dry) and average yield of 29 t/ha (fresh). Curcumin percentage is 5.70%, oleoresin percentage is 14.0% and fibre content present is 3.0 %. Variety is tolerant to leaf blotch and it has consistent curcumin content.

IISR-Pragati: It is a short duration variety and suitable for turmeric growing areas with serious irrigation problems. It is developed through germplasm selection in 2017 and crops matures in 180 days with an average yield of 38 t/ha (fresh rhizomes) and it can be increased up to 52 t/ha under favourable conditions. Curcumin

percentage is 5.02%, oleoresin percentage is 15.29% and fibre content present is 3.33-4.5%. Variety is moderately resistant to root-knot nematode infestation.

IISR Surya: It is developed through clonal and released in 2025. Areas of adoption includes Kerala, Telangana, Odisha, Jharkhand and Arunachal Pradesh. Crop matures in 220-240 days with a high yield (average fresh yield 29 t/ha, potential yield 41 t/ha) with 5.8 t/ha dry yield. Curcumin percentage is 23%, β -sesquiphellandrene 14.13%, 1,8-cineole 3.42%, Zingiberene 21.07% and α humelene 6.30%. It is a light yellow coloured rhizomes, highly preferred for powdering industry.

III. Varieties released from High Altitude Research Station, OUAT, Odisha

Roma (T12): Variety is developed through clonal selection from Tsundur and released in 2019. Crop duration is 250 days with fresh rhizome yield of 20.7 t/ha and 31% of dry recovery. Curcumin content is 6.1% with bold rhizomes. High quality variety suitable for both rainfed and irrigated condition and hilly areas.

Suroma (T13): Variety is developed through X-ray mutant from Tsundur. Crop duration is 253 days with fresh rhizome yield of 20 t/ha and 26% of dry recovery. Curcumin content is 6.1%. It is field tolerant to leaf blotch, leaf spot and rhizome scale.

Ranga (T14): Variety is developed through clonal selection from Rajpuri local. Crop duration is 250 days with fresh rhizome yield of 29 t/ha and 24.8% of dry recovery. Curcumin content is 6.3% with bold rhizomes and moderately resistant to leaf blotch.

Rashmi (T15): Variety is developed through clonal selection from Rajpuri local and released in 2019. Crop duration is 240 days with fresh rhizome yield of 31.5 t/ha and 23% of dry recovery. Curcumin content is 6.4% with bold rhizomes. Suitable for both rainfed and irrigated condition.

IV. Varieties released from Tamil Nadu Agriculture University

Turmeric BSR 1 (T16): Variety is developed through selection from X-ray induced mutant population and released in 1986. Crop duration is 285 days with fresh rhizome yield of 30.5 t/ha and 6.0 t of dried rhizomes/ha. Curcumin content is 3.8%. Rhizomes are attractive yellow colour.

Turmeric BSR 2 (T17): Variety is a induced mutant from erode and released in 1994. Crop duration is 240-250 days with fresh rhizome yield of 42 t/ha and 18% of dry recovery. Curcumin content is 8.4%. Rhizomes are attractive yellow colour, medium statured and are resistant to scale insects.

Turmeric BSR 3: It is a clonal selection from Baguthampalayam. The duration is 240-250 days and planting season is May – June. The average rhizome yield is 51 t/ha. It has the curcumin content of 4.8%. It is suitable for cultivation in the districts of Coimbatore, Tirupur, Erode, Salem, Dharmapurai and Krishnagiri. It has moderate resistant to leaf spot and leaf blotch diseases.

Turmeric CO 1 : Variety is a mutant from Erode local and released in 1983. Crop duration is 270 days with fresh rhizome yield of 35 t/ha and 20% of dry recovery. Curcumin content is 3.20%. Rhizomes are bigger in size with bright orange flesh colour.

Turmeric CO 2 : Variety is developed through Clonal selection from the germplasm collected from Bhavanisagar local and released in 2013. Crop duration is 270 days with fresh rhizome yield of 43 t/ha and Curcumin content is 4.3%. Rhizomes are attractive yellow colour and moderately resistant to leaf blotch and leaf spot. It is highly resistant to rhizome rot and field tolerant to thrips, shoot borer, leaf folder and scale insect.

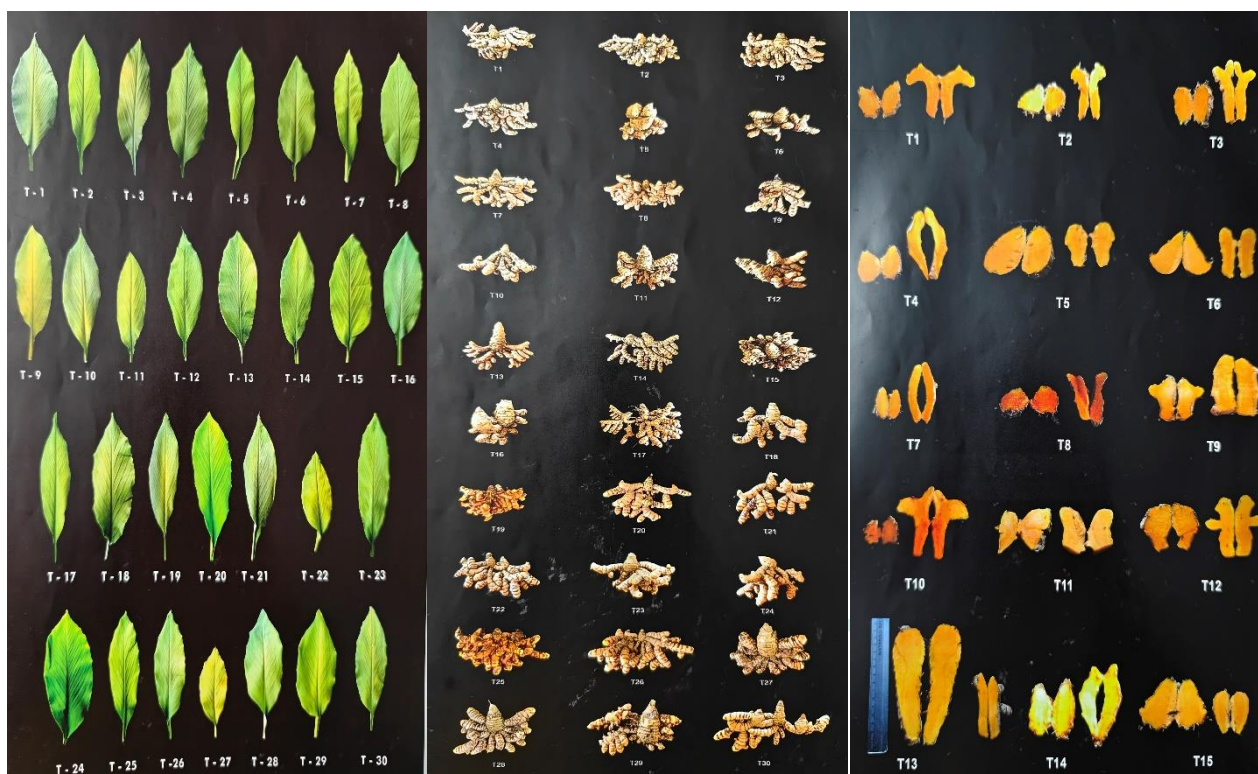
V. Varieties released from Dr. Rajendra Prasad Central Agricultural University, Pusa

Rajendra Sonia (RH-10) (T18): Crop matures in 200-210 days with rhizome yield of 400-450 q/ha, Curcumin content is 7.5-8.0% and 19% of dry recovery. It is moderately resistant to leaf blotch.

Rajendra Sonali (RH-5): Crop matures in 190-200 days with rhizome yield of 450-550 q/ha, Curcumin content is 5.5-6.5% and 19% of dry recovery. It is moderately resistant to leaf blotch and highly resistant to leaf spot

VI. Varieties released from ICAR Research Complex for NEH Region, Shillong

Megha Turmeric 1 (T19): Variety released from ICAR Research Complex for NEH Region, Shillong, Meghalaya. It was developed by Clonal selection from the local genotype Lakadong. Crop matures in 300-315 days with average yield of 27-30 t/ha. Curcumin content is 6.8%. Good in vegetative growth. Tolerant to leaf blotch and leaf spot.



Variability in leaf characteristics
of turmeric varieties

Variability in rhizomes nature of
turmeric varieties

Variability in size and colour of
rhizomes of turmeric varieties

VII. Varieties released from Punjab Agricultural University, Ludhiana

Punjab Haldi 1 (T20): Variety was released on 2015. Crop matures in 215 days with rhizome yield of 27.2 t/ha, Curcumin content is 3.3% and oleoresin percentage is 6.7%.

Punjab Haldi 2 (T21): Variety was released on 2015. Crop matures in 240 days with rhizome yield of 30.6 t/ha, Curcumin content is 2.9% and oleoresin percentage is 7.6%.

VIII. Varieties released from Uttar Bangal Krishi Viswa Vidyalaya, Pundibari, WB

UBKV Turmeric 2 (Surangana) (T24): Variety was released on 2019. Crop matures in 210-220 days with fresh rhizome yield of 26.16 t/ha and 23.3% of dry recovery. Curcumin content is 4.95%, oleoresin percentage is 11.85% and essential oil percentage is 6.74% with bold rhizomes. It is moderately tolerant to leaf spot and leaf blotch.

UBKV Turmeric 3 (Uttar Rangini): Variety was released on 2021. Suitable areas are West Bengal and Tamil Nadu. It is a high yielding variety with fresh rhizome yield of 28.19 t/ha. Curcumin content is 5.10%, oleoresin percentage is 12.25% and essential oil percentage is 6.53%.

IX. Varieties released from N.D. University of Agriculture & Technology, Kumarganj, Faizabad

Narendra Haldi 3 (T25): Turmeric variety with high yield (32-35 t ha⁻¹) with good size fingers, root knot nematode resistance, and moderate resistance against leaf spot and leaf blotch. Suitable for Uttar Pradesh. Recommended for release during 2012-2013.

NDH-98: Turmeric variety with tolerance to salinity and high yield potential (35-37 t ha⁻¹) with 4.3 - 5.2 % curcumin, 11.09 - 12.97 % oleoresin and 6.8 - 7.0 % essential oil. Recommended for release during 2016-2017.

Narendra Saryu: High curcumin content (5- 6%), more number of primaries with yield advantage of 10% over the national check. Suitable for powder industry. Recommended for release during 2017-2018.

X. Other improved varieties

Phule Swarupa: Variety released from Mahatma Phule Krishi Vidyapeeth, Maharashtra. It was developed by clonal selection from the local cultivar Duggirala in 2006 with fresh yield of 35.83 t/ha and 22% dry recovery. 5.19% of curcumin content is present. It is Field tolerant to leaf blotch, leaf spot and rhizome scale.

Sugandham: Variety released from SKSardar krushinagar Dantiwada. It was developed by clonal selection from germplasm with yield of 15.0 t/ha and 23.3% dry recovery. 3.1% of curcumin content is present. It has Thick, round, bold rhizomes with shorter internodes.

Krishna: Variety released from Maharashtra Agriculture University Digraj, Maharashtra. It was developed by Clonal selection from Tekurpeta with dry yield of 9.2 t/ha and 16.4% dry recovery. 2.8% of curcumin content is present. It is moderately tolerant to pest and diseases.

Pant Peetab (T22): Variety released from GBPUAT, Uttarakhand. Slender mother rhizomes with plumpy fingers. Resistant to rhizome rot.

Duggirala Red (T23): Variety was released by YSRAPHU, Jagtial. Early maturing variety with plumpy mother rhizomes and medium sized fingers. Crop matures in 218 days with average rhizome yield of 15.21 t/ha, Curcumin content is 446.04 kg/ha and 12.6% of dry recovery.

XI. Local cultivars

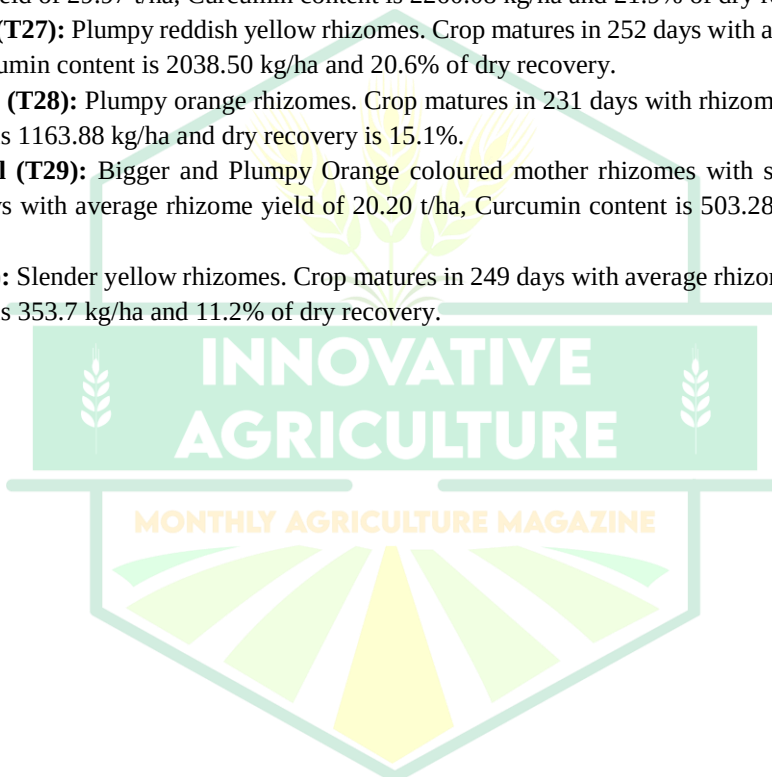
TBGRI Local (T26): Slender yellow coloured rhizomes with closer internodes. Crop matures in 249 days with average rhizome yield of 29.97 t/ha, Curcumin content is 2260.08 kg/ha and 21.9% of dry recovery.

Kasaragod Local (T27): Plumpy reddish yellow rhizomes. Crop matures in 252 days with average rhizome yield of 27.30 t/ha, Curcumin content is 2038.50 kg/ha and 20.6% of dry recovery.

Kanjikuzhy Local (T28): Plumpy orange rhizomes. Crop matures in 231 days with rhizome yield of 21.65 t/ha, Curcumin content is 1163.88 kg/ha and dry recovery is 15.1%.

Kuttipuram Local (T29): Bigger and Plumpy Orange coloured mother rhizomes with slender fingers. Crop matures in 233 days with average rhizome yield of 20.20 t/ha, Curcumin content is 503.28 kg/ha and 19.3% of dry recovery.

Aluva Local (T30): Slender yellow rhizomes. Crop matures in 249 days with average rhizome yield of 9.92 t/ha, Curcumin content is 353.7 kg/ha and 11.2% of dry recovery.



Digital Connectivity as a Pathway to Smart Villages: Opportunities and Challenges for Rural Development



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Abstract

Digital connectivity is becoming an important part of rural development, but simply bringing a network into a village does not guarantee that people will benefit from it. Rural communities may still face weak connections, high service costs, limited access to devices and inadequate digital skills. This article reviews how connectivity can contribute to the idea of the smart village, where technology is combined with local participation, better services and sustainable livelihood opportunities. The discussion covers digital inclusion, agriculture, healthcare, education, renewable energy, e-governance and rural enterprises. It also considers community-based connectivity, emerging technologies and the need for policies that respond to local conditions. The evidence reviewed suggests that rural digital development works best when infrastructure is accompanied by affordability, digital literacy, reliable electricity, community involvement and institutional support. Smart village initiatives should therefore be judged not only by the number of villages connected, but also by whether rural people can use digital services meaningfully. A people-centred approach can help digital technologies contribute to more inclusive, resilient and sustainable rural communities.

Keywords: digital inclusion; rural digital divide; smart villages; digital literacy; rural livelihoods; e-governance; digital agriculture

1. Introduction

Digital technology is changing the way rural communities obtain information, communicate, learn, access public services and participate in markets. Yet the benefits of this transformation are uneven. Rural locations often face difficulties that are less severe in cities, including sparse populations, difficult terrain and lower commercial returns from network investment. These conditions can leave rural communities with weaker digital infrastructure and fewer opportunities to use online services effectively (Salemink *et al.*, 2017; Philip *et al.*, 2017). The rural digital divide is therefore more than a question of whether a signal is available. A connection that is slow, unreliable or unaffordable may provide little practical benefit. Digital skills and confidence also influence whether people can turn connectivity into useful outcomes (Park *et al.*, 2019; Hollman *et al.*, 2020). This has encouraged interest in the smart village approach, which links technology with local development priorities, community participation and institutional support (Roberts *et al.*, 2017; Zavrtnik *et al.*, 2018). A smart village should consequently be understood as a development approach rather than simply a technologically advanced settlement. Its purpose is to use suitable digital and non-digital solutions to improve livelihoods and access to essential services while strengthening local capacity.

2. Connectivity Must Go Beyond Network Access

Reliable infrastructure is the starting point for rural digital development. Broadband, mobile networks and community access facilities provide the foundation for online education, digital markets, public services and other applications. However, rural areas may experience slower speeds, interruptions and higher costs because providers face greater deployment challenges and weaker commercial incentives (Philip *et al.*, 2017).

The next requirement is digital inclusion. People need affordable services, suitable devices, basic digital literacy and awareness of available platforms. Even when infrastructure reaches a village, households with limited income or digital experience may remain excluded (Tahmasebi, 2023). Research has also shown that connectivity and digital inclusion are closely linked: physical access alone does not ensure meaningful participation (Park *et al.*, 2019). This distinction is important when assessing smart village programmes. Coverage figures can give an incomplete picture if they do not reflect service quality, affordability and actual use. Rural digital development should therefore consider both the availability of infrastructure and the ability of residents to use it effectively (Hollman *et al.*, 2020).

3. Where Smart Village Practices Can Make a Difference

Digital connectivity can support several areas of rural life. In agriculture, digital advisory services can provide farmers with information on crop management, weather and markets. Internet-of-Things applications and precision farming systems can also help monitor farm conditions and improve the management of inputs and resources (Chanak and Banerjee, 2021). The usefulness of these tools, however, depends on affordable connectivity and farmers' digital capabilities.

Healthcare is another important area. Telemedicine, remote consultation and digital health records can help people in remote locations reach health services without travelling long distances. Digital tools can also support frontline health workers with information and decision-support resources (Singh *et al.*, 2022).

Education can benefit through online learning platforms, virtual classrooms and digital learning materials. Community learning facilities and guided digital-literacy programmes can make these services more accessible to students and teachers who may otherwise struggle with technology (Singh *et al.*, 2022).

Digital systems can also strengthen rural enterprises and public administration. Reliable broadband may help small businesses diversify, communicate with customers and improve resilience (Morris *et al.*, 2022). Online government services can make public information and services easier to reach, although users without adequate skills or access may still be left out (Bhatt, 2025).

4. Energy and Connectivity: Two Sides of the Same Coin

Digital services depend on electricity. In places where power supply is unreliable, even a good communication network may not deliver consistent benefits. Decentralised renewable-energy systems, particularly solar power, can provide electricity for households and community facilities and can support digital infrastructure, healthcare equipment and educational technologies (Garai *et al.*, 2017).

This creates an opportunity to combine digital development with clean-energy solutions. Rather than treating connectivity, electricity and rural services as separate programmes, smart village planning can consider them as interconnected components of local development.

5. Community Participation and Local Solutions

Technology is more likely to be useful when rural residents are involved in identifying problems and shaping solutions. Community-led initiatives can strengthen local ownership and help ensure that interventions match actual needs (Roberts *et al.*, 2017). This is particularly important because rural communities differ widely in livelihoods, geography, infrastructure and social organisation.

Evidence from different settings suggests that a single model cannot be applied uniformly to every village. Smart village initiatives need to be adapted to local priorities and capacities (Zavratnik *et al.*, 2018). Community broadband and cooperative models are examples of approaches that can increase local responsibility where commercial providers have limited interest in serving remote locations (Freeman *et al.*, 2019).

6. Barriers That Should Not Be Ignored

Several barriers can prevent digital transformation from becoming inclusive. Infrastructure is expensive in remote locations, while the cost of devices and data services can be difficult for low-income households to meet (Tahmasebi, 2023). Digital skills are another concern, particularly for groups that have had fewer opportunities to use digital technologies.

Inequality can also exist within rural communities. Evidence from Armenia, for example, indicates differences in ICT use associated with distance from urban centres and household economic conditions (Arion *et al.*, 2024). Research from developing rural settings similarly shows that digital inclusion can compete with other basic development priorities (Doloi, 2025).

These issues mean that digital programmes should identify who is benefiting and who is still being excluded. Poverty, age and educational disadvantage can overlap and intensify digital exclusion (Kuteesa *et al.*, 2024).

7. Emerging Technologies and Policy Priorities

New technologies may create additional options for extending rural connectivity. Community networks, satellite systems, dynamic spectrum use and newer network-management approaches are being explored for locations that are difficult to serve through conventional infrastructure (Freeman *et al.*, 2019; Bhatt, 2025). AI-supported

network optimisation and cloud-edge systems have also been proposed as ways of improving the efficiency of rural connectivity (Averineni, 2025).

Technology, however, should not become the only focus. Policies need to address infrastructure, affordability, digital literacy and service quality together. Public investment remains important where commercial deployment is unattractive, while place-sensitive policies can better reflect local conditions (Salemink *et al.*, 2017; De Clercq *et al.*, 2023). Community participation should be built into planning and implementation so that smart village programmes remain relevant and sustainable (Roberts *et al.*, 2017).

8. Conclusion

Digital connectivity can become a powerful rural-development tool when it is treated as a means rather than an end. Internet infrastructure creates possibilities, but meaningful benefits depend on affordability, reliability, skills, appropriate applications and community participation. Smart village approaches provide a framework for bringing these elements together across agriculture, healthcare, education, energy, governance and rural enterprise.

The central lesson is simple: connecting a village is only the first step. The real measure of digital transformation is whether rural people can use technology to improve their livelihoods, access essential services, participate in markets and strengthen their communities. A people-centred and locally adapted approach can make smart village development more inclusive, resilient and sustainable.

9. Way Forward

A more useful measure of a smart village is not how much technology it possesses, but what residents are able to do with that technology. Future initiatives should combine reliable connectivity with digital-skills training, affordable access, dependable electricity and locally relevant applications. Particular attention is needed for groups that may otherwise remain excluded. Further research should examine how digital infrastructure, skills and socio-economic outcomes interact in specific rural settings. Long-term studies can help determine whether smart village initiatives improve resilience and livelihood opportunities over time, while comparisons across regions can reveal how local institutions and policy environments influence results (Arion *et al.*, 2024; Morris *et al.*, 2022; Marshall, 2023).

References

- Arion, F., Harutyunyan, G., Aleksanyan, V., Muradyan, M., Asatryan, H. & Manucharyan, M. (2024). Determining digitalization issues (ICT adoption, digital literacy, and the digital divide) in rural areas using sample surveys: The case of Armenia. *Agriculture*, 14(2), 249. <https://doi.org/10.3390/agriculture14020249>.
- Averineni, A. (2025). Bridging the digital divide: The transformative role of AI-driven infrastructure in rural connectivity. *European Journal of Computer Science and Information Technology*, 13(2), 37–56. <https://doi.org/10.37745/ejcsit.2013/vol13n237695>.
- Bhatt, B. (2025). Enhancing rural e-governance through improved digital access: A case study of Sudurpashchim Province, Nepal. *The Management Review*, 1(1), 1–15. <https://doi.org/10.3126/tmr.v1i1.82217>.
- Chanak, P. & Banerjee, I. (2021). Internet-of-Things-enabled smart villages: An overview. *IEEE Consumer Electronics Magazine*, 10(3), 12–18. <https://doi.org/10.1109/MCE.2020.3013244>.
- De Clercq, M., D'haese, M. & Buysse, J. (2023). Economic growth and broadband access: The European urban–rural digital divide. *Telecommunications Policy*, 47, 102579. <https://doi.org/10.1016/j.telpol.2023.102579>.
- Doloi, H. (2025). Digital inclusion for rural growth: Internet usage and smart villages development. *Asia-Pacific Journal of Rural Development*, 35, 40–57. <https://doi.org/10.1177/10185291251343357>.
- Freeman, J., Park, S. & Middleton, C. (2019). Technological literacy and interrupted internet access. *Information, Communication & Society*, 23(13), 1947–1964. <https://doi.org/10.1080/1369118X.2019.1623901>.
- Garai, R., Maity, P., Hossain, R. & Roy, P. (2017). Smart village. *Proceedings of the 2017 1st International Conference on Electronics, Materials Engineering and Nano-Technology (IEMENTech)*. IEEE. <https://doi.org/10.1109/IEMENTECH.2017.8077008>.
- Hollman, A., Obermier, T., Burger, P. & Spanier, A. (2020). Rural measures: A quantitative study of the rural digital divide. *Journal of Information Policy*, 10, 364–392. <https://doi.org/10.2139/ssrn.3757477>.

- Kuteesa, K., Akpuokwe, C. & Udeh, C. (2024). Theoretical perspectives on digital divide and ICT access: A comparative study of rural communities in Africa and the United States. *Computer Science and IT Research Journal*, 5(4), 1–14. <https://doi.org/10.51594/csitrj.v5i4.1045>.
- Marshall, A. (2023). A new rural digital divide? Taking stock of geographical digital inclusion in Australia. *Media International Australia*, 190, 68–84. <https://doi.org/10.1177/1329878X231202274>.
- Morris, J., Morris, W. & Bowen, R. (2022). Implications of the digital divide on rural SME resilience. *Journal of Rural Studies*, 88, 423–432. <https://doi.org/10.1016/j.jrurstud.2022.01.005>.
- Park, S., Freeman, J. & Middleton, C. (2019). Intersections between connectivity and digital inclusion in rural communities. *Communication Research and Practice*, 5(2), 139–155. <https://doi.org/10.1080/22041451.2019.1601493>.
- Philip, L., Cottrill, C., Farrington, J., Williams, F. & Ashmore, F. (2017). The digital divide: Patterns, policy and scenarios for connecting the ‘final few’ in rural communities across Great Britain. *Journal of Rural Studies*, 54, 386–398. <https://doi.org/10.1016/j.jrurstud.2016.12.002>.
- Roberts, E., Anderson, B., Skerratt, S. & Farrington, J. (2017). A review of the rural–digital policy agenda from a community resilience perspective. *Journal of Rural Studies*, 54, 372–385. <https://doi.org/10.1016/j.jrurstud.2016.03.001>.
- Salemink, K., Strijker, D. & Bosworth, G. (2017). Rural development in the digital age: A systematic literature review. *Journal of Rural Studies*, 54, 360–371. <https://doi.org/10.1016/j.jrurstud.2015.09.001>.
- Singh, K., Sengar, N., Das, D. & Misra, S. (2022). Village 5.0: Enabling technologies and its applications in development of smart village. *Proceedings*, 556–561. <https://doi.org/10.1109/iSES54909.2022.00122>.
- Tahmasebi, F. (2023). The digital divide: A qualitative study of technology access in rural communities. *AI and Tech in Behavioral and Social Sciences*, 1(2), 1–12. <https://doi.org/10.61838/kman.aitech.1.2.6>.
- Zavratnik, V., Kos, A. & Stojmenova Duh, E. (2018). Smart villages: Comprehensive review of initiatives and practices. *Sustainability*, 10, 2559. <https://doi.org/10.3390/su10072559>.



Empowering Smallholders in Soil Health Management for Sustainable Agriculture



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Soil health plays a crucial role in maintaining crop productivity, nutrient availability and sustainable agricultural production. Soil testing is an essential tool for assessing soil fertility and identifying major constraints such as acidity, nutrient deficiencies and salinity. The information obtained from soil analysis helps in developing appropriate and site-specific soil management practices.

Soil acidity is one of the important constraints affecting agricultural productivity in India, covering about 98.71 million hectares (31% of the country's geographical area). Acidic soils often have low availability of essential nutrients, phosphorus fixation and toxicity of aluminium and manganese, which can adversely affect root growth, nutrient uptake and crop yield.

Effective management requires an integrated approach involving soil-test-based liming, balanced fertilizer application, organic amendments, suitable crop varieties and beneficial microorganisms. Regular soil testing and monitoring further help maintain soil fertility and productivity. Therefore, integrated soil health management is essential for improving the productivity, resilience and long-term sustainability of agricultural soils.

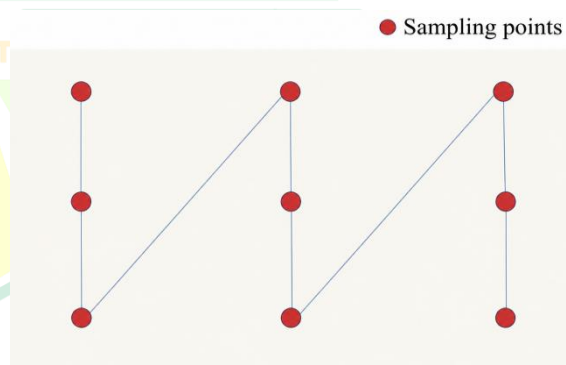
Soil health management basically comprises of soil testing and then management through several approaches. The process of soil testing is based upon collecting an ideal soil sample, followed by its processing. The steps involved are illustrated below:

A. Soil sampling is the collection of a representative soil sample from a field for laboratory analysis of pH, fertility, salinity, organic matter and nutrient status.

Sampling Units: Divide the field into homogeneous units based on soil type, topography, drainage, cropping history, fertilizer/manure use, irrigation and previous land use. Sample each homogeneous unit separately.

Selection of Sampling Points

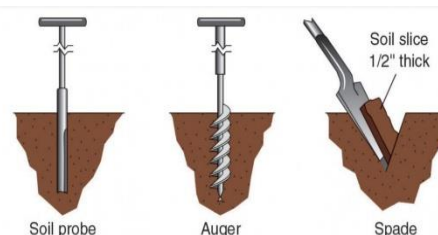
- ✓ Select sampling points using a random or zigzag (Z/W) pattern.
- ✓ Collect 10–20 soil cores from each sampling unit. Preparation of the Sampling Site
- ✓ Before sample collection, remove surface litter, crop residues, stones, and other foreign materials without disturbing the soil surface. This prevents contamination of the soil sample.



Collection of Soil Cores

Collect soil using a soil auger, tube, soil probe, core sampler, or stainless-steel spade. The sampling depth should correspond to the crop rooting zone and the intended analysis:

- ✓ Use a soil auger, soil probe, tube sampler or clean stainless-steel spade.
- ✓ Collect soil uniformly from the required depth:
- ✓ 0–15 cm: Routine soil fertility analysis
- ✓ 15–30 cm: Subsoil/nutrient leaching studies
- ✓ Deeper layers: As required

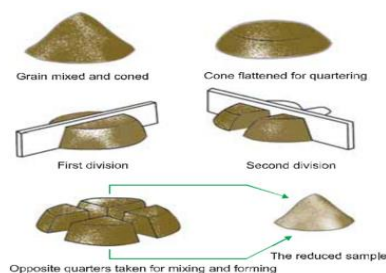


Composite Sample Preparation

- ✓ Mix all cores collected from the same sampling unit thoroughly.
- ✓ Remove stones, roots and coarse debris.
- ✓ Prepare approximately 500–1000 g of representative composite sample.

Sample Processing

- ✓ Air-dry the sample in shade under dust-free conditions.
- ✓ Gently crush and pass through a 2-mm sieve for routine analysis.
- ✓ Use finer sieves where required for specific analyses.



Sample Packaging and Labelling

Label each sample with:

- Sample ID/field number
- Location/GPS coordinates
- Sampling depth
- Date of collection
- Crop history
- Intended analysis

Samples should be transported promptly to the laboratory. For microbiological and enzymatic analyses, maintain samples at 4°C and avoid prolonged storage. For chemical analyses, store air-dried samples in airtight containers to prevent moisture absorption and contamination.



B. Soil health card

The Soil Health Card (SHC) is a comprehensive report provided to farmers under the Soil Health Card Scheme, launched by the Government of India in 2015. It provides information on soil properties, nutrient status and crop-specific fertilizer recommendations, helping farmers adopt balanced nutrient management, improve soil fertility and productivity, and reduce excessive use of chemical fertilizers.

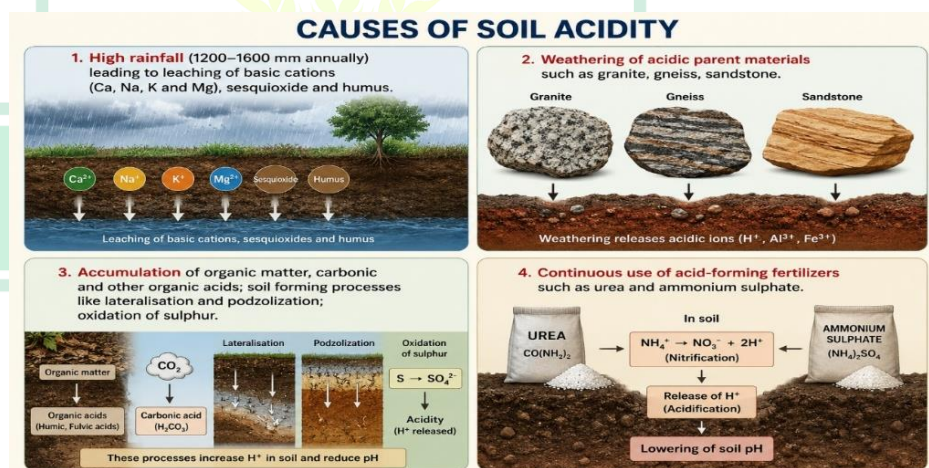


Soil Parameters: A Soil Health Card generally reports the following parameters:

Parameter	Importance	General desirable/fertile range	Unit
Soil pH	Indicates soil acidity or alkalinity, affecting nutrient availability.	6.5-7.5	-
Electrical Conductivity (EC)	Measures soil salinity and its effect on crop growth.	< 1.0	dS m ⁻¹
Organic Carbon (OC)	Indicates soil organic matter and overall soil fertility.	0.75–1.50	%
Available Nitrogen (N)	Essential for vegetative growth and chlorophyll formation.	> 280	kg ha ⁻¹
Available Phosphorus (P)	Promotes root development, flowering, and seed formation.	> 22	kg ha ⁻¹
Available Potassium (K)	Improves water regulation, disease resistance, and grain quality.	> 280	kg ha ⁻¹
Sulphur (S)	Required for protein synthesis and oil formation.	> 20	mg kg ⁻¹
Zinc (Zn)	Essential for enzyme activity and growth hormones.	> 1.2	mg kg ⁻¹
Iron (Fe)	Necessary for chlorophyll synthesis.	> 4.5	mg kg ⁻¹
Manganese (Mn)	Important in photosynthesis and enzyme activation.	> 2.0	mg kg ⁻¹
Copper (Cu)	Supports reproductive growth and enzyme systems.	> 0.2	mg kg ⁻¹
Boron (B)	Essential for flowering, fruit set, and cell wall development.	> 0.5	mg kg ⁻¹

C. Soil Acidity and its management

India has a total geographical area of 318.37 million hectares. Of this, 0.61 million hectares are classified as strongly acidic soils (pH ≤ 4.50), 36.25 million hectares as moderately acidic soils (pH > 4.50 to ≤ 5.50), and 61.84 million hectares as slightly acidic soils (pH > 5.50 to ≤ 6.50).



Collectively, these acidic soils cover 98.71 million hectares, accounting for approximately 31% of India's total geographical area. So, soil acidity is one of the most serious constraints to agricultural production in India.

Soil became toxicity of aluminium (Al) and manganese (Mn) and reduces the availability of nutrients such as calcium, magnesium, phosphorus, nitrogen, boron and molybdenum. It also retards biological activities in the rhizosphere, especially the symbiotic/or mutualistic association of plants with beneficial fauna and flora (Thakuria et al. 2016). These factors directly and indirectly affect plant growth. Other major constraints associated with acidic soils include severe water stress due to restricted root growth in the subsurface horizon (Adams 1984). Together, these severely limit the scope of increasing crop productivity. Phosphorus becomes unavailable because it is fixed by iron and aluminium. (Eswaran et al. 1997).

Classification of soils based on pH

Category	pH range
Extremely acidic	<4.5
Very strongly acidic	4.5-5.0
Strongly acidic	5.1-5.5
Moderately acidic	5.6-6.0
Slightly acidic	6.1-6.5
Neutral	6.6-7.3

Category	pH range
Slightly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9.0
Very strongly alkaline	> 9.0

*(Source: Sarkar 2015)

Acidic soil management

1. Liming-

It refers to addition of application of lime or suitable alternative liming materials in combination for managing both surface and subsoil acidity. Liming also enhances fertilizer use efficiency, herbicides efficacy, minimizes environmental risks associated with soil degradation, and ultimately improves the economic returns to farmers (Prochnow, 2014).

Calcium carbonate equivalent (CCE) values of some important liming materials.

Liming material	Calcium Carbonate Equivalent CCE (%) *
Calcium oxide	179
Magnesium oxide	250
Calcium hydroxide	136
Magnesium carbonate	119
Dolomite	109
Calcium carbonate	100
Basic slag	86
Paper mill sludge	80

*CCE is the acid-neutralizing capacity of the material compared to pure CaCO_3 expressed as a weight percentage of CaCO_3 (Das, 2014).

Lime requirement (t/ha) = (target pH – current pH) x soil texture factor

*Soil texture factor: Loam to clay loam – 4; Sandy loam – 3; Sand- 2

Raising the soil pH by up to 1 unit is recommended. For example: to raise a sandy loam soil of pH 4.8 (CaCl_2) to pH 5.5 (CaCl_2) $(5.5 - 4.8) \times 3 = 2.1$ tonnes of lime per hectare is required.

(source-Department of Environment and Water of South Australia)

2. Integrated Nutrient Management (INM)

The following approach can be adopted:

Soil testing → Lime/dolomite according to lime requirement → Balanced fertilization → Organic manure/compost → P management → Correction of nutrient deficiencies → Acid-tolerant crops → Soil and water conservation → Regular monitoring

Organic amendment	General recommended dose	Main role in acid soil management
<i>Farmyard manure</i>	5-10 t/ha (2–4 t/acre)	Adds organic matter, improves buffering capacity, soil structure and nutrient availability
<i>Vermicompost</i>	2-5 t/ha (0.8–2 t/acre)	Enhances microbial activity, nutrient availability and soil structure
<i>Green manure</i>	10-20 t fresh biomass/ha	Adds organic matter and nutrients and stimulates biological activity
<i>Crop residues</i>	2-5 t/ha	Recycles nutrients and increases soil organic matter
<i>Poultry manure</i>	2-5 t/ha	Supplies nutrients and organic matter; improves soil fertility
<i>Biogas slurry</i>	5-10 t/ha	Adds organic matter and readily available nutrients
<i>Biochar</i>	1-5 t/ha	Improves pH buffering, CEC, water retention and nutrient retention
<i>Neem cake/oil cakes</i>	0.5-1.5 t/ha	Supplies nutrients and organic matter and supports biological activity

3. Suitable Crop Selection

The crop selection should always be prioritized based on soil Ph. Some examples are provided below

Acid-Tolerant Crops	Sensitive Crops
Rice	Chickpea
Groundnut	Lentil
Finger millet (ragi)	Onion
Potato	Cabbage
Pineapple	Cauliflower

4. Biological & Long-term Management: Use of beneficial microorganisms such as mycorrhizae and phosphate-solubilizing microbes; prevention of further soil acidification; periodic monitoring of soil pH and fertility

Management practice	Beneficial microorganism / input	General dose per ha	Method of application	Major benefit in acidic soil
Mycorrhizal inoculation	Arbuscular mycorrhizal fungi (AMF/VAM)	2–5 kg/ha of commercial inoculum	Apply in the root zone at planting/transplanting; mix with FYM/compost and place near roots	Improves P uptake, root growth, water absorption and tolerance to acidic soil conditions
Phosphate solubilization	Phosphate-solubilizing bacteria (PSB)	2–5 kg/ha carrier-based formulation	Mix with 25–50 kg FYM/compost and broadcast/incorporate into soil before planting, or apply in the root zone	Improves availability of fixed phosphorus in acidic soils
Mycorrhiza + PSB	AMF + PSB consortium	As per manufacturer's recommended dose	Apply near the root zone; preferably with organic manure/compost	Provides complementary benefits for root development and P nutrition
Azotobacter inoculation	<i>Azotobacter</i> spp.	2–5 kg/ha carrier-based formulation	Mix with 25–50 kg FYM/compost and apply to soil near the root zone; seed treatment may also be used as per product recommendation	Enhances biological N fixation, plant growth and nutrient availability
Azospirillum inoculation	<i>Azospirillum</i> spp.	2–5 kg/ha carrier-based formulation	Mix with FYM/compost and apply near the root zone, or use as seed/seedling treatment according to the recommended method	Enhances root development, biological N fixation and nutrient uptake under acidic conditions

Conclusion

Soil health management is essential for sustaining agricultural productivity, particularly in acidic soils where aluminium and manganese toxicity, phosphorus fixation, nutrient deficiencies, and restricted root growth can severely limit crop production. A systematic approach beginning with proper soil sampling, laboratory analysis, and interpretation through the Soil Health Card provides a scientific basis for site-specific soil management.

Management of acidic soils should focus on an integrated approach involving soil-test-based liming, balanced nutrient management, organic amendments, suitable crop selection, beneficial microorganisms, and soil and water conservation. Liming or suitable alternative materials can correct soil acidity, while organic manures, compost, green manure, biochar and crop residues improve soil organic matter, buffering capacity, nutrient availability and biological activity.

The use of acid-tolerant crops together with beneficial microorganisms such as arbuscular mycorrhizal fungi, phosphate-solubilizing bacteria, *Azotobacter* and *Azospirillum* can further improve nutrient uptake, root

development and plant tolerance to acidic conditions. Regular monitoring of soil pH and fertility is necessary to prevent further acidification and maintain long-term soil productivity.

Thus, empowering smallholder farmers with knowledge of soil testing, appropriate liming, balanced fertilization, organic resource recycling, biological inputs and suitable crop choices can restore soil health, improve nutrient-use efficiency and productivity, and strengthen the long-term sustainability and resilience of farming systems.

Reference

Das DK. 2014. Soil acidity. Pages 218–244 in *Introductory Soil Science*, 3rd edition. Kalyani publishers: Ludhiana, India.

Adams F. 1984. Crop response to lime in the southern United States. Pages 211–265 in *Soil Acidity and Liming*, 2nd Edn (Adams F, Ed.), American Society of Agronomy, Madison, Wisconsin, USA.

Eswaran H, Reich P and Beinroth F. 1997. Global distribution of soils with acidity. Pages 159–164 in *Plant Soil Interactions at Low pH* (A C Moniz, Ed.). Sao Paulo, Brazil: Brazilian Soil Science Society.

Sarkar AK. 2015. Soil acidity and liming Pages 329-352 in *Soil Science: An Introduction*. New Delhi, India: Indian Society of Soil Science.

Prochnow BL. 2014. Soil acidity evaluation and management. *Better Crops* 98 (1): 22–25.

Thakuria D, Hazarika S and Krishnappa R. 2016. Soil acidity and management options. *Indian Journal of Fertilisers* 12 (12): 40–56.

Department for Environment and Water. (2026, April 8). Soil acidity. <https://www.environment.sa.gov.au/topics/soil-and-land-management/soil-health-and-condition/soil-acidity-monitoring>

Jena D. 2008. Management of acid soils for sustainable crop production. NAE-Acid Soil Bulletin No. 4. Bhubaneswar, Odisha: OUAT

Nanda SK, Mishra A, Pradhan NK and Muralidharudu Y. 2008. Soil testing and fertilizer recommendation in Orissa. STCR technical bulletin. Bhubaneswar, Odisha: OUAT.

Mishra, A., Nayak, R. K., Chander, G., Reddy, M., & Choudhari, P. (2020). Management of acidic soils. In G. Chander, P. Choudhari, G. L. Sawargaonkar, A. Mishra, & R. K. Nayak, *Mapping the nutrient status of Odisha's soils* (pp. 50–55). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Behera S K, Shukla A K, Mishra R, Mohanty M and Nayak A K. 2026. Acid Soils of India. Indian Council of Agricultural Research, New Delhi, 12 p.

NANOTECHNOLOGY IN FOOD AND NUTRITION



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ABSTRACT

Nanotechnology defined as the understanding and control of matter at a nanoscale where unique phenomena enable novel applications. Nanomaterials are further stated as substances between 1 and 100 nm in size showing physical, chemical and biological properties that are not found in bulk samples of the same material. Today, new products can be obtained in various fields (medicine, electronics, defence, textiles, etc.) by taking advantage of the superior features of nanotechnology. Nowadays, food and related applications can be shown among the affected areas in parallel with the nanotechnological developments. In this study, we aimed to determine the use of nanotechnology in foods. Nanotechnology applications have emerged with increasing need of nanoparticle uses in various fields of food science and food microbiology, including food processing, food packaging, functional food development, food safety, detection of foodborne pathogens, and better shelf-life of food and/or food products. The purpose of this review is to provide the applications and perspectives of nanotechnology in foods.

Nanotechnology's implementation in food systems will bring new approaches to improving food safety and nutritional value. It sums up the capability of nanoparticles for their utilization in the food business to give purchasers a safe and tainting-free food and to guarantee the customer adequacy of the food with upgraded useful properties. With the increase in shelf life and enhanced quality, the edible packages or thin-film usage can delay the deterioration of food. To regulate the nanomaterials and applications in the food industry a legal basis has been made. The Organization of Economic Co-operation and Development (OECD) recommended the standard test guidelines be used for the hazard assessment of nanomaterials for chemical safety. Finally, nanotechnology supports the change of the existing food processing systems to attest the safety of the products, nurturing a healthy food, and also the food's nutritive quality to be enhanced. The straightforwardness of security issues and natural effect should be the need while managing the advancement of nanotechnology in food frameworks and hence mandatory testing of nano food varieties is expected before they are delivered to the market.

Keywords: Nanotechnology, foods, food applications.

INTRODUCTION

In the food industry, nanotechnology is used to improve food quality, safety, storage, and nutritional properties. The increasing demand for nutritious, safe, and long-lasting food products has encouraged researchers to develop nanotechnology-based solutions. Nanomaterials have unique properties such as high surface area, increased reactivity, and improved mechanical strength, making them suitable for food applications.

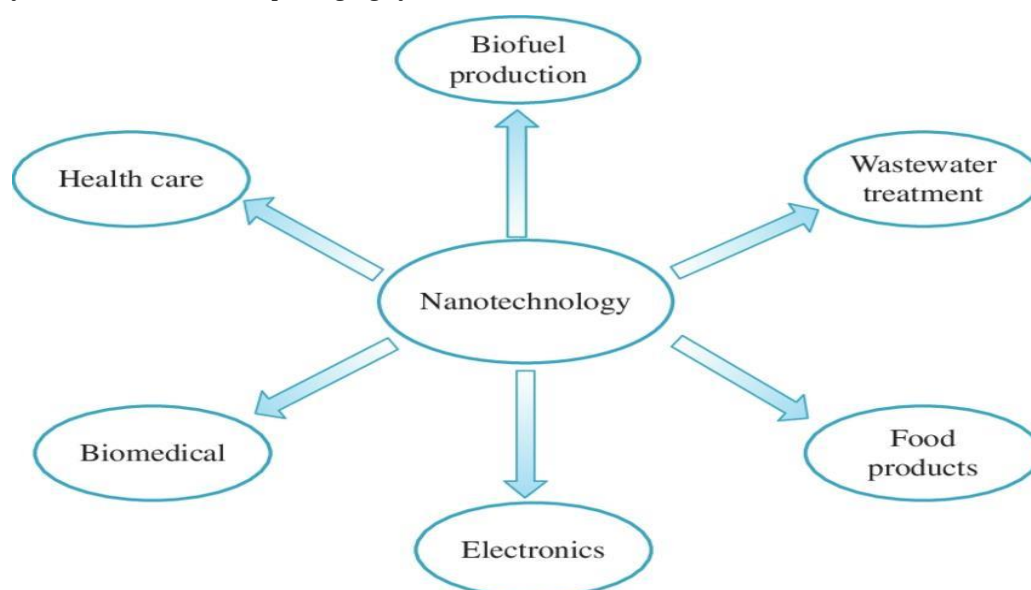
The incorporation of nanotechnology in food and nutrition offers numerous advantages, including enhanced nutrient absorption, targeted delivery of bioactive compounds, improved food packaging, and rapid detection of food contaminants. However, safety concerns and consumer acceptance are important factors that require further research.

In recent years, nanotechnology has gained significant attention in the fields of food and nutrition due to its potential to improve food quality, safety, shelf life, and nutritional value. The application of nanotechnology in food systems has led to the development of innovative products and processes, including nanoencapsulation of nutrients, smart packaging, nanosensors for food safety, and enhanced delivery of bioactive compounds.

In nutrition, nanotechnology offers promising approaches to increase the bioavailability and stability of vitamins, minerals, antioxidants, and other functional ingredients. It can help overcome challenges related to poor solubility, degradation during processing, and limited absorption of nutrients in the human body. Furthermore, nanotechnology-based packaging materials can monitor food freshness and prevent microbial contamination, thereby reducing food wastage and improving consumer safety.

Nanotechnology is defined as the manipulation, production, and application of materials and structures with dimensions ranging from 1 to 100 nanometres to obtain novel properties and functions.

In food science, nanotechnology refers to the use of nanoscale materials and techniques to improve food quality, safety, nutritional value, and packaging systems.



Despite its numerous advantages, the use of nanotechnology in food and nutrition also raises concerns regarding toxicity, environmental impact, and regulatory issues. Therefore, extensive research and proper risk assessment are essential to ensure its safe and sustainable application. Overall, nanotechnology has the potential to revolutionize the food and nutrition sector by providing innovative solutions for global challenges such as food security, malnutrition, and sustainable food production.

APPLICATIONS OF NANOTECHNOLOGY IN FOOD AND NUTRITION

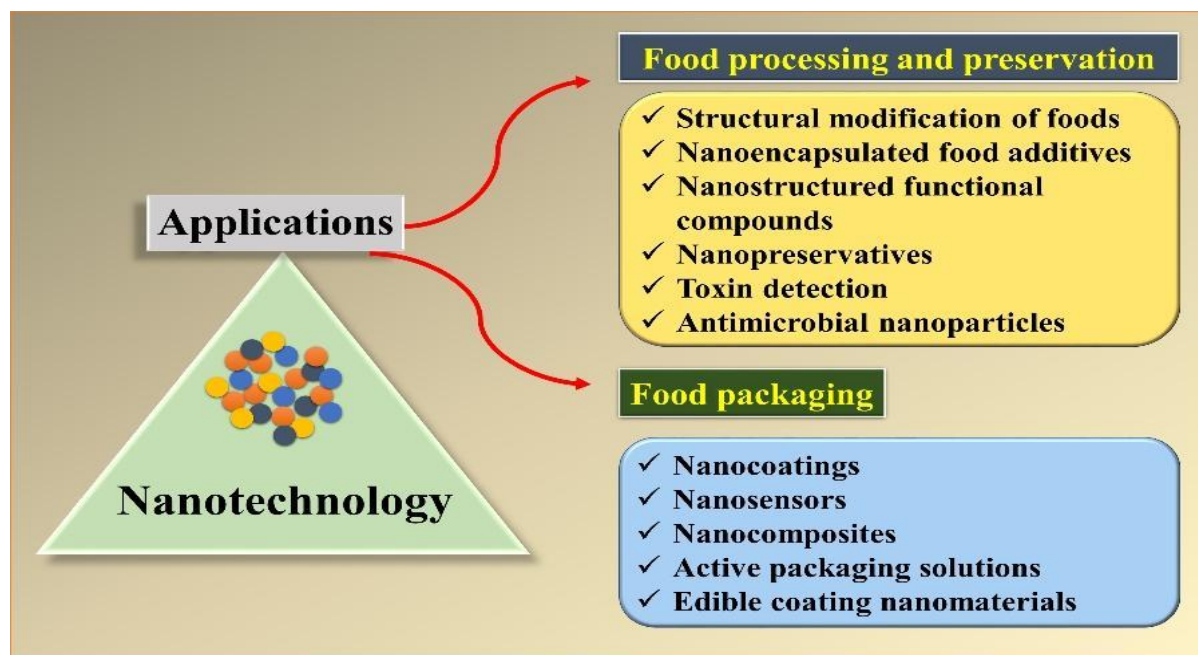
FOOD PROCESSING AND PRESERVATION

Nanoparticles are being applied for the structural modification of foods, e.g., nano-structured lipids have been introduced to duplicate the creamy texture of the foods in place of fat rich products. Such lipids are used as ingredients in frozen desserts, ice cream, nanostructured mayonnaise dairy spreads, etc. Nano-encapsulation is another prospective that provides possibilities for successive release of multiple bioactive compounds. Additives, like, synthetic lycopene, benzoic acid, ascorbic acid, citric acid, isoflavones, fat soluble vitamins, omega-3 and omega-6 fatty acids, lutein, β -carotene are used in nano-encapsulated forms and find wide-ranging applications in functional food. The nanostructured functional compounds are being encapsulated in protein-based carriers (micelles) or oil-based carriers (liposomes). The nano-carriers can help in preventing thermal degradation and masking unusual flavours and Odour of any peculiar additive.

Inorganic nanomaterials of various transition metals and their oxides (e.g. iron, silver, titanium dioxide and others), nonmetals (e.g. selenium, silicates, etc.), and alkaline earth metals (e.g. magnesium, calcium, etc.) find direct applications in health food products. Nano selenium is being advertised as a tea additive with greater redox

equilibrium and antioxidant activity. SiO_2 (E551), MgO (E530), and TiO_2 (E171) are permitted by the U.S. Food and Drug Administration (FDA) as anti-caking agent, flavour carriers and colouring additives. Gums, candies, cake icings, puddings pies, and white sauces are incorporated with TiO_2 (E171) as a colouring material. Major uses of silver nanoparticles are as a source of micronutrient and an antimicrobial agent (Woodrow Wilson International Centre for Scholars, 2008). Its application is therefore gaining importance in health-foods and antimicrobial packaging. Antibacterial nano silver particles have been shown to be effective against a wide range of Gram-positive and Gram-negative bacteria, including antibiotic-resistant species. Ashwood *et al.*, found aluminosilicate nanoparticles suited as anti-caking additives.

FOOD PACKAGING



Nanotechnology applications in the area of food packaging hold new potential for increasing its functionality and efficacy. Antioxidants and antimicrobial nanomaterials are getting incorporated in the packaging material as an active packaging approach aiding preservation of food products. Nano materials are used for the wrapping of food products offering solutions by heat resistant properties and modifying the penetration activities of foils, increasing the mechanical, chemical and microbial obstacle effects. Bentonite and montmorillonite have been certified as “generally recognized as safe” by the USFDA and are classified in the Effective Food Contact Substances (FCS) list. Nano clay particles were embedded in plastic polymers for improved gas-barrier qualities, silver and zinc oxide nanoparticles for antibacterial activities, and titanium dioxide and nitrides nanoparticles for mechanical strength and UV protection, respectively.

The use of active Nano packaging aiming efficient nutrient release into food and edible coating materials to minimize the spoilage and extend shelf life has been verified in multiple studies. Metal nanoparticles are being applied in edible coating materials for its improved barrier properties, antimicrobial capacities and controlled release of nutrients. Nano silver coated fruits and vegetables stay active during transit and storage because of the changed respiration mechanism. Nylon nanocomposite can be utilized to increase oxygen and CO_2 barrier characteristics while also removing odours from food. Flores-Lopez *et al.* found that using thinner hybrid edible films (less than 100 μ thick) enhanced CO_2 , oxygen and moisture barrier capabilities while also improving shelf life and sensory attributes of food items. Graveland-Bikkera studied the measured release of functional ingredients from the nanocomposites in the packaging material and monitored the migration of minerals, micronutrients and probiotics in food. Kumar and Munstedt discovered that Nano silver particles had antibacterial capabilities against yeast, moulds, protozoa, and some viruses. The antibacterial capabilities of metal nanoparticles were attributed to shape, size, exposed surface area, particle internalization, and chemical functions. Moussa evaluated the

antifungal influence on strawberries coated with Nano silver impregnated chitosan. After 7 days of storage at ambient condition (25 °C), the fungal deterioration of coated samples was around 10% contrast to 90% of uncoated ones. Costa determined the effect of alginate coating impregnated with silver-montmorillonite nanoparticles on the shelf life of carrots subsequently packed in polypropylene (PP) bags. They found that the combination of active coating and PP bags extended the shelf-life of fresh cut carrots to around 70 days compared to 4 days in case of the uncoated samples.

Detection of heavy metals, toxicants, pathogens, contaminants, allergens, non-nutritional parameters and microclimatic factors (humidity, light, temperature etc.) are some of the applications of nanosensors. Nanosensors have great ability to expedite the rate of identification, detection, and quantification of pathogens, decaying substances, and allergy-causing proteins having least detection limits and portability along with improved sensitivity. Goldschmidt discovered that using fluorophores and quantum dots lowered the apparatus size while increasing detection sensitivity. As a result, these nanodevices might have a huge influence on food security. Toxin detection has been investigated using nanoparticle-based molecular mimicry and colorimetric assays, with positive findings for cholera toxin detection. A single bacterium could be isolated in less than 20 min utilizing fluorescent-based quantification of bacteria by using antibody doped nanoparticles of silica. Thus, this analytical methodology was able to decrease the typical plating procedure of 16-18 h to only a few min, and it was even able to identify the existence of even some individual cellular impurities, which is impossible to achieve with traditional methods. Nanosensors are often used on food packaging to monitor external and interior product conditions as well as to precisely identify various pollutants in food. Nanosensors are also gaining traction as a powerful tool for monitoring the interactions between food and packaging materials in storage. As a consequence of any interaction, the nanosensors provides a response (visual and electric signal) correlating with the status of the food product. Nano barcodes have already been commercially accepted for food authenticity.

NANOTECHNOLOGY AND NUTRITIONAL ENHANCEMENT

One of the most important applications of nanotechnology in nutrition is nanoencapsulation, in which nutrients are enclosed within tiny capsules to protect them from heat, light, oxygen, and moisture. This technique improves the stability of sensitive nutrients such as vitamins A, C, D, and E, omega-3 fatty acids, and probiotics, thereby increasing their shelf life and effectiveness. Similarly, nano emulsions are used to enhance the solubility and absorption of fat-soluble vitamins and bioactive compounds. These nano-sized emulsions have a larger surface area, which allows nutrients to be absorbed more efficiently by the body. Nanoliposomes, which are microscopic vesicles made of phospholipids, are also used to deliver nutrients and antioxidants in a controlled manner while protecting them from degradation.

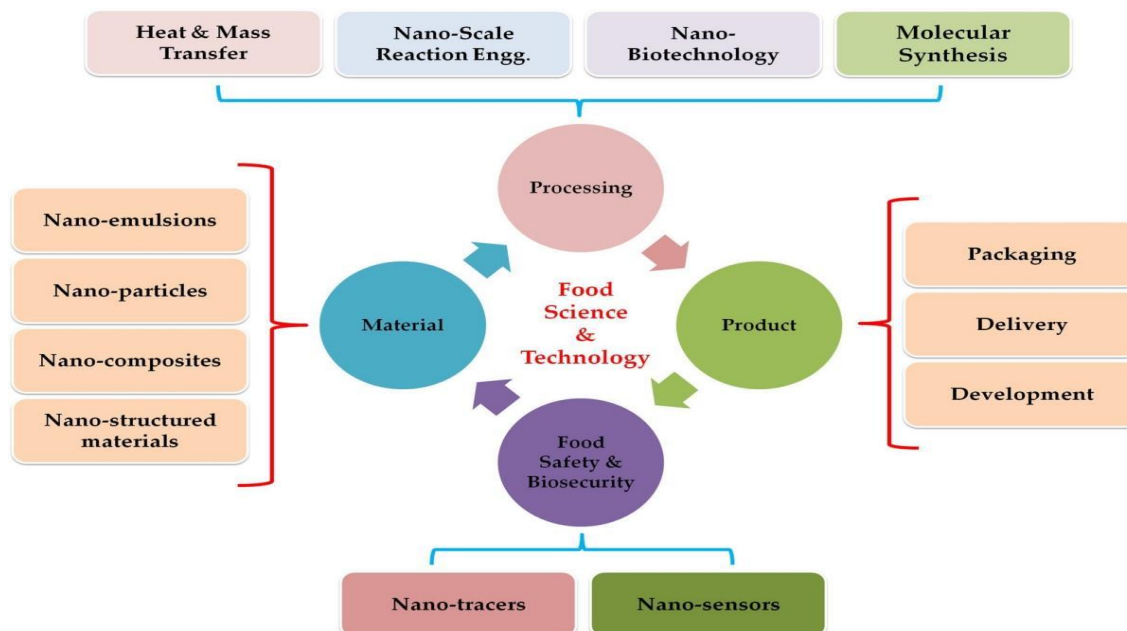
Nanotechnology has significantly contributed to the development of fortified foods, functional foods, and nutraceuticals. Nano-sized minerals such as iron, zinc, and calcium exhibit improved bioavailability and are increasingly being used to combat micronutrient deficiencies. Functional foods enriched with nano encapsulated probiotics, antioxidants, and omega-3 fatty acids provide additional health benefits beyond basic nutrition. Furthermore, nutraceuticals such as nano curcumin, nano coenzyme Q10, and nano resveratrol have shown enhanced absorption and therapeutic effectiveness due to their reduced particle size and improved delivery systems.

The use of nanotechnology in nutritional enhancement offers several advantages, including improved nutrient stability, increased bioavailability, controlled and targeted delivery of nutrients, reduced nutrient loss during food processing, and enhanced sensory qualities such as taste and texture. These benefits make nanotechnology a promising approach for addressing malnutrition and improving public health. However, there are also certain challenges associated with its application. Potential toxicity of nanoparticles, lack of long-term safety studies, high production costs, regulatory concerns, and consumer acceptance remain important issues that need to be addressed before widespread commercialization.

BENEFITS OF NANOTECHNOLOGY IN FOOD AND NUTRITION

Nanotechnology offers several benefits in food and nutrition by improving food quality, safety, and nutritional value. It enables the development of Nano encapsulated nutrients, which enhance the stability, bioavailability, and controlled release of vitamins, minerals, antioxidants, and other bioactive compounds, thereby increasing

their effectiveness in the human body. In food packaging, nanomaterials improve barrier properties against moisture, oxygen, and microbial contamination, extending shelf life and reducing food spoilage. Nanotechnology also facilitates the rapid detection of pathogens, toxins, and contaminants through nanosensors, ensuring better food safety. Furthermore, it contributes to the development of functional foods with enhanced taste, texture, and nutritional properties while reducing the need for artificial additives. Overall, nanotechnology has the potential to promote healthier diets, minimize food losses, and support sustainable food production systems.



CHALLENGES OF NANOTECHNOLOGY IN FOOD AND NUTRITION

Nanotechnology offers numerous benefits in the field of food and nutrition; however, its widespread application faces several challenges. One of the major concerns is **safety and toxicity**, as nanoparticles are extremely small and may interact with biological systems in unexpected ways, potentially causing harmful effects on human health and the environment. Another challenge is the **lack of comprehensive regulations and standardized guidelines** for the production, use, labelling, and safety assessment of nanomaterials in food products. Regulatory authorities in many countries are still developing frameworks to monitor nano-based products effectively.

The **high cost of research, development, and commercialization** is also a significant barrier, as sophisticated equipment and advanced technologies are required to manufacture nanoparticles. In addition, there are challenges related to **large-scale production**, including maintaining uniform particle size, stability, and quality during manufacturing. Consumer acceptance is another important issue because many people are unaware of nanotechnology or have concerns regarding its safety, leading to hesitation in adopting nano-based food products.

Furthermore, the **long-term effects of nanoparticles on human health and the environment are not yet fully understood**, highlighting the need for extensive research and risk assessment. Ethical concerns, such as transparency in labelling and the responsible use of nanotechnology, also need to be addressed. Therefore, while nanotechnology has immense potential, overcoming these challenges is essential for its safe, sustainable, and successful application in food and nutrition.

FUTURE PERSPECTIVES OF NANOTECHNOLOGY

Nanotechnology is an emerging science, which is expected to have rapid and strong future developments. It is predicted to contribute significantly to economic growth and job creation in the EU in the coming decades. According to scientists, nanotechnology is predicted to have four distinct generations of advancement. We are currently experiencing the first, or maybe second generation of nanomaterials. The first generation is all about material science with enhancement of properties that are achieved by the incorporating "passive nanostructures". This can be in the form of coatings and/or the use of carbon nanotubes to strengthen plastics.

The second generation makes use of active nanostructures, for example, by being bioactive to provide a drug at a specific target cell or organ. This could be done by coating the nanoparticle with specific proteins. The complexity advances further in the third and fourth generations. Starting with an advance nano system for e.g. nanorobotics and moving on to a molecular Nano system to control growth of artificial organs in the fourth generation of nanomaterials.

CONCLUSION

Nanotechnology has emerged as a revolutionary technology in the field of food and nutrition. It offers innovative solutions for improving food quality, safety, shelf life, and nutritional value. Applications such as nanoencapsulation, nanosensors, and smart packaging have transformed the food industry by enhancing nutrient delivery and reducing food spoilage. However, concerns related to toxicity, environmental safety, regulatory policies, and consumer acceptance need to be addressed before widespread commercialization. Future research should focus on developing safe, sustainable, and cost-effective nanotechnology-based food systems. With proper regulations and scientific advancements, nanotechnology has the potential to play a vital role in ensuring global food security and improving human nutrition. Nanotechnology holds immense potential across various sectors, offering groundbreaking innovations. However, challenges like safety, scalability, and ethical concerns must be addressed to harness its benefits responsibly. A balanced approach, combining research, regulation, and public awareness, is essential for its sustainable development.

Pharmaceutical nanotechnology has emerged as a discipline having enormous potential as a carrier for spatial and temporal delivery of bioactive and diagnostics and provides smart materials for tissue engineering. It offers new tools, opportunities and scope, which are expected to have a great impact on many areas in disease, diagnostics, prognostic and treatment of diseases through its nano-engineered tools. Pharmaceutical nanotechnology provides opportunities to improve materials, medical devices and help to develop new technologies where existing and more conventional technologies may be reaching their limits. It raises new hope to industries by providing new patientive technologies in view of revenue loss caused due to off-patent drugs. Pharmaceutical nanotechnology has a profound influence on disease prevention efforts because it offers innovative tools for understanding the cell as well as the difference between normal and abnormal cells. It could insights into molecular basis of disease.

REFERENCES (APA 7th Edition)

- Ashwood, P., Thompson, R. P., & Powell, J. J. (2007). Fine particles that adsorb lipopolysaccharide via bridging calcium cations may mimic bacterial pathogenicity towards cells. *Experimental Biology and Medicine*, 232(1), 107–117.
- Bhattacharya, S., & Gupta, R. K. (2005). Nanotechnology and potential of microorganisms. *Critical Reviews in Biotechnology*, 25(4), 199–204. <https://doi.org/10.1080/07388550500361994>
- Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of Colloid and Interface Science*, 363(1), 1–24. <https://doi.org/10.1016/j.jcis.2011.07.017>
- Flores-López, M. L., Cerqueira, M. A., de Rodríguez, D. J., & Vicente, A. A. (2016). Perspectives on utilization of edible coatings and nano-laminate coatings for extending the postharvest storage of fruits and vegetables. *Food Engineering Reviews*, 8(3), 292–305. <https://doi.org/10.1007/s12393-015-9135-x>
- Handford, C. E., Dean, M., Hinchion, M., Spence, M., Elliott, C. T., & Campbell, K. (2014). Implications of nanotechnology for the agri-food industry: Opportunities, benefits and risks. *Trends in Food Science & Technology*, 40(2), 226–241. <https://doi.org/10.1016/j.tifs.2014.09.007>
- Jain, K. K. (2008). *The handbook of nanomedicine*. Humana Press.
- McClements, D. J., & Xiao, H. (2017). Is nano safe in foods? Establishing the factors impacting the gastrointestinal fate and toxicity of organic and inorganic food-grade nanoparticles. *NPJ Science of Food*, 1(1), Article 6.
- Pathakoti, K., Manubolu, M., & Hwang, H.-M. (2017). Nanostructures: Current uses and future applications in food science. *Journal of Food and Drug Analysis*, 25(2), 245–253.

Woodrow Wilson International Centre for Scholars. (2008). *The project on emerging nanotechnologies consumer products inventory*. <https://www.nanotechproject.org/inventories/consumer/>

World Health Organization. (2022). *Food safety aspects of nanotechnology*

Organisation for Economic Co-operation and Development. (2022). *Safety assessment of manufactured nanomaterials*.

Sahoo, S. K., Parveen, S., & Panda, J. J. (2007). The present and future of nanotechnology in human health care. *Nanomedicine: Nanotechnology, Biology and Medicine*.



SELECTING THE BEST SCIENTIFIC LEADERS FOR ICAR *Appreciating the Reform, Examining Its Limitations and Proposing a Strategic Evaluation System*



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The Indian Council of Agricultural Research (ICAR) deserves appreciation for recognising that appointments to senior research-management positions must be transparent, objective and demonstrably based on merit. The Office Memorandum dated 24 July 2026, notifying revised scorecards and a consolidated Standard Operating Procedure for selecting Deputy Directors General, Directors, Assistant Directors General and equivalent officers, is evidence of this concern. It attempts to replace vague impressions and personal preference with declared criteria, specified marks and documentary proof. In a large national organisation, this is an important administrative advance.

The intention is especially commendable because the quality of ICAR's leadership affects much more than the careers of individual scientists. Senior leaders decide research priorities, allocate public money, build multidisciplinary teams, guide young scientists, respond to national emergencies and connect laboratory knowledge with farmers' needs. A weak appointment can slow an institute for several years; an outstanding appointment can transform its scientific culture and public impact. ICAR is therefore right to search for a system that is consistent, fair and resistant to favouritism.

Yet a legitimate question remains: will a detailed scorecard necessarily select the best person? Measurement is essential, but not everything that can be counted represents merit, and not every quality required for leadership can be reduced to a count. A scorecard may establish eligibility and comparability; by itself, it cannot reliably identify wisdom, scientific judgment, integrity, courage, team-building ability or the capacity to lead an institution through uncertainty. If too many fragmented indicators are given mechanical marks, the system may select the best compiler of credentials rather than the best scientific leader.

What the revised framework gets right

The revised framework has several strong features. It publishes the criteria in advance and distributes 100 marks across major domains: management and administration; research and innovation; technology development and commercialisation; desirable qualifications; exposure, recognition and performance; and teaching, coordination or extension contributions. It asks candidates to support claims with certified records and warns against false claims or tampered documents. It also limits the number of entries that may be submitted, discouraging the dumping of bulky dossiers. These provisions can reduce ambiguity and make scrutiny more disciplined.

The framework also recognises that senior scientific merit is broader than journal publication. It includes leadership experience, resource mobilisation, policy contribution, partnerships, interdisciplinary research, technology adoption, patents, socioeconomic impact, work in difficult areas, mentorship and outreach. This is a welcome departure from a narrow publication-only culture. The provision of separate teaching, research-coordination and extension routes acknowledges that ICAR scientists may contribute through different professional roles.

The scorecard is therefore not without merit. Its problem lies less in its objectives than in the assumption that highly specific numerical rules will always produce a valid ranking.

Why excessive precision may create false objectivity

The first difficulty is false precision. Awarding fractions of marks for every year, grant slab, student, technology, germplasm accession, training, partnership or activity produces an impressive numerical total, but the final difference between two candidates may not represent a meaningful difference in competence. One candidate may lead a difficult institutional reform whose value cannot be captured by a prescribed item, while another may

accumulate numerous minor entries that fit the form. Arithmetic then gives an appearance of scientific accuracy to what remains a judgment about quality.

Second, opportunity is unequal. External grants are easier to obtain in some disciplines, institutions and locations than in others. A scientist leading a large, well-established institute may mobilise crores of rupees more readily than a scientist working in a small centre, a remote region or a less fashionable discipline. Similarly, H-index and journal ratings vary greatly among genetics, engineering, economics, extension, soil science and agrometeorology. Comparing raw values across disciplines without normalisation can reward the citation culture of a field rather than the excellence of a scientist.

Third, institutional revenue growth and near-total budget utilisation are imperfect proxies for administrative efficiency. Revenue opportunities depend on mandate, infrastructure, location and marketable services. Spending 99 per cent of a budget does not automatically demonstrate prudent management; unspent funds can indicate delay, but complete expenditure can also conceal low-value spending. The proper question is whether resources produced high-quality, timely and relevant outcomes—not merely whether money was obtained or spent.

Fourth, counts often ignore attribution and depth. A technology may be formally released but little used. An agreement may exist without active collaboration. A policy contribution may be difficult to attribute to one individual. A patent may have small scientific or social value, while an unpatented public-good innovation may transform farming practices. Conversely, the requirement for documentary certification by senior authorities may disadvantage genuine contributions made in complex teams or under leaders unwilling or unable to provide recognition.

Fifth, the publication provisions can create distortions. H-index is cumulative and favours older, citation-rich fields. Journal rating is a useful indicator of visibility but not a direct measure of originality, reproducibility or value to Indian agriculture. Linking publication credit to whether a candidate served as principal investigator may exclude genuine intellectual leadership, especially in modern collaborative science. The best thirty papers should be judged for contribution and influence, not only processed through a journal-based multiplier.

Sixth, APAR ratings and awards are not perfectly comparable. APARs can be inflated and may reflect local reporting cultures. Awards and academy fellowships can signal distinction, but access to nominations and professional networks is uneven. They should corroborate merit, not substitute for an independent assessment of it.

Finally, the framework may encourage strategic behaviour. Once every activity carries marks, scientists and institutions naturally optimise for the scorecard. They may prefer multiple countable outputs to one demanding long-term programme; seek short trainings for certificates; divide contributions; or pursue grants and papers that improve scores but do not address the most urgent problems of farmers. A good evaluation system should reward mission-oriented achievement, not turn scientific careers into the collection of tokens.

The danger of one composite total

A further difficulty is the construction of a single total from fundamentally different kinds of evidence. Leadership experience, publication impact, technology adoption, training, awards and extension work do not operate like identical units that can simply be added. A high score in one domain can compensate mathematically for a serious weakness in another. Thus an eminent researcher with limited people-management ability, or an efficient administrator with weak scientific credibility, may reach the top through compensation across categories. For a senior leadership post, however, some qualities are indispensable. Integrity cannot be traded for citations, and the ability to lead people cannot be replaced by grant income.

The scorecard also uses alternative routes for teaching, coordination and extension. The intention is fair, but the routes may not be equal in difficulty or opportunity. Their numerical equivalence should be tested empirically rather than presumed. Candidates serving at headquarters, institutes, universities, bureaux and project directorates encounter different assignments. A uniform score may therefore standardise the form without standardising the underlying opportunity.

Another concern is the burden placed on certification. Heads of institutions, finance officers, PME cells and controlling authorities must verify numerous claims. This may increase administrative workload, delay recruitment and create inconsistent interpretations. When a large number of certificates becomes essential, the

process can favour candidates with better administrative access and record keeping. Verification is necessary, but it should concentrate on a smaller number of decisive claims and use independent sampling or audit wherever possible.

None of these observations implies that quantitative evidence should be discarded. Counts are valuable warning signals and useful checks. The mistake is to allow them to make the final judgment. A grant figure may prompt inquiry into resource mobilisation; an H-index may indicate sustained scholarly influence; adoption data may suggest impact. Each becomes meaningful only when the committee asks how the result was achieved, what the candidate personally contributed, what constraints existed, and whether the achievement is relevant to the vacant post.

What ICAR should actually seek

For senior research-management posts, ICAR is not merely selecting the most productive scientist. It is choosing a custodian of an institution and a leader of people. The ideal candidate should combine five qualities: credible scientific achievement; demonstrated institutional leadership; measurable contribution to farmers, policy or public good; integrity and collegiality; and a convincing strategy for the position sought.

Past achievement is necessary because promises without performance are unreliable. However, performance must be interpreted in context. A candidate should be assessed against the opportunities, constraints and responsibilities actually faced. Rescuing a weak programme, building a team in a remote centre, developing a nationally useful advisory service, or defending scientific standards under pressure may reveal more leadership than managing an already prosperous unit.

The evaluation must also distinguish contribution from participation. Candidates should identify a small number of their most important achievements and explain their personal role, the problem addressed, evidence of outcome and lessons learned. Quality should take precedence over volume.

A simpler strategic evaluation system

ICAR could retain the present scorecard as a source of verified information but replace mechanical aggregation with a two-stage system. Stage I should establish eligibility and shortlist credible candidates. Stage II should make a holistic, evidence-based assessment of leadership suitability.

Stage I: eligibility and evidence screening

The screening committee should verify essential qualifications, prescribed experience, service record, integrity status and the authenticity of submitted claims. Instead of asking for every possible accomplishment, each applicant should submit a concise evidence portfolio containing no more than ten major contributions: three scientific contributions, three leadership or institutional contributions, two farmer/policy/public-good impacts and two contributions to human-resource development or professional service. A standard contribution note should state the challenge, the candidate's role, collaborators, output, independently verifiable outcome and contextual constraints.

Stage I should not rank candidates through tiny fractions of marks. It should classify applicants as qualified, highly qualified or not qualified, using clear thresholds. The purpose is to identify a manageable pool for serious evaluation, not to declare a winner before the selection committee meets.

Stage II: weighted strategic assessment

The final assessment may use five broad domains totalling 100 marks.

1. Scientific distinction and judgment – 20 marks

Evaluate the originality, rigour and significance of the candidate's five best scientific contributions. Use discipline-appropriate bibliometric information only as supporting evidence. Expert reviewers should judge whether the work advanced knowledge, solved an important problem or created a durable research platform.

2. Leadership and institution building – 25 marks

Examine evidence of setting direction, improving systems, managing resources responsibly, building multidisciplinary teams, resolving conflict, mentoring successors and delivering programmes on time. Results should be assessed relative to institutional size and constraints. A confidential 360-degree reference process, drawing from supervisors, peers and former subordinates, can test whether claimed leadership was inclusive and ethical.

3. Impact on farmers, policy and public value – 20 marks

Assess adoption, beneficiaries, economic or environmental benefit, contribution to policy, preparedness for climate and biological risks, and value to disadvantaged regions. Independent evidence should receive greater weight than institutional certificates. Long-term public-good impact should be valued alongside commercialisation.

4. Integrity, professional conduct and people development – 15 marks

Examine research ethics, fairness, transparency, respect for colleagues, support to young scientists, gender and social inclusion, and responsible handling of public funds. This domain should have a minimum qualifying score. A candidate with serious, substantiated integrity concerns should not be selected merely because the aggregate is high.

5. Vision and suitability for the specific post – 20 marks

Each shortlisted candidate should receive the same realistic institutional case and prepare a short written response. The candidate should also present a five-year vision based on the institute's mandate, national priorities, farmer needs, emerging science, resource limitations and measurable milestones. The committee should test priorities, trade-offs, crisis management and the ability to communicate clearly. This exercise is more predictive of future leadership than another count of past certificates.

Assessment domain	Marks	Central question
Scientific distinction and judgment	20	Did the candidate make original, rigorous and consequential contributions?
Leadership and institution building	25	Did the candidate improve people, systems and programme performance?
Farmer, policy and public value	20	Did the work produce independently verifiable public benefit?
Integrity and people development	15	Did the candidate lead ethically, fairly and inclusively?
Vision and post-specific suitability	20	Can the candidate set priorities and lead the institution's next five years?

Safeguards for fairness and credibility

Several safeguards are essential. The selection committee should contain scientific experts, an experienced research administrator, an external specialist in institutional leadership and, where relevant, a stakeholder familiar with farmer or industry needs. Members should declare conflicts of interest, and conflicted members should recuse themselves. At least part of the evidence review should be conducted independently before the committee discussion.

Scores should be anchored with behavioural descriptions. For example, a high leadership score should require evidence of institution-wide improvement and team development; an average score may reflect competent management without transformation; a low score should indicate mainly positional authority without demonstrated results. Such anchors reduce arbitrary marking.

Discipline and opportunity must be normalised. Grant mobilisation should be evaluated relative to field, institutional baseline and the candidate's role. Bibliometrics should be field-normalised and age-sensitive. Work in remote or resource-poor settings should be treated as context influencing all relevant achievements, not merely as a small bonus item.

The committee should record a brief reasoned assessment for every shortlisted candidate, identifying strengths, risks and suitability for the particular post. The final recommendation should require both a threshold score in integrity and leadership and a majority judgment that the candidate is appointable. If the top arithmetic score belongs to a candidate judged unsuitable, the committee should be able to recommend another candidate—but only through a written, auditable justification.

ICAR should review the system after two recruitment cycles. It should examine whether selected leaders subsequently improved research quality, staff climate, financial governance, technology uptake and stakeholder confidence. A selection system is valid only if its scores predict successful leadership. Feedback from candidates and committee members should be used to remove redundant criteria and unintended biases.

Implementation can be gradual. ICAR could pilot the proposed method for a small group of comparable vacancies while continuing the notified scorecard for formal screening. Independent observers could compare the ranking produced by the mechanical score with the assessment produced by the portfolio, references, case exercise and vision presentation. Where the two systems disagree, the reasons should be examined—not to favour either method automatically, but to learn which evidence better predicts subsequent performance. The pilot would allow ICAR to refine behavioural anchors, train committee members and develop common standards before wider adoption.

Conclusion

ICAR's effort to make senior appointments transparent and merit-based deserves sincere appreciation. The revised scorecard reflects institutional seriousness, broadens the meaning of scientific contribution and demands evidence. These are valuable reforms that should be preserved.

However, the best scientific leader cannot be discovered by adding a very large number of small, heterogeneous marks. Excessive detail can obscure strategic merit, magnify unequal opportunity and reward documentation over depth. The solution is not to abandon measurement, but to use it intelligently: verify eligibility, examine a limited portfolio of major contributions, assess achievements in context, obtain independent evidence, test integrity and people leadership, and evaluate a candidate's vision for the specific institution.

A transparent process need not be mechanically rigid, and professional judgment need not be subjective if it is structured, diverse, documented and accountable. By combining evidence with informed peer judgment, ICAR can move from selecting the highest-scoring applicant to selecting the person most capable of advancing science, strengthening institutions and serving Indian farmers. That is the standard worthy of India's premier agricultural research system.

Source: Indian Council of Agricultural Research, Office Memorandum F. No. 3(1)/2025-Per. IV, dated 24 July 2026, "Notification of Revised Scorecards, Weightage Framework and Standard Operating Procedure (SOP) for Selection to Research Management Positions in ICAR."

The Paradox of the Country's Food Basket: Overflowing Cereal Granaries, Declining Crop Diversity and Widening Nutritional Imbalances:

Current Status, Key Drivers and the Way Forward



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Introduction

The country's total food production has undergone a spectacular transformation, from acute scarcity in the mid-sixties to an all-time high of 357 MT in 2024-25, and is estimated to scale further heights in 2025-26 (third advance estimate: 376 MT) — thanks to the availability of agro-ecological region- and situation-specific, input-responsive superior cultivars and their matching agro-production and protection technologies. Little surprise, then, that the country has emerged today not only as the world's largest producer (2025-26 estimate: 154 MT) and exporter (2025-26: 24.5 MT) of rice, but also maintains strategic reserves of rice and wheat almost five times the buffer stock norm as on April 2026 (Gulati et al., 2026).

Equally impressive is the performance of various other commodities in the domestic food sector, namely edible oils (1970-71: 2.7 MT; 2024-25: 12.5 MT), fruits (a seven-fold increase over the 16 MT of 1970-71), freshwater, marine and brackish water aquaculture fisheries (an eleven-fold increase over the 1.76 MT of 1970-71), poultry (1970-71: 6.2 billion eggs; 2024-25: 149.1 billion eggs) and dairy (1970-71: 2.16 MT; 2024-25: 247.9 MT).

The country has been known for its rich diversity of crops and cropping systems since times immemorial. This raises a pertinent question — whether the incredible performance of the country on the farm front has been achieved without compromising on its inherent agro-ecological resilience, the sustainability of its natural resources and its environmental health, or at the cost of the latter. This article is an attempt to unravel answers to the above question, to identify major shifts, if any, in the exploitation of these precious twin natural resources and the key factors driving them, and to suggest a way forward towards a sustainable, eco-friendly and more balanced food production system across the food groups.

1. The Country's Changed Scenario on the Farm Front vis-à-vis its Diverse Food Crop Groups

The net cropped area (NCA) in the country has remained more or less stable at around 141 M ha since 1970-71. Unlike NCA, the gross cropped area (GCA) shot up from 165.8 M ha in 1970-71 to as high as 226 M ha in 2024-25, on account of a steep increase in cropping intensity (1970-71: 117.8%; 2024-25: 159.7%). As is obvious from the facts highlighted in Table 1, the post-Green Revolution era witnessed decisive shifts in cropping patterns — from a diverse system to an overwhelmingly cereal-dominated one.

1.1 Cereals

The cereal group of crops underwent a major transformation in its aggregate acreage and output, as well as in the share of its different constituents. While the overall area under cereals increased only marginally (+7.9%), there were nevertheless several losers and gainers within the group, owing to an imbalanced intra-group redistribution among its different players.

Wheat and rice displayed remarkable momentum, both in the growth of their combined acreage (+50.6%) and in their contribution to total food grain output (=75%) as well as total cereal output(=93%)in 2024-25; what is more, together they both captured not only 3.5 and two times the additional area available for cultivation by 24-25 for cereals (=8Mha) and and total food grains(=13.24Mha)but more than 65% of the entire food basket(=43 Mha) as well.Maize is another major beneficiary: its area under cultivation (=6.24Mha I.e 106.7%) and its production (+479.6%) as well as coverage under irrigation (+27%; total area under irrigation in 24-25:31%))registered remarkable spurt over the period in question.

The nutri-cereal group of crops, acclaimed as a powerhouse of nutrition, has turned out to be the biggest loser — not only in terms of its overall area (a decline of 26.42Mha), but also in its share of the aggregate acreage under cereals (1970-71: 39.4%; 2024-25: 12.45%) as well as total food grain output (1970-71: 21.3%; 2024-25: 5.7%). Several crops from the group, such as sorghum, bajra, ragi and a host of other minor millets, either went into near oblivion or were totally marginalised.

Although the cereal group as a whole received the highest coverage under irrigation (2024-25: 65%), only rice (70% irrigated) and wheat (96% irrigated) benefitted most from bulk of the extra area brought under irrigation by 24-25 under cereals (91% of 43Mha) as well as food grains (82% of 48Mha).

Notwithstanding the steep decline in the share of nutri-cereals over the period, the cereal group not only surpassed all other food groups in aggregate domestic production, but was also left with substantial structural surpluses far above the buffer stock norms — unlike every other food category — even after the export of 20.63 Mt of rice (basmati: 6.50 MT; non-basmati: 14.13 MT) in 2024-25, amounting to total foreign exchange earnings of US\$ 14.6 billion. This is in addition to the sale of 5.2 MT of broken and damaged rice from FCI stocks to distilleries in 2024-25, at a fixed price under the Open Market Sales Scheme (OMSS) as mandated in the ethanol policy.

1.2 Grain Legumes

Unlike the nutri-cereal category, the pulse group as a whole exhibited positive growth in area (+23.0%) as well as in total output (+117.3%), though not as pronounced as in cereals. Despite these improvements, the overall share of the pulse group in GCA declined (1970-71: 13.6%; 2024-25: 12.3%), as did its share of total food grain output — from 10.9% in 1970-71 to 7.2% in 2024-25 — reflecting the disproportionate growth of cereal crops at the expense of pulses.

As with the nutri-cereal group, a number of grain legumes — particularly cowpea, red peas, lentil and lathyrus, which otherwise hold considerable promise as catch, relay or sequence crops and are known for their resilience and adaptability to marginal growing situations — suffered badly. Whatever improvement is visible in the group, be it in total area or output, comes entirely from tur, chickpea, moong and urd; together, these four legumes account for more than 80% of the area and production under pulses.

Unlike cereals, pulse production (2024-25: 25.68 MT) continues to lag behind domestic demand (2024-25: 32.94 MT), resulting in chronic import dependency (2024-25: 22.04%) at a huge cost to the exchequer (2024-25: US\$ 5.48 billion).

1.3 Oilseeds

The oilseed group as a whole benefitted not only in terms of increased area under cultivation (+84.3%) and share of total GCA (1970-71: 9.9%; 2024-25: 13.5%), but also in total output, which went up by more than four times over 1970-71(=9.54MT)

What is shocking is that a number of predominantly rainfed oil crops — safflower, sunflower, niger and linseed — which at one time attained peak acreage and were projected to offer enormous scope under limiting-moisture and low-input conditions as potential candidates in the country's march towards a second yellow revolution, have fallen by the wayside. Though not as severely affected as the above, both castor (2024-25: 0.96 M ha) and sesame (2024-25: 1.58 M ha) also exhibited shrinkage in acreage as well as in total production.

Surprisingly, groundnut — which ruled the oilseeds front prior to the 1990s — also lost its supremacy to soybean and rapeseed-mustard; by the end of 2024-25 it had suffered a loss of as much as 1.57 M ha of its area. Interestingly, soybean, which was little known until the mid-1980s (1985-86: 1.34 M ha), occupied the highest acreage (12.95 M ha) as well as the largest share of total oilseed output in 2024-25 (36.4%). Next to soybean, rapeseed-mustard played a sizeable role in boosting the total availability of edible oils in 2024-25; though the crop's share in GCA changed little over the period, its acreage rose from 3.32 M ha in 1970-71 to 8.66 M ha in 2024-25, taking its share of total oilseed area and output to 28.4% and 29.5% respectively — thanks to coverage of more than 80% of its acreage under irrigation. No surprise, then, that the top three performers together accounted for a lion's share of both total acreage and total output under oilseeds (>90%), with all other crops reduced to insignificant players.

Despite significant improvements in the domestic availability of edible oils — by as much as 6.3 and 2.5 times over 1970-71 and 1990-91 (coinciding with the erstwhile yellow revolution) respectively — the country still faces a huge demand–supply gap, forcing it to resort to heavy imports in 2024-25 (16.41 MT; value: US\$ 17.37 billion) on account of rapidly rising incomes, changing lifestyles and dietary patterns, and the resultant spurt in per capita consumption levels.

1.4 Vegetables and Fruits

The contribution to GCA of the two horticultural groups in question — which otherwise hold an important place in human nutrition as sources of fibre, macro- and micronutrients and vitamins — rose from 3.20% in 1970-71 to 8.13% in 2024-25. Over the same period, the area under vegetables increased by 223.6%(11.23Mha) and their production by 706.5%(=207MT), while the area under fruits rose by 287.5%(=7.13Mha) and production by 602.7%(=11.3 MT).

As is the case with oil crops, pulses and millets, these groups are predominantly raised under rainfed situations (irrigated share of GCA: 7.75%). If domestic availability based on current production is any indication, then — unlike fruit crops — the production of vegetables in the country still falls short of requirements based on ICMR-NIN daily dietary intake rates for the group. More than production per se, it is affordability and distribution that limit consumption levels in this group.

1.5 Sugarcane

As in the case of wheat and rice, sugarcane is yet another highly favoured crop, particularly in water-stressed areas such as Maharashtra and elsewhere. Between 1970-71 and 2024-25 its area more than doubled from 2.61 Mha of 70-71 (+109.2%) and total cane output rose more than three-and-a-half fold (+260.1%). Notwithstanding limited surface water resources in most of its areas of cultivation, as much as 97% of the crop is today under irrigation based on extracted groundwater.

Contrary to the continued imbalances noticed in grain legumes, millets and edible oils, the country is surplus in sugar (total gross production in 2024-25: 29.5 MT). As per 2024-25 data, the country not only exported 3.5MT of sugar but also diverted as much as 3.4 MT (sugar equivalent) of its overall output towards ethanol production.

2. What Really Prompted Farmers to Resort to Such Large-Scale Shifts?

As already highlighted, the country's major concern is no longer cereal security but nutritionally balanced and sustainable food security coupled with agro-ecological health. Even today, as much as 45–50% of the country's net cropped area depends on the wayward monsoon. This rainfed area forms the principal habitat of anna/nutri-cereals, pulses and most oilseed crops, which are known not only for their climate resilience but as important sources of human nutrition. What, then, is driving farmers resort to such large scale shifts from oilseeds, grain legumes, nutricereals, horticultural crops from even their traditional heartlands namely rainfed areas—whether technological constraints, or policy-induced ones? As is obvious from the factors set out below, the root cause for the marginalisation of this group of crops lies in the continuation of a decades-old policy framework designed for a food scarcity era, and in several subsequent initiatives, rather than the low per hectare yields of the affected crops per se.

2.1 Highly discriminatory procurement. Guaranteed 100% procurement at minimum support prices (MSPs) is effectively confined to rice and wheat and is all but denied to other crops, barring limited procurement of pulses and nutri-cereals for the PDS or for strategic reserves. MSPs therefore continue to be more or less ornamental for all of the affected crop groups, despite the major thrust given to them under special national missions for oilseeds (NMEO-OS), pulses (Mission Atmanirbharata) and millets (NFSM).

2.2 State bonuses over and above MSP. The payment of additional bonuses on every quintal of paddy procured by state after state, over and above the MSP — in the form of either inputs or a cash bonus, as in Telangana (+20%) and Chhattisgarh (+40%) — and the resultant demand push, set against the total absence of any such incentive for the affected crops in question.

2.3 Free and subsidised power. The availability of free or subsidised power and the resultant indiscriminate expansion of water-intensive crops, even under borewell and tubewell irrigation, in the hitherto traditional habitat of pulses, millets, oilseeds and horticultural crops. The result is increased groundwater extraction (2024-25: 245.64 BCM), of which agriculture is the biggest beneficiary (87%, i.e. 213.29 BCM). Available data on the

irrigated share of rice (70%), wheat (96%), maize (32%) and sugarcane (97%), as well as the overall increase in irrigated area as a percentage of GCA (1970-71: 23%; 2024-25: 60.64%), amply demonstrate the powerful impact of free power on crop shifts.

2.4 Captive demand created by the ethanol blending programme. The creation of captive demand for the water-intensive crops rice, maize and sugarcane through their promotion as feedstocks for ethanol production under the E20 blending policy (EBP), backed by direct procurement at or above MSP with prompt payment by distilleries. This is clear from the high share of maize (45%), rice (21%) and sugarcane (34%) as feedstocks, and from the sale of broken and damaged rice by FCI to ethanol producers at well below its economic cost to FCI (₹43/kg against an OMSS sale price of ₹23/kg) (Gulati et al., 2026). Little surprise, then, that after the scaling up of EBP in 2020 the area under maize (+22.24%), sugarcane (+12.4%) and rice (+12.02%) registered a significant surge by 2024-25, particularly in the water-scarce areas of Punjab, Haryana, western Uttar Pradesh and parts of Maharashtra.

2.5 Free grain distribution under NFSA. Free distribution of rice and wheat at 5 kg per family member per month to close to 800 million persons under the NFSA — despite a substantial reduction in the poverty index to as low as 5% (World Bank) and 11% (NITI Aayog) (Gulati et al., 2026) — and the assured demand it offers for the most preferred grain crops.

2.6 Deep urea subsidy. The supply of urea to farmers at throwaway prices (₹242 per 45 kg bag), which works out to 5–6% of its actual economic cost (US\$ 935 per tonne), the bulk of which goes to irrigated crops such as rice, wheat and sugarcane. This has led not only to a grossly imbalanced N:P:K ratio (norm 4:2:1; actual >12.6:2.6:1) but also to the loss of as much as 50–60% of applied urea through leaching as nitrate and atmospheric loss as nitrous oxide.

2.7 Other policy-driven distortions. These include the export of the country's scarce virtual water resources in the form of basmati (2024-25: 6.50 MT) and non-basmati rice (2024-25: 14.13 MT) at a huge cost to the health of the domestic agro-ecosystem, its environment and its crop diversity — in the face of burgeoning imports of edible oils (2024-25: 16.41 MT) and pulses (2024-25: 7.26 MT), which are in fact a far bigger drain (combined value: US\$ 22.85 billion) than what the country earns through the above exports (US\$ 14.6 billion).

As amply highlighted above, the country's widening food basket imbalances are more a cumulative negative outcome of decades-old policy distortions — compounded by procurement, input subsidy and irrigation biases — than of any deficit in technological support per se.

3. Towards a Nutritionally Secure, Balanced and Sustainable Domestic Food Basket: The Way Forward

As is abundantly clear from the foregoing, the country has not only achieved cereal security but produces far beyond its domestic needs. What it needs today is a well-balanced total food and nutritional security, in accordance with the ICMR-NIN recommended daily dietary consumption of the various food groups, for ensuring optimal growth, development and good health.

Barring cereals, per capita annual availability continues to fall far short of nutritional benchmarks for visible edible oils, protein-rich pulses, nutrient- and micronutrient-rich nutri-cereals and vegetables. Realising such a goal calls for the expeditious removal of a host of policy-driven constraints and biases currently limiting the horizontal and vertical expansion of these food crops, through appropriate policy interventions or their re-balancing away from cereal crops, as outlined below.

- **Disincentivise water-intensive crops grown on extracted groundwater.** Disincentivise the cultivation of highly water-intensive crops such as rice and sugarcane based on groundwater extraction from borewells and tubewells in hitherto dryland areas — which takes advantage of 24×7 free or subsidised power and various other policy-induced favourable conditions — and instead promote, in all such areas and situations, oilseeds, millets, pulses, vegetables and horticultural crops. These not only make efficient use of scarce water resources but help reverse the adverse effects associated with the traditional flooded rice-based mono-cropping system: poor fertiliser and irrigation water management, soil degradation, groundwater contamination and the emission of methane.
- **Shift the fertiliser subsidy from product to farmer.** The current fertiliser subsidy regime calls for a shift from product to farmer, in the form of direct benefit transfers on a per acre basis, leaving fertilisers to open

market prices. Such a system would not only wean farmers away from the prevailing harmful practice of excessive reliance on urea but encourage them to adopt the most economical, balanced and efficient option. Alternatively, the current nutrient-based subsidy should be extended to nitrogenous fertilisers alongside phosphatic and potassic fertilisers, to discourage rampant excessive use and the associated serious imbalance in the N:P:K ratio.

- **Move the country's energy security thrust from 1G to 2G feedstocks:** Apart from the serious ecological cost in terms of groundwater depletion in the country's already precarious zones and air and sub-soil water pollution, the principal focus of the country's energy security intervention — the EBP's reliance on water-intensive food and feed crops as ethanol feedstocks — has led to the accelerated replacement of oilseeds, pulses and nutri-cereals, particularly after its scaling up in 2020-21. Unless urgent corrective steps are taken to reverse the damage, the country's import burden on edible oils and pulses may shoot up far beyond the current US\$ 22.85 billion (2024-25), thereby making the very goal of achieving atmanirbharata in these critical food groups through either improvement in their domestic availability or through combined savings from EBP and rice exports elusive, if not impossible. The situation therefore, calls for a major shift from first-generation (1G) to second-generation (2G) feedstocks — crop residues, agro-processing wastes/ byproducts such as bagasse, maize cobs etc — which are abundantly available but either burnt or under-utilised, in place of the current diversion of food/feed crops through setting up of a chain of decentralised 2G bio refineries in all potential agro climatic regions of the country on the lines of IOCL Panipat, Haryana, NRL Numaligarh, Assam and BPCL Bargarh, Orissa. Apart from ensuring energy security, such a strategy would not only help the country tackle the widespread practice of burning crop residues and the associated problem of smog and air pollution but offer additional revenue stream to the farmers. The Translation of the country's humongous biomass potential into reality at ground level nevertheless, warrants strong R&D efforts towards development of most cost-efficient technologies for conversion of cellulosic material into 2G ethanol, backed by matching supply chain infrastructure for aggregation, storage and transport. Latest reports of shortages and emerging inflationary pressures in sugar and the moves of government imposing restrictions on stock limits for large buyers, if any indication only further strengthens the need for urgency towards 2G shift for averting the impending threat of food-feed crisis.
- **Exploit sisal and other non-competing biomass for 2G ethanol.** Besides multipurpose crops such as sweet sorghum, agricultural residue, processing (bagasse) and other organic waste, sisal (Agave), which comes up well on waste and degraded lands and hence competes with cultivated crops for neither food, feed nor land (Basu, 2026), also offers immense potential for the production of 2G ethanol. Efforts need to be initiated to exploit such non-problematic renewable plant resources.
- **Revive pongamia and jatropha for biodiesel on a stronger research base.** The country not only offers huge avenues for harnessing various food/non-food/ multipurpose sources of biofuels, be it CBG (cattle dung, press mud, vegetable and fruit waste etc) or 2G ethanol (Bagasse) or IG (molasses) but also production of biodiesel as well. The exploitation of oil-yielding species such as pongamia and jatropha — which at one time created enormous hype under the erstwhile national mission on biodiesel but failed completely because of a premature launch without the necessary backing of high-yielding varieties or production technologies — also offer considerable promise as feedstocks for biodiesel production (Ranga Rao, 2006). Unlike ethanol feedstocks, neither of them competes for land, food or feed, as both come up well on wastelands. What the country requires to capitalise on their full potential is a stronger research effort for the development of superior varieties and planting material with matching production technologies.
- **Extend assured procurement beyond rice and wheat.** The denial of guaranteed procurement at minimum support prices to crops other than rice and wheat continues to be one of the major reasons for the increasing shift of farmers away from traditionally cultivated dryland crops — pulses, oilseeds, millets and horticultural crops — towards irrigated rice, wheat, sugarcane and, since 2020, maize. Besides restriction of current open-ended procurement of paddy as well as additional bonus to a pre-fixed quantity /farmer for dissuading the latter from their obsession with rice, also extend assured procurement and other incentives to crops which are in deficient supply more particularly oilseeds and pulses; such an incentive would give a tremendous boost to

their cultivation and reverse crop shifts in their favour, which is crucial for restoring balance to the domestic food basket.

- **Re-orient edible oil policy from consumer-centric to win-win.** The widening demand–supply gap in edible oils, rapidly rising consumption levels in the face of a declining share of GCA, and the resultant chronic dependence on imports warrant a shift from the decades-old consumer-centric policy framework towards one that is a win-win for both vulnerable consumer segments and farmers, if the country is to free itself from overwhelming import dependence (~60%) and achieve hitherto elusive self-reliance in edible oils (Ranga Rao, 2026). These measures include, inter alia: declaration of MSPs as per the M. S. Swaminathan Committee formula, i.e. $C_2 + 50\%$ of C_2 cost, backed by 100% guaranteed procurement; adoption of a calibrated import tariff structure taking advantage of the wide leverage available under the WTO trade regime (soybean 45%; other oils 300%) in place of the current zero (unrefined) and low (refined) duties, which permit the dumping of cheap imports to the disadvantage of oilseed producers; distribution of edible oils through the PDS to marginalised consumers; and the issue of special incentives to oilseed growers in the form of a per acre bonus funded from the savings accruing from reduced imports.
- **Enable genome editing for stress-prone rainfed crops.** The high vulnerability of predominantly monsoon- and receding-moisture-dependent components of the food basket — namely oilseeds and grain legumes — to one or another biotic and abiotic stress continues to hold back breakthroughs on the productivity and nutritional quality fronts, on account of persistent obstacles to the exploitation of state-of-the-art genome editing technologies, which are otherwise entirely free of any foreign genetic material. Efforts need to be stepped up to bring the domestic anti-genome lobby on board and remove this hurdle, in the larger interest of the country's food and nutritional security and of *atmanirbharata* in all such areas of persistent demand–supply gaps.
- **Re-appraise the policy of promoting rice exports.** The present policy of promoting exports of basmati and non-basmati rice — which in reality amounts to exporting millions of litres of virtual water — needs critical re-appraisal, as the foreign exchange earnings from such a strategy are too low compared with what the country spends on imports of edible oils and pulses. Instead, steps may be taken to remove the key stumbling blocks discouraging farmers from growing oil and pulse crops and, through that, accelerate the pace of self-reliance in these crucial areas of concern.

Conclusions

Despite the country's spectacular achievements on the food production front over the last five decades and more, its overall output is disproportionately skewed in favour of rice and wheat, whether in terms of their share of gross cropped area or their contribution to the total food grain basket. Several other critical components of the food basket — oilseeds, grain legumes and nutri-cereals — which otherwise occupy the lion's share of the country's rainfed ecosystem and its diverse cropping systems, and which play a pivotal role as vital sources of health and nutrition, continue to remain grossly marginalised, thereby creating serious structural imbalances in the food basket.

Notwithstanding its reputation as the world's largest producer and exporter of rice, the country's food production system is left with a paradox: huge and unmanageable surpluses and overflowing cereal stocks in the central pool, alongside chronic shortfalls in per capita dietary consumption of pulses and of visible fats and oils relative to the recommended dietary requirements of ICMR-NIN.

The country's continued cereal-centric policy framework — inherited from the food scarcity era of yesteryear — together with the associated overwhelming preferential bias in the form of liberal input subsidies with 100% assured procurement, and the recent promotion of water-intensive food and feed crops as principal feedstocks for ethanol production, are primarily responsible for the increasingly worsening scenario: rising food basket imbalances, rapidly declining crop biodiversity, and threats to ecological health and to sustainable, balanced nutritional food security.

In view of these grave concerns, this article underlines the urgent need for a total revamping of the current, highly skewed policy framework governing the country's crucial farm sector as well as its interventions towards accomplishment of energy security if the latter is to be transformed into a vibrant, ecologically sustainable,

climate-resilient, biodiverse, pro-farmer and self-reliant economy with well-balanced food , nutrition and energy security.

References

- Basu, M. S. (2026). *Harvesting ethanol from sisal (Agave): a strategic pathway for India's dryland bio-economy*. LinkedIn post, 25 March 2026.
- Gulati, A., Juneja, R. and Thangaraj, P. (2026). Rice to ethanol policy is deepening economic and environmental stress. *The Indian Express*, 7 July 2026.
- ICMR-NIN Expert Committee (2024). *Dietary Guidelines for Indians*. National Institute of Nutrition, Hyderabad.
- Ranga Rao, V. (2006). Jatropha hype: promise and performance. In: *Proceedings of the Biodiesel Conference Towards Energy Independence — Focus Jatropha* (eds Brahma Singh et al.), organised by the Rashtrapati Bhavan Secretariat, Bolarum, Hyderabad, 9–10 July 2006, pp. 16–19.
- Ranga Rao, V. (2026). What ails the domestic edible oil economy — stagnation on the production front, or weak farmer- and consumer-health-supportive policy interventions? *Agri-India*, 6(3): 464–466.



Table 1. Major shifts in the country's cropping pattern and food production basket, 1970-71 to 2024-25*

Crop / crop group	Area (M ha)			Share in GCA (%)		Production (MT)			Share in total food grain / oilseed output (%)	
	1970-71	2024-25	% change	1970-71	2024-25	1970-71	2024-25	% change	1970-71	2024-25
CEREALS										
Rice	37.59	51.27	+36.4	22.7	22.3	42.22	150.18	+255.7	38.9	42.0
Wheat	18.24	32.80	+79.8	11.0	14.53	23.83	117.94	+394.9	22.0	33.0
Rice + wheat	55.83	84.07	+50.58	33.7	37.2	66.05	268.12	+305.9	61.0	74.8
Maize	5.85	12.09	+106.7	3.5	5.35	7.49	43.41	+479.6	6.9	12.13
Anna / nutri-cereals	40.09	13.67	-65.9	24.2	6.1	23.06	20.51	-11.06	21.3	5.7
All cereals	101.78	109.83	+7.9	61.4	48.6	96.60	332.05	+243.7	89.1	92.6
PULSES										
Chickpea	7.84	9.12	+16.33	4.7	4.0	5.20	11.11	+113.6	4.8	3.1
Tur	2.65	4.34	+63.8	1.6	1.9	1.88	3.62	+92.5	1.73	1.0
Moong ¹	NA	5.90	NA	NA	2.6	NA	4.24	NA	NA	1.2
Urad ¹	NA	3.16	NA	NA	1.4	NA	2.24	NA	NA	0.62
Other pulses	12.04	5.20	NA	7.26	2.3	4.74	4.47	NA	4.4	1.2
All pulses	22.53	27.72	+23.04	13.6	12.3	11.82	25.68	+117.3	10.9	7.2
Total food grains	124.31	137.55	+10.65	75.0	60.9	108.42	357.73	+229.9	100	100
OIL CROPS										
Groundnut	7.33	5.76	-21.42	4.40	2.6	6.11	11.94	+95.4	64.0	27.8
Rapeseed-mustard	3.32	8.66	+160.8	2.0	3.8	1.97	12.67	+543.1	20.6	29.5
Soybean	Nil	12.95	-	-	5.7	0	15.67	-	-	36.4
Sesame	2.40	1.58	-34.2	1.4	0.70	0.56	0.89	+58.9	5.9	2.1
Other oilseeds	3.44	1.49	-56.7	2.07	0.66	0.90	1.82	+102.0	9.4	4.2
Total oilseeds	16.49	30.44	+84.3	9.9	13.5	9.54	42.99	+358.6	100	100
HORTICULTURE AND SUGARCANE										
Vegetables	3.47	11.23	+223.6	2.09	4.97	25.69	207.20	+706.5	-	-
Fruits	1.84	7.13	+287.5	1.11	3.16	16.08	113.00	+602.7	-	-
Sugarcane	2.61	5.46	+109.2	0.98	2.42	126.40	454.61	+260.1	-	-

* GCA — 1970-71: 165.79 M ha; 2024-25: 225.79 M ha. NCA — 1970-71: 140.78 M ha; 2024-25: 141.37 M ha. Cropping intensity — 1970-71: 117.8%; 2024-25: 159.7%.

¹Separate data for moong and urad were not reported for 1970-71, as they were clubbed with other pulses.

Abbreviations: M ha = million hectares; MT=million tonnes; GCA = gross cropped area; NCA = net cropped area; NA=not available or not applicable