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Eco-Friendly Guardians: Biodegradable Packaging and Storage Pest Management for Sustainable Agriculture



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Abstract

The global agricultural ecosystem is currently navigating a dual crisis: the escalating impacts of anthropogenic climate change and the persistent challenge of post-harvest food loss. In India, where agriculture supports over 50% of the population, the post-harvest sector is uniquely vulnerable to climate variability. Rising temperatures and atmospheric CO₂ concentrations have fundamentally altered the biology of storage pests. Being poikilothermic, insects like the rice weevil (*Sitophilus oryzae*) and pulse beetle (*Callosobruchus* spp.) exhibit accelerated metabolic rates, increased annual voltinism, and expanded geographical ranges in warming environments. Concurrently, the legacy of the "Green Revolution"—characterized by a heavy reliance on petroleum-derived plastic packaging and hazardous synthetic fumigants—has reached a point of environmental unsustainability. This article presents a comprehensive analysis of **Biodegradable Insect-Repellent Packaging (BIRP)** as a transformative, multi-intervention innovation. By synthesizing advanced biopolymer science with the micro-encapsulation of botanical secondary metabolites, BIRP offers a toxin-free "active" storage solution. We provide a clear storyline demonstrating how BIRP serves as a cornerstone for achieving the 2030 Sustainable Development Goals (SDGs), specifically SDG 2, SDG 12, and SDG 13.

Keywords: Climate-resilient agriculture, Biodegradable packaging, Insect pest dynamics, Sustainable Development Goals (SDGs), Post-harvest management.

1. Introduction: The Silent Post-Harvest Crisis

While global agricultural discourse often focuses on crop breeding and field productivity, the storage phase remains the most significant "leak" in the food supply chain. In India, post-harvest losses are estimated at 10–15% annually, a figure that is being exacerbated by the greenhouse gas effect. This loss is not merely a waste of calories; it represents the squandering of the water, fertilizer, labor, and land used to produce that grain. We often celebrate record-breaking harvests, yet the reality remains that millions of tons of grain never reach the consumer's plate because they are reclaimed by the ecosystem in the form of insect biomass or mold. This "silent crisis" undermines the economic stability of smallholder farmers and destabilizes national food security frameworks, particularly in the northern regions where heat stress is becoming an annual certainty.

The Warming Warehouse and Poikilothermic Acceleration

Climate change leads to extreme weather conditions that directly impact the micro-environment of storage structures. Insects are poikilotherms; their internal body temperature, metabolic rate, and reproductive speed are entirely dependent on the ambient environment. In northern India, increased nighttime temperatures prevent the natural cooling of grain silos, maintaining a "thermal inertia" that creates a year-round breeding ground within the warehouse. In many regions, the winter "dormancy" that traditionally suppressed pest populations is disappearing. For example, the Khapra beetle (*Trogoderma granarium*), once restricted by cooler temperatures, is now seeing its geographical range expand. To safeguard our national food security, storage adaptations must be as resilient as the crops grown in the field, moving beyond passive barriers to active biological management.

2. The Failure of Conventional Storage Systems

Traditional storage is built on aging pillars: "Passive Protection" through physical barriers like plastic and "Chemical Intervention" via toxic fumigation. Under modern environmental pressures and the rising demand for chemical-free food, both of these pillars are fundamentally crumbling. The reliance on these methods has created a feedback loop of environmental degradation and biological resistance that can no longer be ignored by the scientific community.

Table 1: Impact of Temperature Elevation on Key Storage Pests

Pest Species	Common Name	Optimal Temp (°C)	Generation Time at 25°C	Generation Time at 32°C
<i>Sitophilus oryzae</i>	Rice Weevil	27–31	~35 Days	~25 Days
<i>Tribolium castaneum</i>	Red Flour Beetle	32–35	~30 Days	~20 Days
<i>Callosobruchus chinensis</i>	Pulse Beetle	28–32	~28 Days	~21 Days
<i>Trogoderma granarium</i>	Khapra Beetle	33–37	~45 Days	~30 Days

2.1 The Plastic Menace: Life Cycle and Soil Health

Conventional polypropylene (PP) and polyethylene bags are non-biodegradable and highly carbon-intensive. Research indicates that every ton of plastic packaging produced releases approximately 1.8 tons of CO₂, fueling the very climate change that drives pest outbreaks. Once discarded, these bags fragment into microplastics which alter soil porosity and reduce water-holding capacity. Most alarmingly, microplastics can be translocated into plant tissues, eventually entering the human food chain through a "plastic-soil-plant" transfer. In India, where rural waste management is still developing, these plastics are often burned, releasing dioxins and furans into the atmosphere, further complicating the agricultural health landscape.

2.2 The Chemical Burden and the "Red Queen" Effect

Fumigants like Aluminum Phosphide are "broad-spectrum" killers that pose severe systemic risks. Repeated chemical use leads to residues in staple grains that are often undetected but contribute to chronic neurological issues in rural populations. Furthermore, warming climates allow pests to produce more generations per year, a phenomenon known as increased voltinism. This rapid turnover increases the rate of natural selection, allowing pests to develop physiological resistance to fumigants faster than scientists can develop new chemicals. This follows the "Red Queen" hypothesis: we are running faster by using more chemicals just to stay in the same place and prevent absolute loss.

Table 2: Comparative Analysis of Packaging Material Properties

Property	Polypropylene (Conventional)	Biodegradable (PLA/PHA)	BIRP (Active Shield)
Degradation Time	400+ Years	6–12 Months (Compost)	6–12 Months (Compost)
CO ₂ Footprint	High (1.8 kg/kg)	Low (0.5 kg/kg)	Negligible (Carbon Neutral)
Pest Protection	Passive (Barrier Only)	Passive (Barrier Only)	Active (Repellent)
Moisture Reg.	Poor (Sweating)	Moderate	High (Selective Permeable)

3. The Innovation: Biodegradable Insect-Repellent Packaging (BIRP)

BIRP represents a paradigm shift toward "Active Guardianship." It is not just a container; it is a biological shield that interacts dynamically with the storage environment. This innovation bridges the gap between material science and entomological defense, creating a packaging solution that breathes with the grain while repelling its enemies.

3.1 Material Composition: From Agricultural Waste to Wealth

The polymer matrix of BIRP is derived from Polylactic Acid (PLA) and Polyhydroxyalkanoates (PHAs), which are synthesized from fermented plant sugars or lignocellulosic waste like rice straw and bagasse. In India, converting stubble into bioplastics provides a massive economic incentive to stop the environmentally disastrous practice of stubble burning, thereby improving air quality while creating a high-value product. Unlike plastic, which traps moisture and causes "sweating" that leads to carcinogenic aflatoxins produced by *Aspergillus* species, BIRP has selective permeability. It allows CO₂ (a byproduct of grain respiration) to escape while maintaining a stable moisture level, suppressing mold growth naturally without the need for additional chemical desiccants.

3.2 The Active Mechanism: Nano-Infused Botanical Defense

The breakthrough in BIRP technology is nano-encapsulation, trapping essential oils in the polymer fibers to be released slowly over a period of 12–18 months. Natural extracts like Azadirachtin from Neem act as ecdysone blockers, ensuring that even if a larva managed to hatch, it cannot molt and dies before reaching maturity. Simultaneously, volatile compounds like Eugenol from Clove and Cineole from Turmeric create a "scent barrier." The bag effectively becomes "invisible" or repulsive to adult insects seeking a host, preventing the initial penetration and egg-laying that typically starts an infestation cycle. This slow-release mechanism ensures long-term protection without the "peak-and-valley" concentration issues associated with manual spraying.

Table 3: Efficacy of Selected Botanicals in BIRP Systems

Botanical Extract	Active Constituent	Mode of Action	Repellency Rate (%)
Neem Oil	Azadirachtin	Growth Inhibition	85–92%
Clove Oil	Eugenol	Neurotoxicity/Repellency	90–95%
Cinnamon	Cinnamaldehyde	Antifungal/Insecticidal	78–84%
Turmeric	Curcumin/Cineole	Respiratory Inhibition	70–75%

4. Aligning with Sustainable Development Goals (SDGs)

The narrative of BIRP is a clear storyline of how a single technological intervention can meet the multi-faceted demands of the 2030 agenda. It serves as a practical manifestation of the "One Health" approach, linking the health of the soil to the health of the harvest and the consumer.

4.1 SDG 2: Zero Hunger through Horizontal Intensification

Post-harvest losses represent "lost hectares" of land and "wasted gigaliters" of water. Saving 15% of the harvest through BIRP is equivalent to increasing India's arable land by millions of hectares without clearing a single forest or using an extra drop of irrigation water. This concept of "horizontal intensification" is the most sustainable way to increase food availability for a growing population while staying within planetary boundaries. It ensures that the efforts of the farmer in the field are fully realized in the food system.

4.2 SDG 12 and 13: Circular Economy and Climate Action

BIRP eliminates the "waste" phase by ensuring that at the end of its life, the bag is fully compostable. It breaks down into organic fertilizer, returning carbon to the soil rather than the atmosphere. Bioplastic production emits up to 80% less CO₂ than traditional plastic. By replacing chemical sprays—which are energy-intensive to manufacture and transport—with plant-based botanicals, we significantly lower the carbon footprint per calorie of our food system. This aligns with the National Mission on Sustainable Agriculture (NMSA) and the National Innovations in Climate Resilient Agriculture (NICRA) projects by reducing the climate vulnerability of the storage phase.

5. Technical Dynamics: Disrupting Pest Fitness

Climate change disrupts the "Tri-trophic" interaction between the Host (Grain), the Pest (Insect), and the Natural Enemy (Parasitoid). In standard plastic bags, humidity spikes favor the pest while killing natural predators that are sensitive to desiccation or extreme moisture. BIRP maintains a "Climate-Smart" micro-environment. Its moisture-regulating properties ensure that natural enemies, such as tiny parasitoid wasps that often require specific humidity to survive, can coexist and help suppress any pests that might survive the botanical repellents. Furthermore, elevated CO₂ can lead to "dilution" of nitrogen in grains, causing insects to eat more to meet their nutritional needs; BIRP mitigates this by preventing the initial infestation from taking hold despite the increased palatability of the grain.

6. Implementation: The Cyber-Physical Warehouse

The future of storage is data-driven, bridging the gap between the physical bag and the digital cloud. Digital tools like PESTPREDICT-EMS integrate local weather data with pest biology models to offer real-time advice. If the humidity in a specific district rises above a critical threshold, the app sends a push notification to farmers to ensure

their BIRP bags are properly sealed. Furthermore, future BIRP bags can be embedded with low-cost RFID or NFC tags that monitor temperature and CO₂ levels internally. This provides a "health report" for the grain directly to the farmer's smartphone without ever opening the bag, which would otherwise introduce oxygen and break the protective environment.

7. Economic Impact and Future Research

While the primary hurdle is the initial cost—currently approximately 50% higher than plastic—the socio-economic benefit is clear when looking at the whole system. Saving just 5kg of grain in a 50kg bag pays for the bag multiple times over in a single season. Beyond direct profitability, the reduction in exposure to toxic fumigants leads to lower long-term healthcare costs for farming families. As we look to the future, research using CRISPR-Cas9 could develop "Self-Protecting Grains" that work in synergy with BIRP, creating a redundant, multi-layered defense system. Collaborative efforts between breeding, entomology, and material science departments are essential to make this technology accessible to the marginal farmer.

Table 4: Estimated Economic Comparison (Per Ton of Grain Stored for 6 Months)

Parameter	Conventional (PP + Fumigation)	BIRP (Active Packaging)
Packaging Cost	₹400	₹850
Chemical/Labor Cost	₹300	₹0
Estimated Grain Loss	12% (₹2,400)	2% (₹400)
Total Cost of Loss/Storage	₹3,100	₹1,250
Net Savings per Ton	-	₹1,850

8. Conclusion

Climate-resilient agriculture (CRA) is the only path forward for a "Viksit Bharat." Biodegradable insect packaging bridges the gap between traditional botanical wisdom and high-tech material science. By integrating BIRP into national policies like NICRA and NMSA, we can transform the Indian warehouse from a point of loss to a fortress of sustainability. Our "Eco-Friendly Guardians" ensure that the hard work of our farmers results in a resilient, food-secure, and plastic-free future. Without understanding these complex interactions between genotype, environment, and pests, our productivity may be compromised; however, with BIRP, we offer a message of hope and prudence for a sustainable tomorrow.

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Pest Control as Applied Ecology: Case Studies



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ABSTRACT

A pest management system known as "integrated control" keeps pest populations below those that are causing economic harm by using all appropriate techniques and methods in the most compatible way possible, taking into account the associated environment and the population dynamics of the pest species. Ecological IPM programs are uniquely designed to balance two objectives: the targeted suppression of harmful pests and the active conservation of beneficial organisms (natural enemies). Ecologically based IPM leverages fundamental ecosystem, such as predation, parasitism, competition, and mutualism, to create a self-regulating environment. This shift from "pest control" to "pest management" relies on these primary ecological pillars, such as the deliberate employment of living things to reduce pest numbers is known as biological control. The Vedalia beetle (*Rodolia cardinalis*), which was introduced to successfully control the Cottony Cushion Scale (*Icerya purchasi*) and prevent the citrus industry from collapsing, is a great example of success. Habitat Manipulation: Altering the farm landscape to favor beneficial species. In rice ecosystems, specific cultural practices, such as synchronous planting, field sanitation, need-based use of pesticide *etc* significantly reduce pest pressure. Then one of the best examples of habitat management is the Push-Pull Strategy. This method uses the Pull component: "Trap" crops (like Napier grass) are planted around the field perimeter. These crops emit chemicals that are attractive to pests than the primary crop, drawing them away from the harvest and the Push component: "Intercrops" (like Desmodium) are planted between the main crop rows. These emit repellent volatile chemicals that drive pests out of the field.

Keywords: pest control, IPM, applied ecology, push-pull strategies

INTRODUCTION

Integrated control is a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in the most compatible manner possible and maintains pest populations at levels below those causing economic injury (FAO, 1967). Chemical insecticides have long been used to manage pests, but excessive use of them has resulted in environmental pollution, secondary pest outbreaks, resistance, and resurgence (Miller *et al.*, 2010). To attain agricultural production that is sustainable without upsetting the natural equilibrium, which is crucial to implement a sound management system founded on ecological principles (Overton, 1996). The publication of Rachel Carson's book *Silent Spring* in 1962 was a turning point for bringing in the integrated pest management (IPM) idea. This concept aims to minimize the negative effects of pesticides and reduce the use of chemicals to control crop pests. The goal of this new method is to change management techniques such that they depend less on pesticides and more on the biology of pests and how they affect crops. Therefore, the only way to sustain productivity and preserve ecosystem health is through ecologically-based IPM that integrates all methods, such as cultural, physical, biological, and chemical (Kennedy and Sutton, 2000). IPM programmes need to be designed in a way to manage pests on the one hand and ensure the build-up of beneficial organisms on the other (Carriere *et al.*, 2010). Ecologically based IPM focuses on an understanding of how ecosystem processes, such as predation, parasitism, herbivory, competition, and mutualism, can be manipulated effectively for the management of pests. It places a strong emphasis on controlling nematodes, bacteria, viruses, fungi, insects, mites, and weeds that interfere with crop yield.

2. Ecological Principles in Pest Control

The term ecology is derived from the Greek word 'oikos' meaning 'house or place to live' & 'logous' meaning 'the science of' or 'the study of'. It is the science that deals with the study of the relationship of organisms with their environment, including both biotic and abiotic factors.

2.1 Biological Control

Biological control is an action of predators, parasitoids, and pathogens that manages the population of insects at a lower average than would occur in their absence.

Types of Biological Control:

1. Importation

- ✓ Introduction of exotic natural enemies into an area where it does not occur naturally to control invasive pests.
- ✓ Importation involves the introduction of a pest's natural enemies to a new locale where they do not occur naturally. The intentional introduction of an exotic, usually co-evolved, biological control agent for permanent establishment and long-term pest control is referred to as classical biological control.
- ✓ Example: *Rodolia cardinalis* (ladybird beetle) to control cottony cushion scale in citrus.

2. Augmentative

- ✓ It is focused on enhancing the numbers and/ or activity of natural enemies in agroecosystems. This strategy involves mass multiplication and periodic release of natural enemies so that they may multiply during the growing season (Gurr *et al.*, 2017).
- ✓ Ex: **Inoculative release:** In Gujarat, introduction of *Fulgoraacia melanoleuca* during 1982, from Maharashtra and Haryana for control of *Pyrilla perpusilla* in sugarcane; **Inundative release:** massive release of *Trichogramma* spp. (Stenberg *et al.*, 2021)

3. Conservation

- ✓ Conservation is a kind of habitat manipulation (environmental modification) that favors an organism for its survival and the effective suppression of targeted injurious fauna and flora (Gurr *et al.*, 2017).
- ✓ e.g., Provide artificial nesting and shelter, avoid harmful practices. Preserve the inactive stage (Burning of trash of sugarcane leaves destroys the resting stage of *Fulgoraacia melanoleuca*).

Key Ecological Mechanisms:

- ✓ Predator-Prey (e.g., ladybugs, spiders) regulate pest populations.
- ✓ Parasitism – Parasitoids (e.g., Braconid wasps) lay eggs inside pests, killing them.
- ✓ Pathogens– Fungi (*Beauveria bassiana*), bacteria (*Bacillus thuringiensis*), and viruses infect insect-pests.

2.2 Habitat Manipulation (Ecological Engineering)

Altering agricultural environments to encourage the control of pests naturally. In addition to the limited and selective use of pesticides, it encompasses appropriate diversity, the use of alternative food sources such as pollen and nectar, refugia and shelters, a moderate microclimate, the use of alternate host/prey insects in the absence of the primary host, behavioral manipulation, host plant resistance, and other cultural practices.

2.3 Biodiversity and Pest Suppression (Hatt and Doring, 2023)

Higher biodiversity leads to natural pest suppression through:

- (i) embracing complexity, by jointly considering the multiple pests and their enemies;
 - (ii) considering traits, in mobilizing the functional grammar;
 - (iii) stacking diversification practices, by strategically combining the multiple facets of plant diversity at multiple scales;
 - (iv) translating ecological processes into socio-economic benefits to adopt a multifunctional perspective.
- ✓ Example: In rice fields, duck-fish-rice polyculture reduces pests by increasing predator diversity.

Case Studies in Applied Ecological Pest Control

1. Biological Control of the Cottony Cushion Scale (*Icerya purchasi*) in California: A Landmark Success in Pest Management (Caltagirone and Doult 1989).

Introduction

The cottony cushion scale (*Icerya purchasi*), a sap-sucking insect origin to Australia, became a devastating pest in California's citrus orchards in the late 19th century. Accidentally introduced around 1868, it spread rapidly, causing severe damage to citrus trees by draining their sap and excreting honeydew, which promoted sooty mold growth. Traditional control methods, such as chemical sprays and manual removal, proved ineffective, leading to significant economic losses for citrus growers.

The Search for a Solution

Recognizing the limitations of conventional pest control, entomologists turned to biological control, a strategy that utilizes natural predators to suppress pest populations. In 1888, the U.S. Department of Agriculture (USDA) sent entomologist **Albert Koebele** to Australia to search for natural enemies of the cottony cushion scale.

Koebele identified two key predators:

1. The vedalia beetle (*Rodolia cardinalis*): A small, red and black ladybird beetle highly specialized in feeding on *I. purchasi*.
2. A parasitic fly (*Cryptochaetum iceryae*): A secondary biocontrol agent that also targeted the scale insect.

Implementation and Rapid Success

In 1888–1889, Koebele shipped 129 vedalia beetles to California. They were released on an infested orange tree in Los Angeles under a tent where they were mass-reared.

The results were astonishing:

- ✓ Beetles multiply quickly. By mid-1889
- ✓ One grower reported millions of beetles clearing his 3200 trees.
- ✓ This scale was wiped out in months. Saving the citrus industry. Orange shipments triple in a year.
- ✓ Cost: only 1500\$ (cheap for saving an entire industry).

Why does it work so well?

1. **Vedalia's superpowers:**
 - Ate scales voraciously.
 - Multiplies fast (8–12 generations per year).
 - Could find hidden scale colonies.
2. **The fly helped too:** Thrived in cooler coastal areas where beetles struggled.
3. **Scale's weakness:** Lived in dense groups, making it easy for predators to feast.

Impact

First major success: This proved that biological control (using natural enemies) could save crops without chemicals

Global inspiration: Beetles were sent worldwide (e.g., South Africa, Peru, Chile) to control the same pest. Sparked interest in finding natural predators for other pests.

Long-Term Legacy: Still working, over 100 years later, vedalia beetles and the fly still keep the scale in check in California and globally.

Exceptions: Failed where:

- ✓ Climate was too cold (e.g., Alps).
- ✓ Scales fed on toxic plants (e.g., Spanish broom) that made them poisonous to beetles.

Scientific milestone: It proved that nature-based solutions could be sustainable and cost-effective, too.

2. Integrated Pest Management (IPM) in Rice Farming: A Sustainable Solution to Stem Borers and Planthoppers in Asia (Way and Heong, 1994)

Introduction

Rice is a primary food for 50 per cent of the global population, mostly within Asia, where it supports millions of smallholder farmers. However, rice production has long been threatened by stem borers (*e.g.*, *Scirpophaga incertulas*) and planthoppers (*e.g.*, *Nilaparvata lugens* and *Sogatella furcifera*). However, the heavy application of man-made pesticides during the mid-to-late 20th century, led to pesticide resistance, secondary pest outbreaks, and environmental degradation. Farmers found themselves trapped in a cycle of increasing chemical use with diminishing returns.

To address these challenges, Integrated Pest Management (IPM) was introduced as an ecological alternative. IPM combined biological practices, cultural control and selective use of pesticide to restore balance in rice ecosystems while maintaining yields.

The Pest Problem: Stem Borers and Planthoppers

1. Stem Borers

- ✓ Damage: Larvae bore into rice stems, causing "dead hearts" (dying tillers) and "white earheads" (empty panicles).
- ✓ Impact: Yield losses of 10-30 per cent, sometimes higher in severe infestations.

2. Planthoppers

- ✓ Damage: Both nymphs and adults suck sap from rice plants, leading to hopper burn (yellowing, drying, and plant collapse).
- ✓ Secondary Issues: They also transmit viral diseases like rice grassy stunt virus.

The Pesticide Paradox

- ✓ Initially, chemical pesticides like organophosphates and pyrethroids provided short-term control.
- ✓ However, indiscriminate spraying led to:
 - Resistance- Planthoppers evolved resistance within a few years.
 - Secondary Pest Outbreaks – Natural predators (*e.g.*, spiders, parasitoid wasps) were killed, allowing pests to rebound.

Environmental Harm– Pesticides contaminated water, harmed fish, and affected farmer health.

The Shift to Integrated Pest Management (IPM), to break the pesticide dependency cycle, researchers and extension programs in the 1980s-90s promoted ecological pest management through IPM.

Key strategies included:

Biological Control: Restoring Natural Predators

- a. Spiders (*e.g.*, *Lycosa pseudoannulata*, *Tetragnatha* spp.)- Major predators of planthoppers; a single spider can consume 5-15 hoppers per day.
- b. Parasitoid Wasps (*e.g.*, *Anagrus* spp. and *Trichogramma* spp.)- Lay eggs inside pest eggs, preventing them from hatching.
- c. Conservation: Farmers reduced broad-spectrum sprays to allow these natural enemies to thrive.

Cultural Practices: Disrupting Pest Life Cycles

- a. Synchronized Planting: Farmers in a region planted rice simultaneously to create a "host-free period," starving pests between cropping cycles
- b. Field Sanitation: Removing crop residues reduced overwintering pest populations.
- c. Resistant Varieties: Some rice cultivars (*e.g.*, IR varieties) had partial resistance to planthoppers.

Judicious Pesticide Use (Only When Necessary)

- a. Threshold-based spraying: Instead of calendar-based spraying, farmers monitored fields and only applied pesticides when pest numbers exceeded economic thresholds.
- b. Selective Insecticides: Using chemicals less harmful to natural enemies (*e.g.*, buprofezin, which targets hoppers but spares spiders).

Outcomes and Success of IPM Adoption

1. Reduced Pesticide Use

- ✓ In Indonesia, pesticide use dropped by 50-60 per cent after IPM adoption, saving costs and reducing resistance (FAO, 1999).
- ✓ Vietnam's "Three Reductions, Three Gains" program (reducing seeds, fertilizers, pesticides) cut pesticide use by 30 per cent without yield loss.

2. Stabilized Yields & Improved Farmer Profits

- ✓ IPM maintained or increased yields by 5-10 per cent in long-term studies (Heong *et al.*, 2015).
- ✓ Lower input costs improved farmer incomes by 15-20 per cent.

3. Ecological Benefits

- ✓ Biodiversity Recovery- Spider and parasitoid populations rebounded, enhancing natural pest control.
- ✓ Health Improvements- Fewer pesticide poisonings among farmers.

4. Policy & Farmer Training Successes

- ✓ Indonesia's National IPM Program (1989): Trained over 200,000 farmers in IPM through Farmer Field Schools (FFS).
- ✓ Philippines and Vietnam- Adopted similar programs, scaling IPM across millions of hectares.

Challenges and Lessons Learned

- Farmer education is critical; IPM requires knowledge of pest ecology, which takes time to adopt.
- Market and policy support were needed for pesticides initially discouraged IPM; policy shifts were necessary.
- Climate Change & New Pests, rising temperatures may alter pest dynamics, requiring adaptive IPM strategies.

3. Push-pull strategy for stemborers and striga weed in african maize fields: a revolutionary agroecological solution (Khan *et al.*, 2000)

Introduction

Maize is a critical staple crop in sub-Saharan Africa, supporting food security and livelihoods for millions of smallholder farmers. However, two major challenges have historically devastated maize yields:

- Maize stemborers (*Busseola fusca*, *Chilo partellus*): Larvae tunnel into stems, causing "dead hearts" and yield losses of 20-80 per cent.
- Striga weed (*Striga hermonthica*, *S. asiatica*): A parasitic plant that attaches to maize roots, draining nutrients and reducing yields by 30-100 per cent.

Conventional control methods (synthetic pesticides, hand-weeding) were often too expensive, ineffective, or environmentally harmful for small-scale farmers. In response to scientists at the International Centre of Insect Physiology and Ecology (ICIPE) and Rothamsted Research developed the Push-Pull Technology (PPT). This innovative agroecological strategy leverages plant biodiversity for sustainable pest management.

The Science Behind Push-Pull Technology

The system works by manipulating pest behaviour through strategic intercropping:

1. The "Push" Component (Repellent Plants)

Desmodium spp. (*Desmodium uncinatum*, *D. intortum*): A forage legume intercropped with maize that:

- ✓ Repels stemborer moths through volatile chemicals (e.g., (E)- β -ocimene, DMNT).
- ✓ Suppresses striga by releasing root exudates that inhibit its germination (allelopathy).
- ✓ Improves soil fertility via nitrogen fixation.

2. The "Pull" Component (Trap Plants)

Napier grass (*Pennisetum purpureum*) - Planted as a border crop, it:

- ✓ Attracts stemborers away from maize (females prefer it for egg-laying).
- ✓ Traps larvae- The grass produces sticky sap that kills young stemborers.
- ✓ Provides livestock fodder, adding economic value.

Implementation and Adoption Across Africa

1. Early Research & Field Trials (1990s-2000s)

- ✓ Pioneered by Prof. Zeyaur Khan (ICIPe) and collaborators (Khan *et al.*, 2000).
- ✓ Field trials in Kenya showed stem borer infestations reduced by 80 per cent and striga counts dropped by 90 per cent.

2. Scaling Up (2010s-Present)

- ✓ Adopted in Kenya, Uganda, Tanzania, Ethiopia, and beyond.
- ✓ Over 250,000 smallholder farmers trained by 2023 (ICIPe, 2023).
- ✓ Women-led adoption, the system's low cost and multifunctionality empowered female farmers.

Documented Benefits of Push-Pull

1. Agricultural Benefits

- ✓ Increased maize yields: From <1 ton/ha to 3-4 tons/ha (doubling or tripling production).
- ✓ Striga suppression: Up to 40-fold reduction in weed density.
- ✓ Reduced pesticide use: Eliminated the need for chemical sprays against stem borers.

2. Ecological Benefits

- ✓ Enhanced biodiversity: Predatory insects (*e.g.*, parasitic wasps) increased.
- ✓ Soil health: Desmodium improves nitrogen levels and reduces erosion.
- ✓ Climate resilience: Drought-tolerant Desmodium varieties (*e.g.*, *D. intortum*) were developed.

3. Socioeconomic Benefits

- ✓ Livestock integration: Napier grass and Desmodium provide high-quality fodder, enabling dairy production.
- ✓ Cost savings: Farmers spend less on pesticides and weeding labour.
- ✓ Gender equity: Women farmers report higher incomes and decision-making power.

Challenges and Adaptations

1. Initial labour requirements: Establishing Desmodium requires weeding in early stages.

- ✓ Solution: Training programs emphasized long-term gains over short-term labour.

2. Region-specific adaptations:

- ✓ Dry areas: Drought-tolerant Brachiaria grass replaced Napier in arid zones.
- ✓ Acidic soils: *Desmodium distortum* was introduced for low-pH soils.

3. Market access: Farmers needed links to sell surplus fodder/milk.

- ✓ Solution: Cooperatives and mobile apps (*e.g.*, Cow) connected producers to buyers.

Case Study Impact in Western Kenya

- ✓ Location: Vihiga County (high striga infestation).
- ✓ Results after 3 years:
- ✓ Maize yields increased from 0.5 to 2.8 tons/ha.
- ✓ Milk production rose by 30 per cent due to fodder availability.
- ✓ Household incomes grew by \$500/year (ACDI/VOCA, 2019).

While ecological pest control is promising, challenges include:

- ✓ Climate change alters pest distributions and natural enemy efficacy.
- ✓ Non-target effects: Some biocontrol agents become invasive.

Future strategies should incorporate genetic, microbial, and landscape ecology approaches.

Several successful implementations of the strategy (Chatterjee and Kundu, 2022):

- Cereal Stem Borers (Africa): The most successful model involves intercropping maize with repellent "push" plants (*e.g.*, silverleaf desmodium) and surrounding the field with "pull" trap crops like Napier grass.
- Cotton (Australia): Use of neem seed extracts as a push stimulus combined with trap crops of pigeon pea or maize.
- Vegetable Pests: Successful management of the Colorado potato beetle (using neem and aggregation pheromones), pea leaf weevil, and onion maggot (using cinnamaldehyde deterrents).
- Oilseed Rape: Use of turnip rape as a pull stimulus and lavender volatiles as a push component to manage pollen beetles.

4. New Biotechnological Approaches to Insect Pest Management in India (Nanda, 2016)

1. The Pest Challenge in India

Insect pests remain a massive economic burden, causing annual crop losses between 15% and 25%, which equates to approximately ₹50,000 crore.

Major Pests: Key threats include Bollworms in cotton, Yellow Stem Borer in rice, and Pod borers in pulses.

Chemical Overuse: In 2012, India consumed roughly 55,000 metric tonnes of chemical pesticides, with insecticides making up 76% of that volume. This has led to toxic residues in food and the decline of beneficial insects.

2. Key Biotechnological Interventions

It includes several high-tech strategies currently being utilized or researched in India:

Bt Cotton: The most significant success story. Since its adoption in 2002, it has grown to cover 90% of India's cotton acreage. It has resulted in a 24% increase in yield and a 37% reduction in insecticide use.

RNA Interference (RNAi): A next-generation gene-silencing tool that targets specific vital genes in pests like *Helicoverpa armigera* and whiteflies. While, currently in lab and field trial stages, it offers high specificity with minimal off-target effects.

Microbial Biopesticides: Utilizing organisms like *Bacillus thuringiensis* and *Beauveria bassiana*, India has over 970 registered formulations. These are particularly effective in organic farming and Integrated Pest Management (IPM).

Sterile Insect Technique (SIT): Releasing sterile males to disrupt insect reproduction, pilot programs for fruit flies in Himachal Pradesh have shown promising results.

3. Field-Level Impact and Case Studies

Empirical data suggests these technologies are viable across different regions:

Maharashtra & Gujarat: Bt cotton adoption reduced pest incidence by over 50% and lowered input costs.

Tamil Nadu: RNAi trials on brinjal (eggplant) achieved 80% larval mortality of the shoot borer.

Karnataka: Using microbial biopesticides in vegetable clusters led to a 20-25% reduction in aphid and whitefly populations.

4. Barriers to Widespread Adoption

Despite technical promise, several hurdles slow the mainstreaming of these tools:

- Regulatory Delays: Complex approval processes by the Genetic Engineering Appraisal Committee (GEAC) often stall progress, as seen with the moratorium on Bt brinjal.
- Resistance: Reports of *Helicoverpa armigera* developing resistance to Cry1Ac proteins in certain zones (e.g., Gujarat) raise concerns about long-term efficacy.
- Socio-Economic Factors: High initial costs and a lack of awareness 60% of farmers remain unaware of non-Bt biotech tools limit adoption among smallholders.
- Research Funding: Investment is low; as of 2013, less than 0.3% of India's agricultural GDP was allocated to biotech research.

Conclusion: It concludes that biotechnology is essential for a "climate-smart" agricultural future in India.

Recommendations

Streamlining Regulations: Creating a "single-window" clearance for low-risk technologies like RNAi.

Farmer Education: Scaling up Farmer Field Schools to bridge the knowledge gap.

National Integration: Incorporating biotech into missions like the National Mission on Sustainable Agriculture (NMSA).

5. Artificial Intelligence & Nature-Based Solutions in Agriculture: A BT Cotton Pest Management Case Study in India (Hemlatha *et al.*, 2025)

Objective & Methodology

The study evaluates an AI-based app, "cottonace," developed by the Wadhwani Institute of AI. The app assists "lead farmers" by identifying and counting PBW moths caught in pheromone traps. When pest counts exceed a specific threshold, the app triggers a localized pesticide spray advisory for a group of farmers, ensuring the chemical application targets the vulnerable larval stage rather than ineffective phases like moths or eggs.

Key Experimental Findings

They conducted two primary pilot programs in 2020-21:

1. Karnataka Pilot (Summer Cotton)

- Participants: 100 irrigated farmers across 13 villages.
- Economic Impact: Adopter farmers saw a 16.6% increase in yield and 7% increase in crop quality (due to cleaner fiber), resulting in 24.6% higher gross income compared to the control group.
- Cost Efficiency: While adopters spent more on pesticides (Rs. 3,500/acre vs. Rs. 1,600/acre), the yield gains significantly outweighed the costs.

2. Maharashtra Pilot (Monsoon Cotton)

- Methodology: Used the "double difference" method to compare current yields against a 3-year historical average to account for external variables.
- Climate Resilience: Despite unusually heavy rains in 2021 that caused widespread crop loss, AI-adopter farmers maintained more stable yields (4% variation) compared to BCI-only farmers (14% loss).
- Result: The study calculated a 25% yield benefit specifically attributable to the AI tool.

Comparative Technologies & Limitations:

Nature-Based Solutions (NBS): Discusses "mating disruption" (using high-density pheromone traps to prevent reproduction) as a successful organic-compatible alternative.

Mechanical Algorithms: Mentions GDD-based (Growing Degree Day) models, like those from the startup "Fasal," which provide effective but "unintelligent" (non-AI) advisories.

Barriers to Adoption: The AI tool currently requires manual weekly trap checking, a labor-intensive task that many farmers disliked. High initial costs for farm sensors (e.g., Rs. 50,000) also pose a barrier to smallholder farmers.

Conclusion

It concludes that while AI offers significant benefits in cost reduction, yield improvement, and cleaner production, its implementation should be cautious and gradual. They highlight that AI may eventually monopolize decision-making roles (irrigation, spraying), while manual labor for sowing and harvesting is more likely to be impacted by mechanical automation rather than AI itself.

6. Conservation biological control in forest: A case study with the pine processionary moth (Plat *et al.*, 2025)

It explores conservation principle in biological control in forest ecosystems, specifically investigating how broadleaved hedgerows can mitigate infestations of the pine processionary moth (PPM), a major native defoliator in Southern Europe.

Objectives and Methodology

To determine if hedgerows provide a favorable habitat for the great tit (*Parus major*), a key avian predator of PPM. The study was conducted in the Landes de Gascogne forest in France, comparing 14 focal pine stands that were adjacent to broadleaved hedgerows on one side and mature pine stands on the other.

They measured three primary metrics:

PPM Infestation: Counting winter nests in pine tree rows.

Bird Predation: Using 1,344 dummy plasticine caterpillars to record attack marks.

Great Tit Activity: Utilizing passive acoustic monitoring and the BirdNET algorithm to quantify vocalizations.

Key Findings

- Reduced Infestation: Pine edges adjacent to hedgerows had significantly lower PPM nest densities (12.00 to 3.12) compared to those adjacent to mature pine stands (16.29 to 3.43).
- Increased Predation: Bird predation on dummy caterpillars was significantly higher on pine edges next to hedgerows (12%) than on those next to mature pine stands (2%).
- Predator Correlation: A significant positive correlation was found between great tit vocal activity and the rate of bird predation on the dummy caterpillars.

- **Habitat Utility:** While great tit activity was similar across both edge types (likely due to their large winter foraging ranges), the increased predation suggests hedgerows serve as critical hunting "launchpads" or resource hubs.

Conclusion and Practical Implications

The study concludes that broadleaved hedgerows represent an effective case of conservation biological control by acting as both a physical/chemical barrier and a habitat for natural enemies. This recommends planting broadleaved hedgerows in conifer monocultures as a sustainable alternative to nest boxes, as they enhance biodiversity and the multifunctionality of the landscape.

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Agro-ecological v/s Natural ecosystem - Characterization



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INTRODUCTION

Characterizing the differences between agroecosystems and natural ecosystems is fundamental to understanding how human intervention reshapes the natural world to meet socioeconomic needs. While both systems operate on the same ecological principles, they differ significantly in their goals, structural complexity, and functional dynamics.

A. Natural Ecosystems (www.nios.ac.in)

Natural ecosystems are self-sustaining systems with minimal human intervention. They maintain biodiversity, nutrient cycling, and energy flows through natural processes.

Key Features:

- ✓ High biodiversity (plants, animals, microbes)
- ✓ Self-regulation (natural pest control, nutrient cycling)
- ✓ Stability and resilience (adapted to local conditions)
- ✓ No external inputs (fertilizers, pesticides)
- ✓ Succession over time (ecological progression)
- ✓ E.g., Terrestrial ecosystem, Deserts, Grassland ecosystem

B. Agroecological Systems

Agroecology applies ecological principles to agriculture, creating sustainable farming systems that mimic natural ecosystems while producing food in a manner that is environmentally friendly.

Key Features:

- ✓ Designed biodiversity (polycultures, crop rotations)
- ✓ Reduced external inputs (organic fertilizers, biocontrol)
- ✓ Soil health focus (cover crops, no-till farming)
- ✓ Integration of livestock and crops (mixed farming)
- ✓ Social and economic sustainability (farmer knowledge, local markets)

Comparative Analysis

Parameter	Natural Ecosystem	Agroecological System
Biodiversity	High (native species)	Managed (selected species)
Nutrient Cycling	Closed loop (natural decay)	Enhanced (compost, green manure)
Energy Input	Solar energy only	Solar+some external (labour, organic inputs)
Pest Regulation	Natural predators	Biocontrol, crop diversity
Human Influence	Minimal	High (but sustainable)
Productivity	Low (for human food)	Moderate to high (food yield)
Resilience	High (adapted)	Variable (depends on management)

Title: Ecology-Based Agriculture and the Next Green Revolution P. Larry Phelan

Source: Sustainable Agroecosystem Management: Integrating Ecology, Economics and Society (2009)

Energy Flow

In natural ecosystems, solar energy is captured and utilized primarily for the maintenance of biomass and the continuation of life cycles within the system. In contrast, agroecosystems are highly subsidized by external energy (fossil fuels for machinery, synthetic fertilizers) to maximize the "provisioning services" of the food, fiber, and fuel harvested for human use (Power, 2010; Marten, 1988).

Nutrient Cycling

Natural Ecosystems: These systems are largely conservative. Nutrients like nitrogen and phosphorus are recycled internally; as plants die and decay, they return nutrients to the soil (Rustad *et al.*, 2020). Agroecosystems are essentially "engines" designed for export, whereas natural ecosystems are "closed loops" designed for maintenance.

Agroecosystems: These are open and "leaky" systems. Large quantities of nutrients are removed during harvest, requiring constant replenishment via fertilizers. This openness can lead to environmental issues like nutrient leaching into groundwater (Rustad *et al.*, 2020).

Resilience and Sustainability

The capacity of a system to sustain its structure and productivity over time in the face of disruptions is known as sustainability.

Inherent Resilience: Natural ecosystems possess high inherent resilience due to their high biodiversity, which acts as "biological insurance" if one species fails, another can often fill its functional niche (Yachi and Loreau, 1999).

Acquired Resilience: Agroecosystems often lack this natural buffer and rely on acquired resilience, human adaptations, and technological fixes to survive climate variability or pest outbreaks⁺.

Stability: Agroecosystems are often more productive in the short term but less stable. Without constant human intervention, they would quickly revert to a natural state or collapse under pest and weed pressure (Marten, 1988).

Properties of the agroecosystem contrast with the natural ecosystems

Parameter	Natural ecosystems	Agro agriculture
Control mechanism	Self-regulating through internal biological feedback system	External (human management), goal-oriented
Successional stage	Naturally progresses towards mature, stable climax communities	Artificially maintained
Nutrient cycling	Closed: nutrients are recycled within the system with minimum loss	Open: nutrients are frequently added and removed
System composition and function	Determined by the success of biotic components interacting with environment and each other	Artificially managed to maximize yield
Selective pressure	Multifactorial	Single traits
Nutrient origin	Soil food web	Chemical salts
Complexity level	Complex with many interacting biotic components	Simplified with relatively few biotic components
Habitat variety	High diversity	Low diversity
Ecological Niches	Niches mostly occupied	High number of open niches
Food chains	Complex and weblike	Relatively short and linear
mutualism	Common	Few
System stability	High (more resistant or resilient to disturbance and invasion)	Low (more susceptible to disturbance or invasion)
Measurement of system efficiency	Energy and resources	Economics

Reference:

www.nios.ac.in

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PLANT SECONDARY METABOLITES AND THEIR ROLE IN BIOTIC STRESS TOLERANCE



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ABSTRACT

Plants face constant challenges from herbivores and disease-causing organisms and they depend on secondary metabolites as vital parts of their defense system. Even though these compounds are not directly involved in the basic metabolic processes of plants, they play a critical role in helping plants survive when under stress. The main types of these secondary metabolites include terpenoids, phenolic compounds, sulphur-containing substances, nitrogen-containing compounds and lectins. Terpenoids function as both toxic agents and signalling molecules, while glucosinolates and phytoalexins help plants respond quickly through enzymatic actions. Alkaloids and cyanogenic glycosides prevent herbivores from feeding by being poisonous and phenolic compounds like flavonoids, tannins and lignin help plants resist damage both structurally and chemically. Lectins interfere with the digestion of insects by attaching to carbohydrates in their gut. These compounds are accumulated in specialized plant structures like trichomes, resin canals and laticifers, where they are strategically retained and released in a regulated manner upon tissue injury. It is important to understand how these secondary metabolites are made and what roles they play, as this knowledge is essential for creating effective and sustainable methods to control pests and enhance the ability of crops to resist damage.

Keywords: Secondary metabolites; Plant secondary metabolites; Biotic stress; Plant defense mechanisms; Terpenoids; Phenolic compounds; Alkaloids; Glucosinolates; Phytoalexins; Cyanogenic glycosides; Lectins

Introduction

Plants are constantly exposed to various types of living stressors, such as insect herbivores, fungi, bacteria, nematodes and viruses. These stressors can greatly reduce plant growth and productivity. Since plants are immobile, they cannot move away from these threats. Instead, they use advanced biochemical mechanisms to defend themselves. A key part of this defense system is the production of secondary metabolites (SMs), which are a wide variety of organic compounds. These compounds are not directly involved in the basic processes plants need to survive, such as growth and reproduction. However, they play a vital role in helping plants adapt to stress and survive. Major types of SMs include alkaloids, phenolics, terpenoids, and glycosides. Each of these groups has different functions, such as deterring insects, inhibiting feeding, acting as toxins, and fighting off infections. The variety and development of these compounds are largely influenced by their interactions with herbivores and pathogens over time, which helps plants improve their ability to resist damage and thrive in their environment. Because of their vast range of structures and biological effects, plant secondary metabolites are becoming more important in areas like sustainable pest control, protecting crops, and using plants in biotechnology (War *et al.*, 2012; Wink, 2016; Thirumurugan *et al.*, 2018; Osman, 2020;).

❖ Major Secondary Metabolites in Biotic Stress Tolerance

Plant secondary metabolites are broadly categorized into three primary groups: terpenoids, phenolic compounds and nitrogen-containing compounds. Each group plays a distinct role in the plant's defence against stress. Phenolic compounds, often used in combination with volatile chemicals, help repel herbivores and prevent their growth.

1. Terpenes

Isopentenyl diphosphate (IDP) and dimethylallyl diphosphate (DMAPP) serve as the fundamental precursors in terpene synthesis. These building units are synthesized through two distinct metabolic pathways: the pyruvate-derived plastidial 2-C-methyl -D-erythritol -4-phosphate (MEP) pathway and the acetyl-CoA derived cytosolic mevalonate (MVA) pathway (Divekar *et al.*, 2022). In plants, terpenes serve diverse physiological and ecological roles, including functioning as precursors of plant hormones such as gibberellins and abscisic acid,

as well as contributing to defense against insects, allelopathic interactions and the attraction of pollinators. Menthol, camphor, pyrethrins, artemisinin's and farnesol are terpenoid compounds that demonstrate important antimicrobial and antiprotozoal properties (Tiku, 2018).

❖ **List of terpenes with their categories and biological roles in different plants (Al-Khayri *et al.*, 2023)**

1	Pyrethrin	Monoterpenes found in <i>Chrysanthemum indicum</i> that act as neurotoxic compounds against parasitic wasps, insects, and moths.
2	Hemi gossypol	A sesquiterpene present in <i>Gossypium hirsutum</i> with antifungal activity.
3	Gossypol	A diterpene produced by <i>G. hirsutum</i> that exhibits antifungal and antibacterial properties.
4	Cucurbitacin-C	A triterpene found in Cucurbit species that is toxic to spider mites.

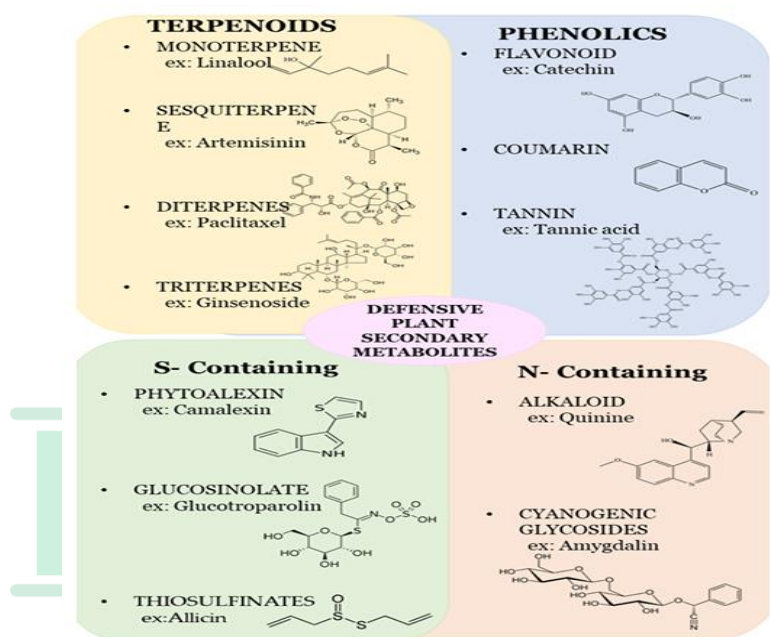


Figure 1. Major categories of secondary. metabolites

2. Sulphur Containing Secondary Metabolites

Secondary metabolites that contain sulphur contribute to plant protection against pathogens, acting either as phytoalexins or Phyto anticipatory compounds. Common examples include glucosinolates, thiosulfinates (like allicin, derived from cysteine sulfoxides) and antimicrobial peptides such as defensins and thionins , which are often volatile, bitter or strong-smelling (Tiku, 2018). These metabolites are synthesized via two main pathways:

- Glucosinolate myrosinase pathway:** In the glucosinolate pathway, the enzyme myrosinase breaks down glucosinolates into defensive compounds when plant tissues are damaged (e.g., cabbage, broccoli, etc.) (Ahmed *et al.*, 2017).
- Alliin–alliinase pathway:** In the alliin pathway, the enzyme alliinase produces alliin, a compound involved in herbivore and pathogen resistance, making these pathways crucial in plant defense strategies (e.g., garlic, onion, leeks — *Allium* genus) (Sayadi *et al.*, 1999).

2.1 Glucosinolates (GSLs)

These low-molecular-weight glycosides have a thioglucose component in their structure, and when broken down by enzymes, they release volatile compounds that help the plant respond to threats. These breakdown products can deter or kill pests and pathogens. Common examples include mustard oil glycosides found in the Cruciferae family and allyl sulfoxides found in the Allium family (Leustek & Saito, 1999). These compounds are predominantly distributed in the Cruciferae family and are also reported in related families such as Resedaceae , Moringaceae , Capparaceae and Tovariaceae. Glucosinolates exhibit notable antibacterial activity and can additionally function as attractants for herbivorous insects, including aphids and caterpillars (Harborne, 1998).

Myrosinase is an enzyme found in plants that helps break down glucosinolates by removing the glucose portion that contains sulphur. This reaction creates unstable intermediate compounds, which quickly transform into active substances like isothiocyanates, nitriles and thiocyanates. These substances have a strong, sharp smell and act as chemical defenses to repel or harm herbivores and invading pathogens (Geu-Flores *et al.*, 2009). In healthy plant cells, glucosinolates and myrosinase are stored separately in different parts of the cell. When the plant tissue is damaged by insects, pathogens, or mechanical injury, the enzyme and its substrates mix, triggering a chemical defense. For example, cabbage exhibits resistance to *Plasmodiophora brassicae*, whereas oilseed rape and Indian mustard demonstrate resistance to *Leptosphaeria maculans*, largely attributed to elevated concentrations of glucosinolates. In Brassica species, the compounds formed from glucosinolate breakdown act as natural antifungal agents, helping to protect the plant from various pests and diseases (Tiku, 2018).

2.2 Sulphur Containing Phytoalexins

Phytoalexins are antimicrobial substances that plants produce as part of their natural defense mechanism to protect themselves from bacterial and fungal infections (Pedras *et al.*, 2011). In members of the Brassicaceae, various phytoalexins including camalexin, brassinin, and rapalexin A are sulphur-containing indole-derived compounds synthesized from the amino acid tryptophan (Bednarek, 2012; Czerniawski & Bednarek, 2018). The process of making camalexin starts when plants experience stress and it involves specific enzymes like GSTF6 and GSTU4, as well as compounds such as indole-3-acetonitrile (IAN) and glutathione (GSH). In Arabidopsis, the cytochrome P450 enzymes CYP79B2 and CYP79B3 are important in increasing the amount of camalexin that accumulates when the plant is attacked by pathogens (Lemarié *et al.*, 2015). Plants that lack the PAD3 gene are more likely to become infected, while those with the transporter gene AtABCG34 show higher levels of camalexin secretion and better resistance to diseases. Some plants, such as tomato and garlic, also respond to infection by producing elemental sulfur, which acts as an inorganic form of phytoalexin (Glawischnig, 2007).

❖ Examples of phytoalexins found in various plants

1	Camalexin	Sulphur-containing phytoalexin produced by members of the Brassicaceae.
2	Glycosides	Glucosinolates are characteristic defensive metabolites of the Brassicaceae.
3	5-(3-buten-1-ynyl)-2,2'-bithiophene	Dithiophene compound found in species of Tagetes.
4	Allicin	Thiosulfinate compound present in <i>Allium sativum</i> (garlic).

3. Lectins

Lectins are widely distributed plant proteins that bind to carbohydrates and play a crucial role in protecting plants from insect herbivores. They recognize and bind specific sugar moieties on insect gut epithelial cells, leading to physiological disruption. Leguminous seeds are particularly rich sources of lectins with multiple carbohydrate-binding domains that enable agglutination of target cells. Notable examples include Wheat Germ Agglutinin (WGA), Phaseolus Hemagglutinin (PHA) and Galanthus Nivalis Agglutinin (GNA). GNA exhibits strong affinity for mannose-containing glycoconjugates, whereas PHA preferentially binds α -N-acetylgalactosamine. WGA interacts with chitin in the insect peritrophic membrane, impairing gut integrity and digestion. Lectins act as antinutritional factors by damaging the midgut epithelium and reducing nutrient absorption. Mannose-binding lectins are particularly effective against sap-sucking insects such as aphids. Transgenic expression of lectin genes, especially GNA, has enhanced resistance in crops like tobacco. Owing to their stability across a broad pH range, lectins remain active in the insect digestive system and represent promising tools for pest-resistant crop development (Yamane *et al.*, 2010; War *et al.*, 2012).

4. Nitrogen Containing Secondary Metabolites

Nitrogen-containing secondary metabolites are found in smaller quantities than carbon-based compounds in plants. However, they are essential components of a plant's defense system, especially against herbivorous insects and animals (Tiku, 2018). Main types of these compounds include: Alkaloids, Cyanogenic glycosides & non-protein amino acids.

4.1 Alkaloids: Alkaloids are nitrogen-based organic compounds that usually have a bitter taste. They are produced from amino acids such as tryptophan, tyrosine, lysine and aspartic acid. These compounds play a

significant role in the plant's chemical defense mechanism. They help protect plants by reducing damage from herbivores and limiting the growth of harmful microorganisms. For example, caffeine found in tea, coffee and cocoa plants has toxic effects on various fungi and insect pests. Nicotine, present in tobacco, is made in the roots and then transported to and stored in leaf vacuoles, where it acts as a defensive substance (Tiku, 2018).

4.2 Cyanogenic Glycosides: Some plant compounds can release hydrogen cyanide (HCN) when their tissues are damaged by herbivores. This release serves as a quick chemical defense mechanism. When cells are broken, enzymes like glycosidases and hydroxynitrile lyases become active and help break down these compounds into their toxic forms, which prevent further herbivore attacks. Common examples: Lotaustralin and linamarin found in *Trifolium repens*, *Linum usitatissimum* and *Lotus corniculatus*. Dhurrin found in *Sorghum bicolor*. In clover plants, cyanogenic glycosides act as a protective measure for young seedlings, helping them defend against slugs and snails (Tiku, 2018).

5. Phenolic Compounds

Phenolic compounds are vital for plant growth and defense, especially against herbivory. The phenylpropanoid pathway is activated during herbivore attacks, leading to the production of various defensive phenolic compounds. Enzymes such as polyphenol oxidase and peroxidase convert phenolic compounds into quinones, which attach to insect proteins and prevent them from feeding. Onion produces catechol and protocatechuic acid to protect against *Colletotrichum circinans*. Wheat varieties with high phenolic content resist *Rhopalosiphum padi*. Strawberry leaves with high catechol levels deter *Tetranychus urticae* (Mostafa *et al.*, 2022).

5.1 Coumarins: Found in plant families such as Leguminosae, Poaceae, Apiaceae and Rutaceae. These are made through the shikimate pathway and have selective toxicity against aphids (e.g., *Myzus persicae*) while being harmless to beneficial insects like ladybugs and earthworms (Tiku, 2018).

5.2 Furano-Coumarins: Mainly found in Umbelliferae, these compounds become toxic under UV-A light exposure. Psoralen, a common furano-coumarin, has antifungal properties, especially in untreated plants (Tiku, 2018).

5.3 Lignin: Formed from coniferyl, sinapyl and coumaryl alcohols, lignin provides mechanical strength and makes plant tissues hard to digest (Tiku, 2018). High lignin content makes it difficult for herbivores and even mammals to break down plant structures.

5.4 Flavonoids: Flavonoids are involved in plant reproduction, hormone transport, fruit ripening and defense. They act against viruses, fungi, bacteria and herbivores but also attract pollinators. These compounds are used as models for developing biopesticides due to their low environmental impact. Flavonoids inhibit insect enzyme activity and can stop larval development at an early stage. Naringin, rutin and quercetin are effective against *Eriosoma lanigerum* (Mostafa *et al.*, 2022).

5.5 Tannins: Tannins are polyphenolic compounds with molecular weights ranging from 600 to 3000 Da. They discourage herbivores by binding to insect proteins, which reduces digestion efficiency. Plants with high tannin levels and low protein content have a stronger defense against herbivores. Tannins cause a tingling sensation in insect mouths, leading to reduced feeding behavior. Mammals like deer, cattle and apes avoid tannin-rich plants due to their unpleasant taste (Tiku, 2018).

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The Sludge Goldmine: Anaerobic Digestion Turns RAS Waste into Energy and Profit



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Abstract

Recirculating Aquaculture Systems offer a sustainable pathway for land-based fish production by drastically reducing water usage. However, the concentrated sludge they produce remains a significant operational cost and environmental liability. This article investigates on-farm anaerobic digestion as a solution for recirculating aquaculture systems waste management. By converting sludge into biogas for on-farm energy and digestate for sale as fertilizer, anaerobic digestion can turn a disposal problem into a dual revenue stream. Drawing on recent research from 2023-2025, we explore the biochemical processes, co-digestion strategies, the agronomic value of the resulting fertilizer, and the compelling economics of integration, which can potentially increase farm profits by over 50%.

Keywords: Anaerobic digestion, recirculating aquaculture systems sludge, biogas, circular economy, digestate

Introduction

Recirculating Aquaculture Systems have revolutionized the aquaculture industry. By filtering and reusing over 95% of their water, these sophisticated land-based farms minimize environmental discharge and allow for precise control over production parameters. This has enabled farming of species from Atlantic salmon to African catfish in locations far from traditional coastlines (Choudhury et al., 2022).

Yet these facilities continuously produce a concentrated stream of sludge - a mixture of fish feces, uneaten feed, and dislodged biofilter solids. This sludge, while rich in organic carbon and nutrients, has traditionally been viewed as a costly disposal problem. Farmers face significant expenses for dewatering, storage, and off-site removal.

However, a paradigm shift is underway. Pioneering farmers and researchers are no longer seeing this sludge as waste, but as a resource. The technology at the heart of this transformation is on-farm anaerobic digestion. By mimicking a natural biological process in a controlled steel tank, anaerobic digestion unlocks the energy and nutrients locked within the sludge. It produces **biogas**, a renewable fuel that can heat the farm's water, and **digestate**, a stable, nutrient-rich fertilizer that can be sold to neighboring farms.

The Science of Sludge Digestion

Anaerobic digestion is a series of biological processes in which microorganisms break down organic material in the absence of oxygen. Within an airtight digester, a complex microbial community works in stages to convert complex organic matter into biogas - primarily a mixture of methane, typically 50-70%, and carbon dioxide.

For a recirculating aquaculture systems farmer, the methane is the prize. It can be captured and combusted in a combined heat and power unit to generate electricity. More critically for aquaculture, the waste heat from this process can warm the facility's water. For farms raising warm-water species like tilapia, shrimp, or catfish, heating represents one of the largest operational expenses. By substituting grid electricity and fossil fuels with self-generated biogas, farms can drastically reduce energy bills.

The efficiency of this process depends heavily on feedstock quality. A pivotal 2023 study by the United States Department of Agriculture's Agricultural Research Service, investigating sludge from Atlantic salmon and Rainbow trout, demonstrated the critical importance of sludge concentration. The researchers found that thickening sludge from 1.5% to 3.5% total solids resulted in a **23% increase in methane production**, achieving yields as high as 519 milliliters of methane per gram volatile solids. This underscores that dewatering is not just for reducing volume - it is crucial for maximizing energy recovery.

The Co-Digestion Advantage

While salmonid sludge is a potent energy source, some of the most exciting innovations are emerging from integrated farming systems. Co-digestion - mixing multiple organic waste streams in a single digester - can create synergistic effects that boost biogas yields beyond what any single material could achieve.

A 2024 study from the University of Rostock in Germany explored this by examining integration of African catfish recirculating aquaculture systems with existing biogas plants and greenhouse agriculture. Researchers found that co-digesting catfish sludge with just 25% greenhouse crop residues - such as rejected cucumbers, paprika, and tomato plants - boosted methane production by nearly **44%** compared to sludge alone (Klein et al., 2024). The carbon-rich plant material balanced the nutrient profile, creating a more favourable environment for methane-producing microbes.

This finding has profound implications for aquaponic or integrated agri-aquaculture systems. It creates a closed-loop circular economy: plant waste feeds the digester, which produces energy to power both greenhouse and fish farm, while the resulting digestate fertilizes new crops.

From Biogas to Byproduct: The Value of Digestate

The material remaining after digestion, known as **digestate**, is far more than "spent" sludge. Microbial action stabilizes organic matter, reduces odours and pathogens, and converts organic nitrogen into ammonium - a form immediately available for plant uptake. The result is a consistent, low - odour biofertilizer rich in nitrogen, phosphorus, and potassium.

While long-term studies on fish sludge digestate are still emerging, research on similar organic wastes provides compelling evidence. A 2025 study investigating digestate from fruit and vegetable waste found it contained 1.74 g/L total nitrogen and 0.62 g/L phosphorus. When applied to bean crops, this digestate led to a remarkable **71% increase in seed yield per plant** compared to untreated controls (Triki et al., 2025).

For the recirculating aquaculture systems farmer, this transforms digestate from waste into a marketable product for nearby organic farmers, horticultural operations, or landscapers -creating a second revenue stream and closing the loop by returning nutrients from fish feed back to the soil.

The Economic Bottom Line

The core promise of on-farm anaerobic digestion is turning a cost center - waste disposal - into a profit center - energy and fertilizer. Recent economic modelling strongly supports this.

A comprehensive 2025 analysis from the University of Reading in the United Kingdom modelled the financial impact of integrating anaerobic digestion and recirculating aquaculture systems into existing arable farms. For a standard arable farm, adding an anaerobic digester alone boosted net margins by an average of **24%**. However, when the model included a fully integrated system combining arable crops, an anaerobic digester, and a recirculating aquaculture systems unit farming prawn, projected farm profits soared by an average of **56%** (Campos-González et al., 2025). While the study focused on prawns, the principle applies widely: synergies between waste treatment, energy recovery, and nutrient recycling create a powerful economic engine.

Challenges on the Path to Implementation

Despite its potential, adoption faces obstacles. The primary barrier is high **capital cost** of a digester and associated combined heat and power unit and gas cleanup equipment, requiring significant upfront investment.

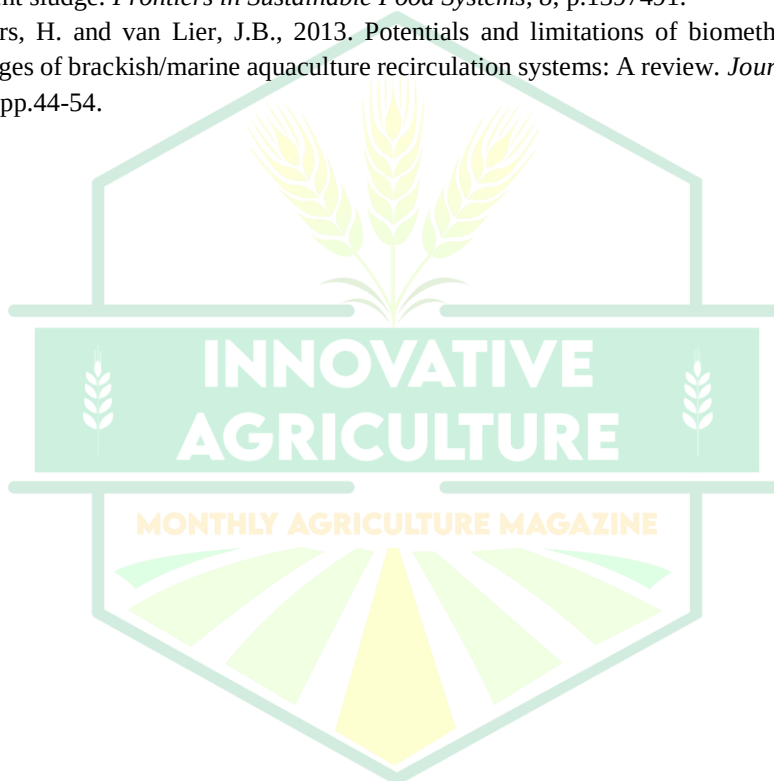
Additionally, the biogas itself presents technical challenges. Anaerobic digestion of protein-rich fish sludge can produce significant **hydrogen sulfide**, a corrosive and toxic gas. If not removed before combustion, hydrogen sulfide rapidly damages engines and boilers. The United States Department of Agriculture study noted that while methane yields were high, so were hydrogen sulfide concentrations, necessitating gas cleanup technology that adds to costs (Choudhury et al., 2023). Successful implementation requires careful system design including biological or chemical scrubbing.

Conclusion

The sludge produced by Recirculating Aquaculture Systems is not an inevitable waste problem - it is an untapped resource. On-farm anaerobic digestion offers a mature, scalable technology to unlock value from this material. By capturing methane for energy and converting residue into valuable fertilizer, farmers can reduce environmental footprint while creating new revenue streams and enhancing farm resilience.

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Conservation Agriculture as a Sustainable Strategy for Carbon Sequestration



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Abstract

Conservation agriculture (CA) is a sustainable farming approach that enhances soil health and supports carbon sequestration, helping to mitigate climate change. It is based on three key principles: minimum soil disturbance, permanent soil cover, and crop diversification. These practices improve soil structure, increase organic matter, and promote the storage of atmospheric carbon dioxide in the soil. In addition to reducing greenhouse gas emissions, CA improves soil fertility, water retention, and agricultural productivity. Although challenges such as limited awareness, high initial costs, and residue management exist, conservation agriculture offers long-term environmental and agricultural benefits, making it an effective strategy for sustainable farming and climate change mitigation.

Key words: carbon dioxide, zero tillage, greenhouse gas, cover crop, Carbon sequestration

Introduction

Climate change has become one of the most serious environmental challenges of the 21st century. Increasing levels of carbon dioxide (CO₂) and other greenhouse gases in the atmosphere are contributing to global warming and environmental degradation. Agriculture, while often considered a source of greenhouse gas emissions, also offers a powerful solution through the adoption of sustainable practices. One such approach is conservation agriculture, which plays a crucial role in enhancing carbon sequestration in soil.

Conservation agriculture is a farming system that aims to improve productivity while conserving natural resources and protecting the environment. It is based on three main principles: minimum soil disturbance (reduced or zero tillage), permanent soil cover using crop residues or cover crops, and diversified crop rotations. These practices help maintain soil health, increase biodiversity, and improve soil structure.

One of the most important environmental benefits of conservation agriculture is its ability to sequester carbon in the soil. Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide in soil and vegetation. When crop residues are left on the soil surface and tillage is minimized, organic matter accumulates in the soil. This organic matter contains carbon that would otherwise be released into the atmosphere as CO₂. Over time, soils managed under conservation agriculture can store significant amounts of carbon, helping to mitigate climate change.

In addition to storing carbon, conservation agriculture improves soil fertility and productivity. The retention of crop residues protects the soil from erosion, improves water infiltration, and reduces moisture loss. This is particularly important in regions prone to drought and irregular rainfall. Healthy soils rich in organic matter also support beneficial microorganisms, which play a vital role in nutrient cycling and plant growth.

Objective

1. To understand the concept and principles of conservation agriculture.
2. To examine the role of conservation agriculture practices in enhancing soil carbon sequestration.

3. To evaluate the impact of conservation agriculture on soil health and soil organic carbon storage.

A) Fundamentals of Conservation Agriculture

Conservation Agriculture (CA) is a sustainable farming approach defined by the (FAO), that aims to achieve high productivity and profitability while preserving the environment. It focuses on enhancing natural biological processes both above and below the ground to increase water and nutrient use efficiency

1. Principles of Conservation Agriculture

❖ There are three core principles for CA

I) Minimum Mechanical Soil Disturbance

- This principle advocates for no-tillage or zero-tillage to maintain soil structure and biodiversity.
- Disturbance should be limited to the absolute minimum necessary for seed and fertilizer placement.
- Technically, the disturbed area must be less than 15 cm wide or less than 25% of the total cropped area.

II) Permanent Soil Organic Cover

- A minimum of 30% of the soil surface must be covered with organic materials, such as crop residues or cover crops, immediately after seeding.
- This layer acts as a "skin" for the soil, protecting it from erosion, reducing water evaporation, and moderating soil temperature.
- It provides a continuous food source for soil microorganisms, which eventually take over the "tillage" function naturally.

III) Species Diversification

- Farmers should grow a variety of crop species in sequences or associations (rotations).
- An ideal system involves at least three different crop species, including a legume.
- This diversity helps break pest and disease cycles, improves soil fertility through nitrogen fixation, and allows different root systems to explore various soil depths for better nutrient use.

2. Carbon Sequestration: Principles and Processes

Carbon sequestration is the process of capturing and storing carbon dioxide (CO₂) from the atmosphere to reduce the amount of greenhouse gases that contribute to climate change. It helps slow down global warming by preventing CO₂ from accumulating in the atmosphere.

a) Principles of Carbon Sequestration

- i) Capture of Carbon Dioxide: CO₂ is captured from sources such as power plants, industries, or directly from the air.
- ii) Transportation: The captured CO₂ is transported through pipelines or other methods to storage sites.
- iii) Long-term Storage: The CO₂ is stored in a way that prevents it from re-entering the atmosphere.

b) Processes of Carbon Sequestration

i) Biological Sequestration:

Plants, forests, and soil absorb CO₂ through photosynthesis and store it in biomass and organic matter. Examples include afforestation, reforestation, and soil carbon storage.

ii) Geological Sequestration:

CO₂ is injected deep underground into geological formations such as depleted oil and gas reservoirs, deep saline aquifers, or unminable coal seams.

iii) Ocean Sequestration:

CO₂ is absorbed by oceans naturally or can be stored in deep ocean layers, though this method is still under research due to possible ecological impacts.

3. Role of Conservation Agriculture in Carbon Sequestration

Conservation agriculture is a sustainable farming approach that focuses on protecting soil, improving soil health, and increasing agricultural productivity while reducing environmental impacts. It plays an important role in carbon sequestration by capturing atmospheric carbon dioxide (CO₂) and storing it in the soil as organic carbon.

❖ Key Roles of Conservation Agriculture

- I. **Minimum Soil Disturbance (Reduced Tillage)**
Conservation agriculture promotes reduced or zero tillage. Less disturbance of soil helps prevent the release of stored carbon into the atmosphere and allows more carbon to remain trapped in the soil.
- II. **Permanent Soil Cover**
The use of crop residues, mulch, or cover crops keeps the soil covered. This protects the soil from erosion and increases the amount of organic matter, which stores carbon in the soil.
- III. **Crop Rotation and Diversification**
Growing different crops in rotation improves soil fertility and increases the amount of plant biomass returned to the soil. This enhances soil organic carbon storage.
- IV. **Improved Soil Structure and Microbial Activity**
Conservation agriculture enhances soil biodiversity and microbial activity. Soil microorganisms help convert plant residues into stable organic carbon compounds.
- V. **Reduction of Greenhouse Gas Emissions**
By improving soil carbon storage and reducing soil disturbance, conservation agriculture reduces the release of CO₂ and other greenhouse gases into the atmosphere.

4. Challenges in Adoption of Conservation Agriculture

Conservation agriculture (CA) is a sustainable farming approach that improves soil health and enhances carbon sequestration. However, its adoption by farmers faces several challenges.

Major Challenges

- I. **Lack of Awareness and Knowledge**
Many farmers are not fully aware of conservation agriculture practices and their long-term benefits. Limited training and extension services make adoption difficult.
- II. **High Initial Cost**
Some CA practices require specialized equipment such as zero-till seeders and residue management machines, which may be expensive for small farmers.
- III. **Crop Residue Management Issues**
Farmers often use crop residues as livestock feed or fuel. Leaving residues on the field for soil cover can therefore be difficult.
- IV. **Weed and Pest Management**
Reduced tillage may increase weed growth initially, requiring effective weed and pest control strategies.
- V. **Small Land Holdings**
In many developing countries, farmers have small and fragmented land holdings, making it difficult to implement conservation agriculture techniques effectively.
- VI. **Short-term Yield Uncertainty**
Farmers may experience uncertain or slightly reduced yields during the transition period, which discourages adoption.

5. Future Prospects and Recommendations

The future of CA lies in its potential to significantly contribute to global Net Zero goals and climate resilience.

- **Global Sequestration Potential:** The Intergovernmental Panel on Climate Change (IPCC) estimates that agricultural soils can sequester up to 1.2 billion tonnes of carbon annually
- **Carbon Farming & Markets:** Emerging carbon credit markets offer a new revenue stream for farmers, with credits valued between USD 15 to USD 50 per ton, incentivizing the adoption of CA as "carbon farming."
- **Technological Integration:** Future CA will increasingly utilize precision agriculture, including soil sensors, drones, and AI-driven data to optimize nutrient management and accurately verify sequestered carbon for credits.

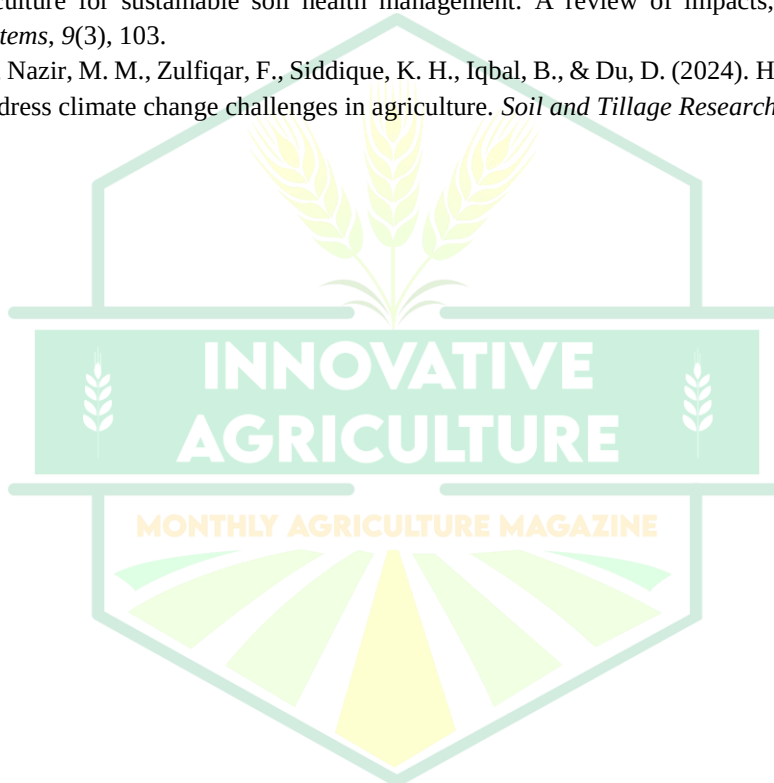
- **Climate Resilience:** Beyond sequestration, CA "weather-proofs" soils by improving water infiltration and retention, which is critical for maintaining yields during the projected increases in extreme droughts and floods.

Conclusion

Conservation agriculture is a sustainable farming approach that helps improve soil health, increase agricultural productivity, and reduce environmental degradation. By minimizing soil disturbance, maintaining soil cover, and practicing crop diversification, it enhances soil carbon storage and contributes to climate change mitigation. Despite some challenges in adoption, conservation agriculture offers long-term environmental and agricultural benefits, making it an important strategy for sustainable farming and effective carbon sequestration.

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Integrating Pulses in Rice-Based Cropping Systems for Sustainable Agriculture



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Introduction

Rice is the principal food crop in many Asian countries and forms the backbone of food security in India. Large areas of agricultural land are dedicated to rice cultivation, particularly in irrigated regions. However, continuous rice cultivation without crop diversification often results in soil nutrient depletion, increased pest and disease incidence, and declining productivity.

Crop diversification is an important strategy to maintain soil fertility and ensure sustainable agricultural production. Pulses, also known as legumes, play a vital role in improving soil health and supporting sustainable farming systems. Integrating pulses into rice-based cropping systems can enhance soil fertility through biological nitrogen fixation while also improving farm income and nutritional security.

Rice-based cropping systems dominate the agricultural landscape in many parts of India, particularly in southern states. While rice provides staple food security, continuous monocropping of rice often leads to declining soil fertility, pest outbreaks, and reduced farm profitability. Integrating pulses into rice-based cropping systems offers an effective strategy to improve soil health, enhance crop productivity, and promote sustainable agriculture. Pulses play an important role in biological nitrogen fixation, improving soil structure, and providing an additional source of income and nutrition for farmers. This article discusses the importance, benefits, and practical approaches for integrating pulses into rice-based cropping systems to achieve long-term agricultural sustainability.

Importance of Pulses in Agriculture

Pulses are rich sources of plant protein, vitamins, and minerals, making them an essential component of human nutrition. Crops such as chickpea, pigeon pea, black gram, green gram, and cowpea are widely cultivated pulses in India.

Apart from their nutritional benefits, pulses contribute significantly to agricultural sustainability. These crops have the unique ability to fix atmospheric nitrogen through symbiotic relationships with rhizobium bacteria present in their root nodules. This process enriches the soil with nitrogen and reduces the need for chemical fertilizers in subsequent crops.

Rice-Based Cropping Systems

A rice-based cropping system refers to agricultural systems where rice is the main crop grown during one or more seasons of the year. In many regions, farmers cultivate rice continuously, often followed by another rice crop or leaving the field fallow.

Such monocropping systems may lead to several challenges:

- Depletion of soil nutrients
- Increased pest and disease pressure
- Declining soil organic matter
- Reduced overall farm profitability

Integrating pulses into these systems helps overcome these challenges and improves the sustainability of rice cultivation.

Methods of Integrating Pulses in Rice Systems

1. Rice-Pulse Crop Rotation

One of the most common methods is growing pulses after the harvest of rice. For example:

Cropping System Benefit

Rice – Black gram Improves soil nitrogen and provides additional income

Rice – Green gram Short duration crop suitable for rice fallows

Rice – Chickpea Enhances soil fertility and diversifies farm production

2. Relay Cropping

Relay cropping involves sowing pulse crops before the rice crop is harvested. This allows pulses to establish using residual soil moisture, reducing the need for irrigation.

3. Intercropping

In some cases, pulses can be grown along with rice in certain spatial arrangements. Although less common in irrigated rice fields, intercropping is practiced in upland rice systems.

4. Rice Fallows Utilization

Large areas of rice fallows remain uncultivated after the rice harvest due to lack of irrigation. Introducing short-duration pulses in these fallows helps utilize residual soil moisture and increases cropping intensity.

Rice is grown during the main season. After harvest, pulse crops are cultivated using the residual soil moisture available in the field. These pulse crops fix atmospheric nitrogen, enrich the soil, and improve soil fertility for the next cropping cycle.

Pulse Crop	Variety	Duration (Days)	Special Features
Black gram	ADT 3	65–70	Suitable for rice fallows; good yield potential
Black gram	VBN 6	65–70	Resistant to yellow mosaic virus
Green gram	CO 8	60–65	Short duration; suitable for residual moisture conditions
Green gram	VBN 3	60–65	Good grain quality and yield
Cowpea	CO 7	70–75	Tolerant to drought and suitable for fallow lands
Chickpea	CO 4	95–100	Suitable for dry conditions and good market demand

These pulse varieties are suitable for cultivation after rice harvest and help utilize the large area of rice fallows in India effectively.

Benefits of Integrating Pulses in Rice Systems

Improvement of Soil Fertility

Pulses fix atmospheric nitrogen and enrich soil nutrient content. This improves the fertility of the soil for the subsequent rice crop.

Reduced Fertilizer Requirement

Because pulses naturally add nitrogen to the soil, the need for synthetic nitrogen fertilizers in the following crops is reduced.

Better Soil Structure

Pulse crops improve soil structure by increasing organic matter content and enhancing microbial activity.

Increased Farm Income

Cultivating pulses as an additional crop provides farmers with extra income and reduces dependence on a single crop.

Nutritional Security

Pulses are an important source of protein in vegetarian diets. Integrating pulses into farming systems improves household nutrition.

Role of Agricultural Research and Extension

Agricultural research institutions and extension agencies play a crucial role in promoting pulse integration in rice-based systems. Improved pulse varieties, better crop management practices, and farmer training programmes help enhance the adoption of pulse cultivation.

In Tamil Nadu, research institutions such as Tamil Nadu Agricultural University have developed improved pulse varieties suitable for rice fallows and different agro-climatic conditions. Extension programmes also promote pulse cultivation through demonstrations and training programmes for farmers.

Future Prospects

With increasing concerns about soil degradation and climate change, integrating pulses into rice-based systems is gaining importance. Researchers are developing improved pulse varieties that are drought tolerant, short duration, and suitable for rice fallow cultivation.

Government initiatives promoting pulses under national food security programmes are also encouraging farmers to diversify cropping systems. Such efforts will help enhance both environmental sustainability and farmer livelihoods.



Key Benefits of Integrating Pulses in Rice-Based Cropping Systems

Improves Soil Fertility

Pulse crops fix atmospheric nitrogen through root nodules, enriching the soil naturally.

Enhances Crop Productivity

Improved soil fertility helps increase the yield of subsequent rice crops.

Efficient Use of Residual Moisture

Pulses can grow using the residual soil moisture left after rice harvest, reducing irrigation needs.

Additional Income for Farmers

Cultivating pulses after rice provides an extra harvest and improves farm profitability.

Improves Nutritional Security

Pulses are rich in protein, minerals, and vitamins, contributing to a balanced diet.

Promotes Sustainable Agriculture

Crop diversification with pulses reduces dependence on chemical fertilizers and improves soil health.

Conclusion

Integrating pulses into rice-based cropping systems is an effective strategy for achieving sustainable agriculture. Pulses improve soil fertility, reduce fertilizer requirements, enhance crop productivity, and provide nutritional

and economic benefits to farmers. By adopting diversified cropping systems that include pulses, farmers can maintain soil health and ensure long-term agricultural sustainability.

Promoting pulse cultivation through research, extension services, and supportive policies will play a vital role in strengthening rice-based farming systems and improving food and nutritional security.

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How to Conduct a Behavioral Study in Social Sciences: A Practical Guide for Designing, Implementing, and Reporting Research



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Introduction

Behavioral research in the social sciences seeks to understand observable actions and the psychological, institutional, and cultural processes that shape them. Depending on the objective, the researcher may want to describe behavior, explain associations, interpret lived experience, or estimate the effect of an intervention. Good studies, therefore, do not begin with a questionnaire or a statistical model; they begin with a well-specified problem, an explicit conceptual framework, and a design appropriate to the question being asked [1-4].

1. Formulate the problem and define the behavior

The first task is to convert a broad topic into a researchable behavioral question. For example, “Why do students delay assignment submission?” is too vague, whereas “Which factors predict procrastination in postgraduate students during online coursework?” is testable. The target behavior should be defined in observable or measurable terms, its unit of analysis should be stated clearly, and the population and setting should be specified. A short conceptual model is useful at this stage because it forces the researcher to distinguish outcome variables, predictors, mediators, moderators, and contextual factors [3,4].

Once the question is fixed, the study's aim should be classified. Descriptive aims document the prevalence or pattern of a behavior. Explanatory aims test associations or mechanisms. Evaluative aims estimate whether a program, policy, or treatment changes behavior. Interpretive aims explore meanings, norms, and experiences through qualitative inquiry. This classification matters because it guides design choice, instrument selection, and analysis strategy [3-6].

A useful operational rule is that every behavioral study should be able to answer three basic questions before data collection starts: What exactly is the behavior? Who performs it? Under what conditions does it occur? If these are not clear, later stages such as questionnaire design, interview guides, coding frames, and analytic models become unstable. In practice, many weak studies fail not because the analysis is poor, but because the behavior was never operationalized sharply enough at the outset [3,4].

2. Select an appropriate design

The design must fit the question's logic. Cross-sectional surveys are suitable when the objective is to estimate the frequency of a behavior or test contemporaneous associations. Longitudinal designs are stronger when temporal order matters, such as tracking attitude change before and after exposure to social media campaigns. Randomized controlled trials are preferred when the aim is to estimate causal effects of behavioral interventions, but quasi-experiments may be more feasible in schools, communities, or institutions where randomization is impractical. Qualitative designs are appropriate when the researcher wants to understand how participants interpret norms, incentives, stigma, or identity in relation to behavior [3,5-8].

Mixed-methods designs are especially valuable in social sciences because behavior is both measurable and meaning-laden. Quantitative data can estimate magnitude and distribution, while qualitative data can explain why a pattern occurs or why an intervention succeeds in one context and fails in another. Integration should be planned at the protocol stage rather than added after data collection; otherwise, the study becomes two disconnected projects instead of one coherent design [4,6,9].

The choice between experimental and non-experimental designs should also reflect feasibility, ethics, and expected threats to inference. When manipulation is impossible or unethical, careful observational work with explicit control of confounding may be preferable to a weak intervention design. Conversely, when causal effect estimation is the main aim, purely descriptive designs will not answer the question no matter how large the sample becomes. Design choice is therefore both a scientific and a practical decision [3,7,8].

3. Plan sampling and sample size

Sampling determines to whom the findings can reasonably apply. In quantitative studies, probability-based sampling improves representativeness and reduces selection bias, although budget and field realities often require multistage or cluster procedures. Non-probability methods such as purposive, quota, or snowball sampling may be acceptable for hard-to-reach populations, but the resulting limitations on generalization must be stated explicitly. In qualitative studies, sampling should prioritize information richness over numerical representativeness, often through purposive selection of participants who vary in key characteristics relevant to the research question [3,4,10].

Sample size should never be justified solely by convenience. For quantitative studies, it should follow the primary analysis and depend on expected effect size, variability, power, confidence level, precision, and design effect, where applicable. Very small samples increase the risk of false negatives and unstable estimates, while unnecessarily large samples may be ethically or financially wasteful [10]. For qualitative work, adequacy is often assessed by information power or thematic sufficiency, but the stopping logic should still be clearly documented in the methods section [5,6].

Researchers should also anticipate loss to follow-up, non-response, and incomplete records. If the study is longitudinal, the initial sample must account for attrition. If it is clustered, the sample size must reflect intra-cluster correlation rather than the raw number of respondents alone. These considerations are often omitted in student projects, yet they materially affect precision, statistical power, and credibility of the final results [7,10].

4. Develop and test the measurement strategy

Behavioral research usually deals with latent constructs such as attitudes, trust, stigma, motivation, compliance, or risk perception. These cannot be captured well by vague or poorly tested questions. Researchers should begin by identifying whether a validated instrument already exists. If it does, adaptation is usually preferable to inventing a new scale from scratch. If a new instrument is required, items should be generated from theory, prior literature, and, where possible, participant language obtained through formative qualitative work [4,11].

Instrument quality must be demonstrated, not assumed. Content validity can be improved through expert review and cognitive interviewing. Pilot testing helps identify ambiguity, social desirability pressure, skip-pattern problems, and respondent burden. Reliability should be assessed using appropriate methods, such as internal consistency, test-retest reliability, or inter-rater agreement, depending on the nature of the measure. Validity evidence may include construct validity, criterion validity, and factorial structure, where scales are multidimensional [11,12].

Question wording deserves special attention in behavioral studies. Items should be specific, time-bounded, and free of double meanings. Sensitive behaviors often require privacy-preserving procedures, careful sequencing, and neutral wording. Survey method research shows that reinterview and related techniques are useful for assessing reliability and identifying unstable responses, especially for attitudinal or self-reported behaviors [12].

For observational protocols, the measurement strategy also includes who records the behavior, when observation occurs, how categories are defined, and how observer drift will be controlled. For interview-based studies, the guide should move from less threatening questions to more reflective or sensitive issues. In all cases, pilot work is not a formality; it is the stage at which poor items, awkward instructions, and unrealistic timing are exposed before they damage the main study [1,11,12].

5. Address ethics and field procedures

No behavioral study involving human participants is methodologically sound if it is ethically weak. Ethics review should occur before data collection, and the protocol should describe participant selection, recruitment, consent, confidentiality, data storage, and risk mitigation. Voluntary informed consent is a core requirement except in narrowly defined situations permitted by ethics rules. Researchers must also consider whether questions may trigger distress, stigma, or reputational risk, particularly when studying mental health, sexuality, violence, deviance, or politically sensitive beliefs [2,13,14].

The field protocol should be standardized. Interviewer training, observer calibration, translation and back-translation where necessary, and pilot deployment in the actual setting all improve data quality. For intervention

studies, treatment fidelity and adherence to protocol should be monitored throughout implementation. A strong operations plan also includes procedures for handling missing data, non-response follow-up, and documenting deviations from the original protocol [7,8].

Confidentiality requires both procedural and technical safeguards. Identifiers should be separated from analytic datasets, access should be restricted, and decisions about audio files, field notes, and transcript storage should be explicit. In digital surveys, researchers should also consider device sharing, password protection, and whether platform settings expose participant identities. Ethical practice in behavioral research is not limited to consent forms; it extends across recruitment, data handling, analysis, and dissemination [2,13,14].

6. Control bias and protect data quality

Behavioral studies are especially vulnerable to bias because many measures rely on self-report, social interaction, recall, or observer judgment. Common threats include social desirability bias, recall bias, interviewer effects, Hawthorne effects, selection bias, and common-method variance. These problems should be anticipated during design rather than acknowledged only as limitations at the end of the paper [3,8,12].

Several practical safeguards are available. Anonymity or confidentiality assurances can reduce socially desirable responding. Short recall periods improve reporting of recent behaviors. Neutral interviewer training reduces cueing and expectancy effects. Multiple-item scales often perform better than single questions for latent constructs, and using more than one data source can reduce dependence on a single error-prone method. When possible, researchers should predefine exclusion rules, conduct range and consistency checks, and document all data-cleaning decisions in an audit trail [1,11,12].

Data quality monitoring should continue during fieldwork rather than after it. Daily review of completed forms, spot checks of interviews, verification callbacks, and automated logic checks in electronic data capture can identify errors before they accumulate. In qualitative projects, memo writing, version control for coding schemes, and documentation of analytic decisions serve the same quality-assurance function. The central principle is simple: credibility depends on traceable procedures, not merely on good intentions [1,5,6].

7. Analyze and interpret the data

Analysis must follow the design and the measurement level of the variables. Descriptive statistics are sufficient only when the objective is prevalence or profile building. Behavioral explanations often require regression models, multilevel approaches, mediation analysis, or longitudinal techniques when participants are nested within households, classrooms, organizations, or communities. The primary outcome and core contrasts should be specified in advance to reduce selective analysis and post hoc storytelling [3,7,10].

Researchers should interpret effect sizes and confidence intervals alongside p-values, because statistical significance alone says little about substantive importance. Missing data mechanisms should be assessed and handled transparently rather than ignored. If subgroup analyses are conducted, they should be justified conceptually and treated cautiously, especially when power is limited. Interpretation should remain proportionate to the design; a cross-sectional association should not be written as proof of causality [7,8,10].

Qualitative analysis should be equally systematic. The researcher should document how transcripts were prepared, how codes were developed, whether coding was inductive or deductive, how disagreements were resolved, and how themes were refined. Reflexivity is important because the researcher is part of the analytic process. Mixed-methods analysis should culminate in integration, not merely parallel presentation; the interpretation should show how the qualitative and quantitative strands converge, diverge, or complement one another [5,6,9].

8. Write the manuscript and report transparently

A submission-ready article should report enough detail for a reviewer or reader to judge the study's rigor. The title, abstract, and methods should explicitly identify the design. Eligibility criteria, setting, timeframe, sampling method, sample size rationale, instrument development or adaptation, ethics approval, and analytic strategy should all be stated transparently. Reporting checklists improve completeness: STROBE is widely used for observational studies, while COREQ and SRQR guide the reporting of qualitative work [5-8].

The discussion should return to the original behavioral question rather than simply repeating statistical significance. Strong papers explain what the findings mean, how context may have shaped the results, and what

limitations qualify the conclusions. Common limitations in behavioral research include self-report bias, common-method variance, residual confounding, attrition, and restricted external validity. Researchers should end by stating the practical, theoretical, or policy relevance of the findings and by identifying the next logical research step [1,3,4].

Before submission, the manuscript should undergo a final technical audit. Check that tables and figures match the text, that all variables are defined consistently, that references are formatted uniformly, and that the wording of conclusions does not exceed the evidence. Behavioral research gains authority when the paper reads as a disciplined account of planned inquiry rather than an exploratory narrative assembled after the results are known [5-8].

Conclusion

Conducting a behavioral study in the social sciences requires more than collecting opinions or running statistical tests. It requires disciplined alignment among research question, theory, design, sampling, measurement, ethics, and analysis. The most credible studies define behavior precisely, use instruments that are demonstrably reliable and valid, justify their sample and design, protect participants carefully, and report methods with enough transparency to support appraisal and replication. When those elements are integrated from the outset, behavioral research becomes more than descriptive; it becomes explanatory, trustworthy, and publishable.

Table 1. Matching the research objective with an appropriate behavioral study design

Objective	Typical design	Strength	Main limitation
Describe prevalence or pattern	Cross-sectional survey/observation	Efficient for broad population snapshots	Weak for causal inference
Explain predictors of behavior	Cohort, panel, case-control, or analytic survey	Supports temporal or multivariable analysis	Susceptible to confounding and attrition
Evaluate the intervention effect	Randomized or quasi-experimental design	Strongest basis for causal claims	Costly and operationally demanding
Understand meanings and processes	Interviews, focus groups, and ethnography	Rich contextual insight	Limited statistical generalization
Combine breadth and depth	Mixed-methods sequential or convergent design	Integrates explanation and interpretation	Requires more time and methodological skill

A concise protocol checklist is often helpful before launching fieldwork: (i) theory and constructs finalized, (ii) design justified, (iii) sample and sample size documented, (iv) instruments piloted, (v) ethics approval obtained, (vi) field team trained, (vii) data management plan prepared, and (viii) analysis plan specified in advance [1,3,7].

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SEED LONGEVITY AND STORAGE: ADVANCEMENT IN SEED BANK TECHNOLOGY AND CRYOPRESERVATION



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ABSTRACT

Seed longevity refers to the duration during which a seed remains viable and capable of germination under suitable conditions. The lifespan of seeds varies significantly among species and even among seed lots of the same species due to differences in physiological and environmental factors. Over the past several decades, scientific research has significantly improved the understanding of seed ageing, storage behavior, and the mechanisms that determine seed viability. Seed longevity is influenced by various biophysical, biochemical, and environmental factors such as moisture content, temperature, and oxygen availability. Modern seed banks use advanced technologies to maintain optimal storage conditions and protect plant genetic resources. Cryopreservation, which involves storing biological materials at extremely low temperatures, has emerged as a powerful technique for preserving seeds and plant tissues that cannot survive conventional storage methods. Advances in biotechnology, digital monitoring systems, and molecular tools have further strengthened seed conservation strategies. These developments contribute significantly to biodiversity conservation, crop improvement programs, and global food security. Overall, integrating knowledge from seed physiology, biophysics, molecular biology, and cryobiotechnology is essential for improving seed storage efficiency and safeguarding plant genetic resources for future generations (Walters & Pence, 2021).

Keywords: Seed Longevity, Cryopreservation, Seed Ageing, Glassy State, Cryo-Biotechnology

INTRODUCTION

The conservation of plant genetic resources is essential for maintaining biodiversity and ensuring sustainable agricultural development. Increasing global population, climate change, and habitat loss have intensified the need to protect plant diversity and secure food production systems. One of the most efficient strategies for preserving plant genetic material is seed storage, which allows plant species to be conserved for extended periods (Walters & Pence, 2021). Historically, scientists have been interested in understanding how long seeds can remain viable. Early research by Ewart (1908) classified seeds into categories based on their lifespan under natural storage conditions. Later, studies revealed that environmental factors such as temperature and moisture play crucial roles in determining seed longevity. Harrington (1960) proposed simple guidelines known as "Harrington's thumb rules," which state that seed lifespan decreases by half with every 5°C increase in temperature and with every 1% increase in seed moisture content. These principles highlighted the importance of maintaining low temperature and humidity in seed storage environments.

Modern seed storage research has expanded significantly, incorporating insights from seed physiology, molecular biology, and materials science. Today, seed banks use controlled environments to preserve seeds for long periods while maintaining their viability. These facilities serve as repositories for crop varieties, wild plant species, and endangered plants, ensuring that valuable genetic resources remain available for future breeding programs and ecological restoration (Justice & Bass, 1978).



SEED STORAGE AND LONGEVITY

Relationship Between Seed Moisture, Relative Humidity, and Temperature

Seed longevity is strongly influenced by the interaction between moisture content, temperature, and relative humidity. Water plays a critical role in biological reactions within the seed, and changes in water content can significantly affect seed stability during storage. Researchers have integrated knowledge from food science and material science to better understand how water interacts with seed tissues (Roberts & Ellis, 1989). Early storage guidelines recommended drying seeds to moisture levels between 3% and 7%, depending on the seed composition. Seeds with higher lipid content generally require lower moisture levels than starch-rich seeds. Instead of measuring moisture content directly, many seed banks now use relative humidity (RH) as an indicator of moisture status because it provides a more reliable measurement across different seed types. The relationship between seed water content and relative humidity follows a sorption isotherm pattern. As relative humidity increases, seed moisture content also increases. However, this relationship is not linear, and moisture levels can change rapidly at very low or very high humidity levels. Maintaining equilibrium relative humidity during storage ensures that seeds remain stable and do not absorb excess moisture, which could accelerate deterioration.



Long-Term Conservation and Molecular Stability:

Long-term seed conservation depends on reducing metabolic activity within the seed. When seeds are dried to low moisture levels, the cytoplasm inside seed cells transitions into a solid, glass-like state. In this condition, molecular movement is greatly restricted, which slows down biochemical reactions that cause deterioration (Walters et al., 2010). Genebanks typically store orthodox seeds at temperatures around -20°C with controlled humidity levels. Under these conditions, many seeds can remain viable for several decades or even centuries. For example, models suggest that lettuce seeds stored at -20°C with optimal moisture levels may maintain high germination rates for more than 60 years. Similar studies indicate that many orthodox seeds could remain viable for over 100 years if stored under ideal conditions (Ellis, 2022). However, seed longevity varies widely between species due to genetic and physiological differences. Therefore, seed banks conduct periodic germination tests to monitor viability and ensure that stored seeds remain capable of germination.

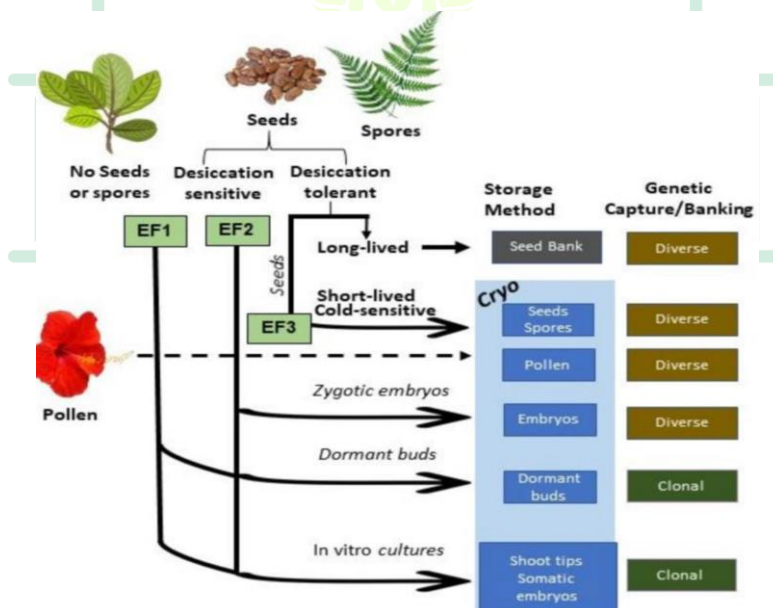
ADVANCEMENTS IN SEED BANK TECHNOLOGY

In recent years, seed bank technology has evolved from simple storage facilities into highly advanced conservation centers. Modern seed banks use automated systems to regulate temperature and humidity, ensuring stable storage conditions. These facilities also use digital cataloging systems, barcode tracking, and international databases to manage large collections of plant genetic resources. Ex situ conservation strategies involve storing

plant materials outside their natural habitats. Botanical gardens and field genebanks maintain living collections, while seed banks preserve germplasm in a dormant state for long-term storage (Chapman et al., 2019). Globally, nearly 1,750 seed banks currently exist, collectively storing millions of seed samples representing thousands of plant species. Seeds are particularly suitable for long-term conservation because many species produce desiccation-tolerant seeds that can survive extreme drying. During seed maturation, cells accumulate protective molecules and storage reserves that stabilize cellular structures when water content decreases. As a result, seeds enter a dormant state known as cryptobiosis, in which metabolic processes are greatly reduced (Walters et al., 2005). Despite these advantages, some plant species produce seeds that do not tolerate drying or freezing. These seeds, known as recalcitrant seeds, cannot be stored using conventional seed bank methods. Examples include certain tropical species and plants from humid environments. For such species, alternative preservation strategies such as cryopreservation are necessary.

CRYOPRESERVATION IN PLANT CONSERVATION

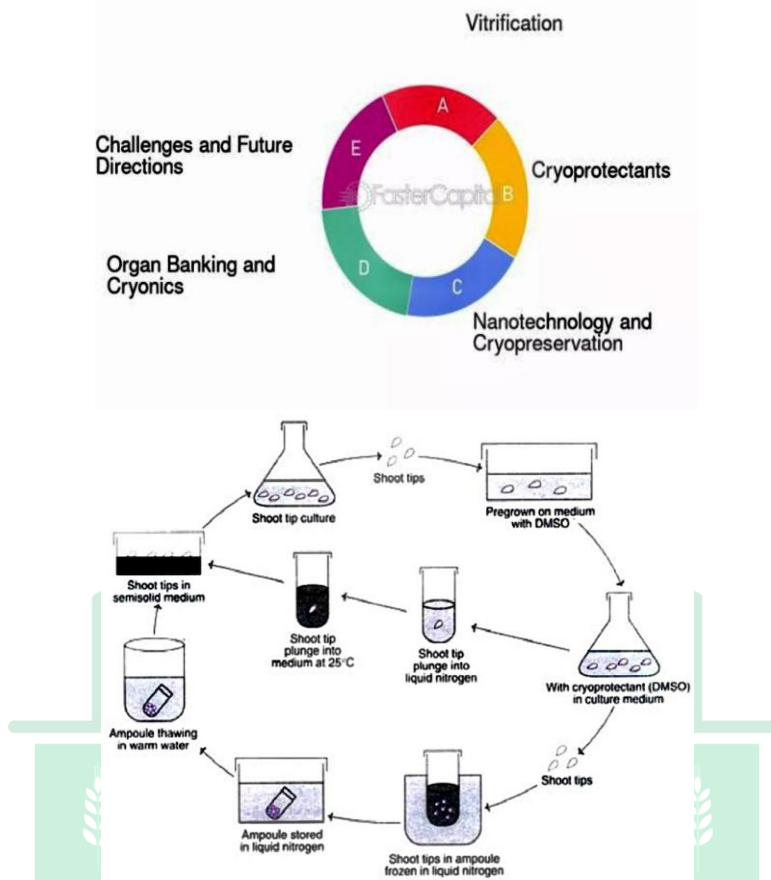
Cryopreservation is a technique used to store biological materials at extremely low temperatures, typically in liquid nitrogen at -196°C . At this temperature, all metabolic processes stop, effectively halting biological ageing and preserving tissues for extended periods. The process of cryopreservation involves several steps. First, plant tissues are dehydrated to remove free water that could form damaging ice crystals during freezing. Cryoprotective substances are then applied to protect cells from freezing damage. Finally, tissues are rapidly cooled and stored in liquid nitrogen (Walters & Pence, 2021). One of the earliest pioneers of plant cryopreservation was Akira Sakai, who demonstrated that plant tissues could survive exposure to liquid nitrogen. Since then, numerous cryogenic techniques have been developed to improve survival rates after thawing.



Modern Cryopreservation Techniques:

Several advanced cryopreservation methods are currently used for plant conservation. Vitrification is one of the most widely applied techniques. During vitrification, cellular fluids transform into a glass-like state without forming ice crystals. This process prevents structural damage and maintains cell viability. Other techniques include encapsulation-dehydration, encapsulation-vitrification, and droplet vitrification. These methods are particularly useful for preserving plant embryos, shoot tips, and other tissues that are difficult to store conventionally. Recent innovations such as V-cryo plates and D-cryo plates allow extremely rapid cooling and warming rates, reducing the risk of ice formation. Researchers continue to improve cryopreservation protocols by optimizing cryoprotectant solutions, adjusting cooling and warming rates, and improving tissue preparation methods. These improvements have significantly increased the success rate of plant recovery after cryogenic storage.

Advancements in Cryopreservation Techniques



Emerging Technologies in Seed Conservation :

Modern technologies are further transforming seed conservation practices. Artificial intelligence and machine learning systems are now used to analyze seed images and detect defects, pests, or empty seeds automatically. These technologies greatly reduce the time required for seed quality assessment. Non-destructive testing techniques such as infrared thermography and lipid thermal fingerprinting allow scientists to evaluate seed viability without damaging the samples. These methods are particularly valuable for rare or endangered species, where seed quantities are limited. Another innovative concept is “resurrection ecology,” where seeds collected at different time periods are stored and later compared to study evolutionary changes in plant populations. This approach helps researchers understand how plants adapt to environmental changes such as climate change.

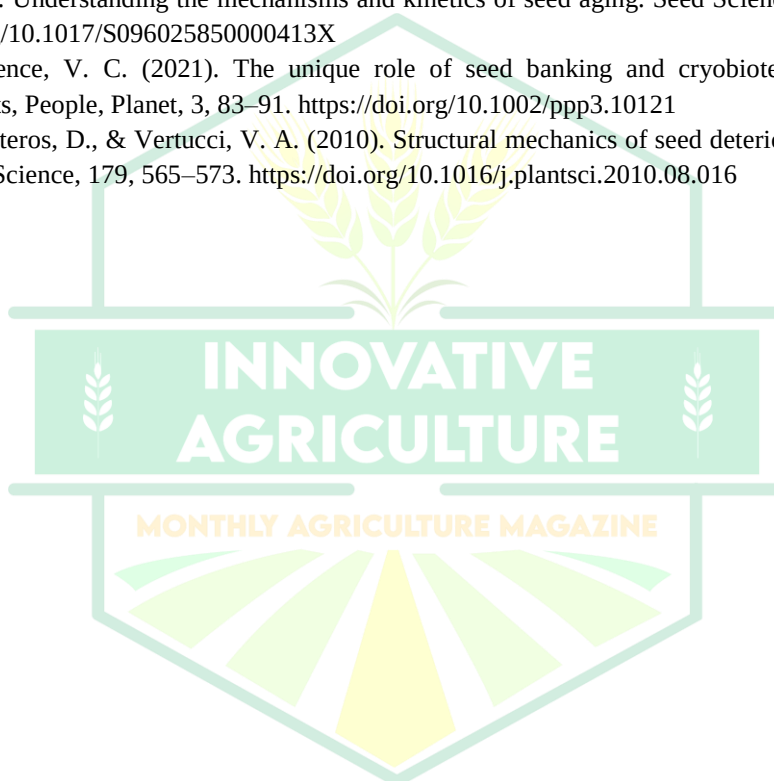
Conclusion

Seed storage and longevity research plays a critical role in conserving plant biodiversity and ensuring future food security. Seeds gradually lose viability over time due to environmental factors such as temperature, moisture, and oxygen exposure. However, proper storage conditions can significantly extend seed lifespan. Maintaining low temperature and low humidity is essential for slowing seed ageing and preserving viability. Advancements in seed bank technology have greatly improved the ability to conserve plant genetic resources. Modern facilities use automated climate control systems, digital monitoring technologies, and molecular tools to ensure the long-term preservation of seeds. Global initiatives such as international seed banks provide secure storage for millions of seed samples, protecting plant diversity from environmental threats. Cryopreservation has emerged as a valuable method for conserving plant species that cannot be stored using conventional techniques. By storing plant tissues at ultra-low temperatures, cryogenic methods prevent cellular damage and allow long-term preservation of genetic material. Continued research in cryobiotechnology and seed physiology will further enhance conservation strategies. Overall, integrating advanced technologies with traditional seed storage methods provides a

comprehensive approach to protecting plant genetic resources. These efforts support sustainable agriculture, biodiversity conservation, and global food security for future generations.

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India's Aquaculture Boom: Global Power, Local Paradox



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Introduction

India has become the forefront of global fish production just after the China, with an astonishing production of 19.76 million tonnes in the year 2024-25 which is more than double from 9.579 million tonnes of earlier in 2013-14 (shows 106% increase). At present, it contributes nearly 9% to the Global Sea food supply whereas China dominates with nearly 45-50% share. This boom, is supported by inland aquaculture with its significant contribution of 16.58 million tonnes and exhibited 159% rise in the same decade. Andhra Pradesh being one of the largest aquaculture producers contributing nearly 41% to the national output positioning India as an aquaculture super power amid 51% global shift to farmed fish consumption. The sector has become the top contributor to agricultural GVA with 7.43%, surpassing milk and eggs, while creating over 74 lakh jobs and powering seafood exports worth ₹62,408 crore which is mainly supported by the schemes like Pradhan Mantri Matsya Sampada Yojana (PMMSY). However, the per capita supply of 14kg found to be less than that of global average of 20.5kg. Fish production in India is largely *supply-oriented* and *export driven* due to resource availability, government incentives, and export potential rather than domestic consumer demand.

Fisheries Resources

India is endowed with vast marine and inland fisheries resources which include 11,099 km coastline, 2.02 million sq km Exclusive Economic Zone (EEZ), and 0.53 million sq km continental shelf, 0.195 million km rivers/canals, 1.2 million ha floodplain lakes, 3.15 million ha reservoirs, 2.45 million ha ponds/tanks, and 1.24 million ha brackish water areas and saline-alkaline conversions (3,159 ha approved).

On other hand, fisheries resources of Andhra Pradesh (AP) reflect 110 reservoirs and vast Godavari-Krishna deltas, 974 km coastline, 0.17-0.20 million sq km of EEZ, and aquaculture area over 2 lakh ha that comprises both shrimp and fish ponds.

Policy and export incentives

In support of the farmers and to maximize output, the Government of India has introduced a bunch of schemes, subsidies, and implemented through PMMSY. These schemes not only increased the level of output but also brought structural changes in the fisheries infrastructure facilities.

Species concentration

India being a carp country, farmers often focus on species with high export value rather than diversifying cultivable species to match with the local consumption preferences. This leads to oversupply of some species and scarce or non-availability of others which have domestic demand. This mismatch creates a discrepancy and leads to price fluctuations, market gluts, and uneven distribution.

Global fish consumption scenario

According to FAO, the global per capita fish consumption is found to be in the range of 20.5 - 21.3kg. The small island countries such as Maldives (80+ kg) and Norway (50+ kg) represent higher fish consumption due to cultural staples and high seafood reliance. Similarly per capita consumption in China (40 kg) and Japan (45 kg) found to be much better than the FAO levels, India (8.89 kg) on other hand ranks low among major producers.

Indian scenario

Though India's per capita fish consumption has increased from 4.9kg in 2005-06 to present 8.89 kg (2024), it remains far below the WHO-recommendation of 18 kg for optimal nutrition. With rising incomes, urbanization, and aquaculture boom, nearly 72% of Indian population now eating fish. However, deep regional disparities are observed between states. While per capita consumption in coastal states like Kerala and West Bengal exceed 15 kg, northern inland areas like Punjab drifting in between 2-3 kg.

Andhra Pradesh context

Despite the fact that state is hub of fish and shrimp production, per capita intake lags surprisingly at 8.07-8.56 kg, and matching with the national average. The reasons behind very low consumption in relation to production are heavy sea food exports, affordability barriers in rural regions, and strong preferences for chicken/pulses amid price volatility. While coastal districts (9.5 kg) exhibit a bit higher consumption, but the urban intake pulls down the state average intake. Though, AquaHubs initiative target for 24 kg by increasing local utilization to 30%, the progress is modest. The following tables 1 and 2 indicates per capita fish intake in highest and lowest fish producing states/UTs in India respectively.

Table 1: Per capita fish consumption in major fish producing states

State/UT	Total Fish Production (LT)	Per Capita Consumption (kg)
Andhra Pradesh	48.13	8.91
West Bengal	18.43	-
Karnataka	10.74	10.55
Odisha	9.9	16.34
Gujarat	8.74	7.44
Kerala	8.26	17.93
UttarPradesh	8.09	11.09
Tamil Nadu	8.07	9.30
Bihar	7.62	9.60
Chhattisgarh	5.91	19.70

Table 2: Highest per capita fish intake Sates/UTs

State	Total Fish Production (LT)	Per capita consumption (kg)
Lakshadweep	0.12	125.00
Goa	1.16	78.00
A and N ls lands	0.44	77.84
Tripura	0.82	25.53
Puducherry	0.47	18.88
Manipur	0.33	18.25
Assam	4.17	11.89
Jharkhand	2.57	10.61
Meghalaya	0.18	9.00
Telangana	3.90	8.70

Interestingly, the highest fish producing states shows less in take than the low producer states whereas coastal and eastern regions viz. Lakshadweep, Goa, Andaman & Nicobar Island and Tripura dominate consumption in where it exceeds more than 25 kg. Northern low intake continues due to preferences and fish availability. The

uneven consumption patterns, price instability and weak cold chain logistics and fragmented retail markets foil efficient distribution of fish to the deficit regions.

Nevertheless, National sample survey organization (NSSO) report (2022-23) on Household Consumption Expenditure (HCE), depicted a rising fish expenditure due to shifting non-vegetarian diets that in both rural and urban India. The data reflects a broader trend toward protein-rich foods over cereals. However, consumption does not increase at the rate fish production is increasing especially in states like Andhra Pradesh.

Initiatives for the promotion of fish consumption in Andhra Pradesh

The state is promoting *Fish Andhra* retail outlets and aqua hubs to ensure fresh, affordable supply targeted particularly the districts like Anantapur where fish production is low and selling up to 50 tonnes monthly through youth entrepreneurship. Further, door-to-door campaigns by women's groups to encourage weekly consumption of 1 kg per family; hosting *Fish Food Festivals* to showcase dishes. Scaling up PMMSY-tied subsidies for more than 2,000 hubs, processing units, and FFPOs targeting domestic use of 30% production.

In order to scall up fish intake in Andhra Pradesh, awareness must be created through campaigning the nutritional benefits particularly in schools and Colleges, Angawadi schools and introduce fish in the menu of Mid-day meal programs. In addition, cold chain logistics, mobile vending centres, youth startups for retails enable job creation, expanding domestic markets and fish availability.



Biochar: A Sustainable Solution for Agriculture



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Abstract

As the world's population grows and climate change intensifies droughts and desertification, we need practical, sustainable ways to grow food. Traditional fertilizers boost crop yields but can harm the environment and release greenhouse gases. Biochar, a nutrient-rich product made from biomass, is emerging as a natural solution. When added to soil, it enhances nutrients, water retention, and beneficial microbes, reducing the need for chemical fertilizers and improving crop yields. Beyond farming, biochar offers environmental and economic benefits and may even contribute to carbon credit systems. In short, biochar could be a key tool for sustainable agriculture.

Introduction

The term biochar is derived from the Greek words "*bios*," meaning life, and "*char*," referring to charcoal produced from the carbonization of biomass. Biochar is a fine-grained, carbon-rich, and porous material formed when biomass is heated under limited oxygen conditions. It is widely used in agriculture and environmental management because of its ability to improve soil quality and support sustainable farming. Biochar is similar to charcoal but is produced under controlled conditions at higher temperatures. It can be made from many organic materials such as wood, crop residues, animal manure, municipal waste, and other agricultural by-products. Biochar is produced through pyrolysis, a process in which biomass is heated between about 300°C and 700°C without oxygen. During pyrolysis, volatile substances are released and the remaining material converts into gases, liquids, and solid biochar while complex compounds break down into simpler ones. The quality of biochar generally increases with higher temperatures, often above 650°C. Its properties, including porosity and chemical composition, depend on the type of raw material and the pyrolysis temperature, while the moisture content of the feedstock affects the yield. When applied to soil, biochar helps improve soil fertility and structure, making it especially useful for degraded or nutrient-poor soils and promoting better crop growth.

Historical uses of biochar

The Terra Preta, sometimes known as "Indian black earth," was the first soil-improving application of biochar. Terra Preta is a kind of soil that originated in Western Amazonia. It is simple to detect because of its black colour, high nutritional content associated with an enhanced microbial population, and high degree of aggregate stability which is caused by the presence of more carbon. The most significant feature of Terra Preta is the deliberate application of biochar by ancient indigenous people to enhance the soil profile. The use of biochar improves the growth of tropical rainforest ecosystems by enhancing soil fertility, particularly in low-fertility sandy soils. Terra Preta showcases this as it is rich in essential nutrients like nitrogen, potassium, calcium, and phosphorus, and offers better soil structure and stability. Alkharabsheh et al. (2021) has discovered clay particles and mica remnants from pottery in the soil layers, suggesting that biochar production utilized clay ovens, with these materials incorporated into the soil matrix. Terra Preta soils contain diverse microbial communities, including a high abundance of acidobacteria, which play an important role in increasing nitrogen availability for plant growth. The bacterial diversity in these soils is about 25% higher than in other soils, highlighting the advanced knowledge of ancient Amazonian inhabitants in producing and applying biochar to improve soil fertility and demonstrating their sophisticated soil management practices.

Resources of biochar

Various biomass sources such as dry leaves, straw, coconut shells, animal waste, and forestry residues are used to produce biochar, although dedicated biomass production for biochar is often economically unviable. Because biomass has multiple uses, existing biochar systems mainly rely on readily available agricultural residues. Plant residues and animal manure support soil health by improving carbon storage, water retention, microbial activity, and agricultural productivity, and are also used as organic fertilizers and livestock feed, contributing to a zero-waste agricultural system. Therefore, careful feedstock management is needed so that enough residue remains to maintain soil quality. Some biochar sources, such as sewage sludge, may contain heavy metals and high moisture content, creating environmental and technical challenges during pyrolysis. When properly produced and applied, biochar can enhance topsoil fertility, improve crop growth, and help increase carbon dioxide absorption, supporting a healthier environment.

Biochar characteristics

The qualities of the feedstock used to prepare it are determined by its physical and chemical properties.

1. It has many microscopic pores, providing it a large surface area to hold water and act as a habitat for microorganisms which are beneficial.
2. Temperature increases during pyrolysis from 400 to 6000C, increase the amount of ash and fixed carbon while decreasing the volatile and N components of the biochar.
3. The total carbon content of biochar produced from various feedstocks ranges between 33 to 82%. Its C:N ratio ranges between 19 to 221.
4. Low levels of N and S are present in biochar produced at high temperatures.
5. Electrical conductivity, high pH, and extractable nitrate are all characteristics of high temperature biochar (>6500C).
6. Biochar made at a low temperature (3500C) contain more extractable P, phenols and NH₄.
7. The amounts of Ca, Mg, K and P in biochar are significant.

Advantages of biochar

Biochar enhances soil quality by storing nutrients over extended periods, reducing soil acidity, and minimizing liming requirements. It offers a favourable environment for beneficial bacteria, which promotes nutrient uptake by crops. Additionally, biochar aids in recycling organic waste, thereby decreasing CO₂ and methane emissions from biomass decomposition and effectively managing livestock manure.

1. Increased rate of fertilizer efficiency.
2. The preservation of toxins like pesticides and herbicides has improved the quality of the water.
3. Reduced emissions of the potent greenhouse gases methane and nitrous oxide, as well as increased emissions of renewable energy sources, all contribute to the mitigation of climate change.
4. Reducing the production of ammonia.
5. Removal of bio-waste from forestry and agriculture.
6. An increase in the soil's electrical conductivity capacity.
7. Increase in soil moisture.
8. Improved soil pH level (less acidic)
9. Increase in the biomass of soil microbes.

Disadvantages of biochar

1. In a few conditions, by the biochar sorption of water and nutrients may cause production to reduce since the plants can access these resources less easily. Sometimes bio-char can also stop sprouting.
2. Bio-char can absorb pesticides and weedkillers, which can reduce their efficiency.
3. Pollutants such heavy metals, PAHs (Polycyclic Aromatic Hydrocarbons), DOC (Dissolved Organic Carbon), etc. may be produced by biochar.
4. Nitrous oxide release can sometimes increase and rarely decline.
5. Fine ash produced from biochar can cause respiratory issues and create dust problems.

6. Long-term use of crop residues for biochar production may decrease soil microbial populations and disrupt nutrient cycling, negatively impacting soil structure, particularly in soils with high organic matter or clay.
7. An increase in soil pH is not necessary for highly alkaline soils, as plants are only able to tolerate a specific pH range.

Biochar preparation is relatively straightforward. Biochar is generated through the pyrolysis of feedstock under specific conditions, resulting in gas and bio-oil as co-products. However, its use in agriculture has drawbacks, including soil compaction, erosion damage, pollution risks, removal of plant residues, and decreased insect life rates.

The application of biogas in top soil management has been evaluated in various case studies, revealing that factors such as the biochar manufacturing process and material source significantly influence soil fertility in the Amazon. Specifically, adding biochar may introduce heavy metals found in sewage biochar and lead to soil compaction. Furthermore, biochar derived from plant debris can negatively affect the soil surface, contributing to erosion caused by wind or water (Faraaz Farooq and Permendra Singh 2022).

Uses of biochar in soils

Biochar significantly enhances soil integrity by improving its physical structure, aeration, and water holding capacity. Its varying porosity and particle sizes contribute to better soil conditions, especially in compacted soils. Combining biochar with compost offers additional benefits, providing an early nutrient boost from compost and long-term nutrient release from biochar, supporting higher crop yields. Biochar also promotes oxidation-reduction processes in the soil and is highly durable, lasting for years without yearly application, making it cost-effective. It helps counteract the decline of soil organic matter caused by weathering, farming, and human activity. Moreover, it increases ethylene detection, a key plant hormone, which subsequently boosts crop yields through enhanced plant growth and ripening.

Impacts of biochar on agriculture

The properties and advantages of biochar, influenced by its production material and processing methods, are significant when applied to land. Biochar can retain nutrients and fertilizers, slowly releasing them to crops, which enhances agricultural productivity. Its ability to hold water and nutrients in surface soil layers leads to increased crop yields and reduced fertilizer dependency, thereby diminishing adverse environmental impacts. It is crucial to distinguish biochar from compost; while compost serves as a nutrient source through the breakdown of organic matter, biochar does not decompose, thus minimizing the frequency of application needed over time.

While biochar application can enhance agricultural production, some studies indicate no yield benefits or even negative responses (Schnell et al., 2012; Spokas et al.; Lentz and Ippolito, 2012). Factors such as low application rates, limited nutrient availability, application on already fertile soils, and poor yield reports may influence these outcomes. Cases with high yields are challenging to decipher but may depend on biochar properties, soil fertility, and the specific crop. Recent studies by Rehman HA, Razzaq R (2017) highlight that biochar's benefits are often seen in extremely weathered and infertile soils.

Impacts of biochar on environment

Biochars, derived from various feedstocks, enhance soil fertility, energy production, carbon sequestration, and waste management. They serve as effective, low-cost sorbents for environmental pollutants, demonstrated through studies at both laboratory and field scales for in-situ remediation of organic and inorganic contaminants. For example, biochar from wheat waste pyrolyzed at temperatures between 300°C and 700°C effectively removed benzene and nitrobenzene from wastewater (Thakur et al., 2021). Similarly, atrazine and simazine were eliminated from aqueous solutions using biochar made from green waste (Zheng et al., 2010), while pine needle-derived biochar was used to remove naphthalene, nitrobenzene, and m-dinitrobenzene from water (Cha et al., 2016). Biochars made from straw effectively eliminated reactive brilliant blue and Rhodamine blue dyes from wastewater, providing a more economical option than activated carbon (Qiu et al., 2009). Additionally, biochar produced from dairy manures through pyrolysis at 200°C to 300°C significantly removed atrazine from wastewater (Uchimiya et al., 2010).

Biochars effectively eliminate metal pollutants and nutrients from wastewater and soil, alongside organic contaminants. Research by Cao et al. (2009) indicated that biochars from dairy manures pyrolyzed at low temperatures were six times more efficient than commercial activated carbon in removing lead (Pb). Uchimiya et al. (2011) found that broiler litter manure biochar enhances the immobilization of heavy metals like cadmium (Cd), copper (Cu), nickel (Ni), and lead (Pb) in the environment. Yao et al. (2011) reported a 73% reduction of phosphate from water using biochar derived from anaerobically digested sugar beet tailings. Magnetic biochar has been shown to efficiently remove both phosphate and hydrophobic organic pollutants simultaneously (Hanuman et al., 2020), illustrating biochar's role in reducing nitrogen leaching in agriculture.

Conclusion

Biochar is produced by pyrolyzing biomass at temperatures above 300°C without oxygen and can be applied to agricultural land to improve soil health and crop productivity. It enhances key soil properties such as pH, cation exchange capacity, and water-holding capacity, while improving nitrogen use efficiency. Biochar also helps sequester carbon and may reduce greenhouse gas emissions, including methane and nitrous oxide from soils. Understanding how different soil types interact with biochar is crucial to determine its effects on the nutrient cycle, soil structure, and biochemical composition, and to evaluate its potential for long-term sustainable agriculture.

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BIOTREMOLOGY IN INSECTS: A HIDDEN VIBRATION



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INTRODUCTION

The natural world is filled with sounds of birds singing, frogs croaking, bees buzzing and crickets chirping. These audible signals form only a small fraction of biological communication occurring around us. Beneath this familiar acoustic environment exists a vast, largely hidden communication system operating through vibrations transmitted across surfaces such as plants, soil and other solid substrates.

Insects, the most diverse group of organisms on Earth, have evolved sophisticated methods of exchanging information without producing audible sounds. Insects employ diverse communication systems involving chemical, visual, tactile and acoustic modalities. Unlike airborne sound transmission, vibrational signals propagate through solid media such as plant tissues or soil surfaces, enabling efficient information exchange among organisms sharing a physical substrate (Cocroft & Rodríguez, 2005). Plant-dwelling insects particularly depend on vibrational communication because vegetation provides continuous mechanical connectivity between individuals. Consequently, agricultural ecosystems contain extensive vibrational networks supporting interactions among herbivores, predators and parasitoids.

Recognition of this hidden communication channel has led to the establishment of biotremology as a specialized interdisciplinary field (Hill & Wessel, 2016). Growing concerns regarding pesticide resistance and environmental sustainability have further stimulated interest in exploiting insect vibrational behavior for crop protection.

CONCEPT OF BIOTREMOLOGY

The term *biotremology* derives from the Greek words *bios* (life), *tremor* (vibration) and *logos* (study). Biotremology refers to the study of communication mediated by mechanical vibrations transmitted through substrates rather than air. Early experimental demonstrations showed that plants function as efficient signal transmission channels for insects inhabiting foliage systems (Michelsen *et al.*, 1982). Subsequent investigations confirmed that vibrational signaling occurs across multiple insect orders including Hemiptera, Orthoptera, Coleoptera and Blattodea.

EVOLUTIONARY ORIGIN OF VIBRATIONAL COMMUNICATION

Vibrational signaling is considered one of the earliest forms of animal communication. Before the evolution of advanced auditory organs capable of detecting airborne sounds, organisms relied on mechanical vibrations transmitted through surfaces to detect predators, prey or conspecifics.

Small-bodied insects inhabiting dense vegetation benefit particularly from substrate communication because plant structures provide continuous physical connections between individuals. Vibrational communication evolved as an adaptive strategy because it requires less energy, functions effectively in complex habitats, reduces detection by predators and enables species-specific signaling (Cocroft *et al.*, 2014). Consequently, vibrational signaling has independently evolved across numerous insect taxa.

MECHANISMS OF VIBRATIONAL SIGNAL PRODUCTION

Insects generate substrate vibrations using several biomechanical strategies.

1. **Tremulation:** Tremulation involves rhythmic oscillatory body movements transmitted through appendages contacting the substrate. This mechanism is common among sap-feeding insects such as leafhoppers and planthoppers, where abdominal or thoracic oscillations produce characteristic signaling patterns (Virant-Doberlet & Cokl, 2004).
2. **Percussion Signaling:** Percussion occurs when insects strike body parts against surrounding surfaces. Termites produce alarm signals by repetitive head-banging within galleries, enabling rapid colony-wide information transfer (Hill, 2008) and stoneflies drum their abdomen on substrates.

3. **Stridulatory Vibrations:** Stridulation results from friction between specialized cuticular structures. Stridulation results from rubbing specialized body structures such as files and scrapers. Although often associated with audible sounds, vibrational components transmitted through substrates play an equally important communicative role.
4. **Tymbal-Based Vibrations:** Certain insects utilize deformable cuticular membranes known as tymbals that generate pulse trains during muscular contraction. These signals may propagate simultaneously through air and substrate media Cicadas are well-known examples, though substrate transmission often accompanies airborne sound.

SENSORY ADAPTATIONS FOR DETECTING VIBRATIONS

The success of biotremology depends not only on signal production but also on precise detection. Insects possess remarkably sensitive vibration receptors. Detection of substrate vibrations requires highly specialized mechanoreceptors.

The subgenual organ, located within insect legs, represents the primary vibration receptor capable of detecting extremely small substrate displacements. Complementary sensory structures such as chordotonal organs and campaniform sensilla enable frequency discrimination and directional perception (Keil, 1997). These sensory adaptations allow insects to interpret signal timing, amplitude and frequency patterns essential for behavioral decision-making.

BEHAVIORAL FUNCTIONS OF VIBRATIONAL COMMUNICATION

- 1) **Mate Location and Courtship (Sexual communication):** Vibrational signaling plays a dominant role in reproductive communication among plant-dwelling insects. Males typically initiate calling signals followed by female reply signals, forming coordinated vibrational duets that guide mate localization. Example vibrational songs of *Nezara viridula*.
- 2) **Species Recognition:** Species-specific signal parameters prevent reproductive interference among sympatric species occupying the same host plant (Cocroft *et al.*, 2014).
- 3) **Alarm and Social Communication:** Social insects employ vibrational signals for alarm transmission and colony defense coordination. Rapid signal propagation through nest structures enhances collective survival responses (Hill, 2008). Examples of vibrational signals produced by honeybees and termites.
- 4) **Competitive and Territorial Behavior:** Vibrational signals may also regulate access to feeding or oviposition sites through competitive interactions. Example territorial vibratory signaling of neonate warty birch caterpillar *Falcaria bilineata*.

VIBRATIONAL COMMUNICATION IN AGRICULTURAL ECOSYSTEMS

Crop plants serve as extensive vibrational transmission networks connecting herbivorous insects. Economically important pests such as leafhoppers, planthoppers, psyllids, and stink bugs rely heavily on substrate-borne communication (Polajnar *et al.*, 2015). Plants effectively function as communication pathways enabling mate finding and aggregation behaviors.

Plant–Insect Vibrational Interactions

Recent research indicates that plants influence signal transmission characteristics through structural properties such as stem stiffness and moisture content. Feeding vibrations produced by herbivores can be detected by predators and parasitoids, suggesting indirect plant defense mechanisms mediated through vibrational cues (Appel & Cocroft, 2014). Thus, plants participate actively in ecological communication systems rather than acting merely as passive substrates.

APPLICATIONS OF BIOTREMOLOGY IN PEST MANAGEMENT

1. **Vibrational Mating Disruption:** Artificial vibration playback can interfere with insect courtship signals, preventing successful mate recognition. Field experiments demonstrate population suppression of vineyard pests using this approach. Vineyards are equipped with vibrational mini shakers attached to the trellis wire to emit disturbance noise, a natural vibrational signal produced by males during rivalry interactions, which effectively blocked mating in 94.3% of cases (Polajnar *et al.*, 2015).
2. **Pest Monitoring Systems:** Sensitive vibration sensors enable early detection of concealed insect infestations, improving decision-making within precision agriculture systems (Mankin *et al.*, 2011).

3. Repellence, attraction and trapping of insects: Vibrational signals orient the pest away from the stimulus and also elicit attraction to trap insects.

- a) Pea aphids (*Acyrtosiphon pisum*) and common angle moth caterpillar (*Semithisa aemulataria*) exhibit dropping behaviour in response to predator- associated vibrational signals and artificial playback of such predator-like vibrations can effectively induce these pests to abandon their host plants.
- b) Vibrational trapping in *Diaphorina citri*: A device microcontroller buzzer which mimics female vibrational signals effectively disrupted mating and reduced mating success from 13% to 57%. The device successfully attracted and trapped 45% of males in a 1-hour field test.

4. Integration with Sustainable Agriculture: Biotremology-based technologies offer major advantages because target specificity, minimal ecological impact and compatibility with integrated pest management programs.

TECHNOLOGIES USED IN BIOTREMOLOGICAL RESEARCH

The advances in instrumentation have enabled detailed study of insect vibrations. Common tools include:

- Laser Doppler vibrometers,
- Piezoelectric accelerometers,
- Contact microphones,
- Digital signal analysis software (Hill & Wessel, 2016).

These tools allow non-destructive monitoring of insect communication under laboratory and field conditions

ADVANTAGES OF BIOTREMOLOGY

- Biotremology avoids chemical use, leaving no toxic residues and preserving ecosystem health.
- It targets pests precisely by disrupting their unique vibrational communication without affecting non-target species.
- Physical signals reduce the chance of resistance evolution compared to repeated pesticide use.
- Easily complements other control methods in integrated pest management for enhanced efficiency.
- Biotremology has reshaped understanding of ecological interactions by revealing hidden communication networks influencing: speciation processes, predator-prey dynamics, habitat adaptation and social evolution.

DISADVANTAGES OF BIOTREMOLOGY

- It requires time to show effects, making it less suitable for rapid pest outbreaks.
- Designing effective signals requires deep knowledge of pest behaviour, vibration physics and plant transmission properties.
- Signal strength and consistency can change with different plants and larger fields making it harder to use on a big scale.
- Developing species-specific devices and validating field effectiveness involves significant investment and time.
- Several constraints limit large-scale implementation: environmental signal interference, complexity of multi-species vibrational communities, variation among crop architectures and field deployment costs.

FUTURE PERSPECTIVES

Biotremology represents a transformative frontier in ecological pest management. Emerging concepts such as vibration-mediated crop protection, automated signal emitters and intelligent monitoring networks may substantially reduce chemical pesticide dependence. As agriculture shifts toward sustainability, manipulation of insect communication systems may become an essential component of next-generation farming technologies.

CONCLUSION

Insect biotremology uncovers a hidden dimension of biological communication occurring continuously within agricultural and natural ecosystems. Insect biotremology reveals a previously underestimated dimension of ecological communication operating through substrate-borne vibrations. These signals regulate reproductive behavior, social organization and species interactions across diverse insect groups. Understanding this invisible vibrational language offers transformative opportunities for sustainable pest management and ecological agriculture. Advancing knowledge in this field provides significant opportunities for environmentally compatible

pest management strategies. Continued interdisciplinary research will be crucial for harnessing vibrational communication as a practical tool for sustainable agriculture.

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BEYOND YIELD: WHY QUALITY TRAITS MATTER IN STAPLE FOOD CROPS



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Introduction:

In a world where food security is paramount, breeding crops isn't just about quantity—it's about quality too. Imagine biting into rice that's not only nutritious but cooks perfectly fluffy, or wheat that bakes the ideal loaf. This article explores the importance of superior quality traits in staple crops like rice, wheat, and maize to meet consumer demands, boost nutrition, and support health.



Why Quality Matters Beyond Yield?

The primary goal of crop breeding has been to ramp up productivity to feed growing populations. But yield alone isn't enough. Quality defined as the "degree of excellence" for a specific use (Gupta, 2001), plays a crucial role in consumer choices and crop popularity. Traits like color, taste, and nutritional content can make or break a variety's success. For instance, in India, amber-colored wheats are favored over darker ones for their appeal.

This focus extends to nutritional aspects, particularly protein content, which is vital for health. Oil quality traits are also key, though we'll touch on them illustratively. Ultimately, quality breeding ensures crops are not just abundant but also beneficial.

Defining Quality and breeding for quality

In crop plants, quality refers to how well an economic plant product suits its end use be it for eating, processing, or storage. Quality breeding, on the other hand, involves developing crop varieties with superior nutritional, processing, storage, or consumer-preferred characteristics, (Fehr 1987) alongside high yield and stress tolerance. These traits can be physical (like size), chemical (like nutrient levels), or functional (like cooking ease), all enhancing the crop's overall value.

Classifying Quality Traits: A Breakdown

Quality traits vary based on needs—from seed appearance to post-harvest handling. According to experts like Gupta (2001), they fall into four main categories:

Morphological Traits: Related to appearance, such as grain or fruit size and color. These are easily observable and often dictate consumer acceptance.

Organoleptic Traits: About palatability, including taste, aroma, smell, juiciness, and softness. They're detectable by senses and heavily influence preferences.

Nutritional Traits: Determine nutritional value, covering protein, oil, vitamin, and mineral content, plus antinutritional factors. Though not always obvious, they're critical for health.

Biological & Other Traits: Define actual usefulness when consumed, like protein efficiency ratio or keeping quality of fruits.

Category	Key Examples	Why It Matters
Morphological	Grain size, fruit color	Drives visual appeal and market value
Organoleptic	Taste, aroma, juiciness	Influences eating enjoyment
Nutritional	Protein/oil quality, vitamins	Boosts health benefits
Biological/Other	Protein digestibility, cooking time	Ensures practical use and safety

Nutritional Powerhouses: Focus on Proteins and Oils

Protein Quality Essentials: Proteins are diet staples, made of amino acids linked by peptide bonds. Their nutritional value hinges on amino acid composition. There are 21 key amino acids, split into essential (must be from diet) and non-essential.

Crop proteins are classified by solubility and amino profile:

Protein Fraction	Soluble In	Amino Acid Profile
Albumin (2S)	Water	Balanced
Globulins (11S and 7S)	Dilute saline	Deficient in S-containing amino acids
Prolamins	Alcohol-water mixture	Deficient in Lys, Trp; Rich in Pro, Gln
Glutelins	Dilute alkali/acid	-

Deficiencies can lead to health issues like kwashiorkor (protein malnutrition) or pellagra (high leucine imbalance).

Oil Quality Traits: Vegetable oils rank high in diets for energy, vitamins, and cell structure. Oilseed crops like soybean and sunflower provide edible oils. Quality depends on fatty acids like oleic and linoleic, affecting nutrition and stability.

Quality Traits in Staple Food Crops: A Crop-by-Crop Overview

Each crop has unique quality benchmarks:

Rice: Hulling/milling recovery (70-79%), endosperm type (waxy/non-waxy), grain shape (slender/bold), aroma, amylose content (affects stickiness) Juliano 1971 cooking qualities like elongation and gel consistency (Fitzgerald et al., 2009)

Amylose and Cooking:

Amylose Content	Endosperm Type	Cooked Rice Traits
Up to 2	Waxy	Sticky, low expansion
20	Low amylose	---
21-25	Intermediate	---
25+	High amylose	Dry, fluffy, hardens on cooling

Wheat: Grain size/color/texture, protein/gluten content, Polshenke value (gluten strength) Payne et al., 1987 sedimentation value, alveogram, mixogram. (Shewry, 2009)

Maize: Seed type/size/color, protein quality (high lysine/tryptophan via opaque-2) (Vasal, S. K. 2000)

Pigeon Pea: Seed size/color, protein (23-26%), cooking time, amylose.

Pearl Millet: Fodder palatability, protein, minerals, low oxalic acid.

Rapeseed/Mustard: Oil content (46%), low erucic acid/glucosinolates ("canola" types) Downey & Robbelen 1989

Chick Pea: Seed type/color/size, protein (18-29%), cooking time.

Cow Pea: Large uniform seeds, no hilum scar, protein, cooking quality.

Lentil: Seed size/color, protein (23-36%), cooking time.

Mungbean/Urdbean: Seed size/color, protein (21-36%), low flatulence factors.

Where Do Quality Traits Come From?

The sources of quality traits include:

- Cultivated varieties (easiest to use, e.g., Atlas-64 for high protein).
- Germplasm lines (e.g., IR36 for amylose).
- Mutants (e.g., P721 sorghum for lysine).
- Wild relatives (e.g., QTLs from wild cotton for fiber).
- Somaclonal variants (e.g., Scarlet sweet potato for color; Ratan khesari for low BOAA).
- Transgenes (genetic engineering for targeted traits).

The Genetics of Nutritional Traits

The nutritional traits follow: Oligogenic and polygenic inheritance

Oligogenic Inheritance: Governed by few major genes with detectable effects. Simpler breeding. (Allard, 1999)

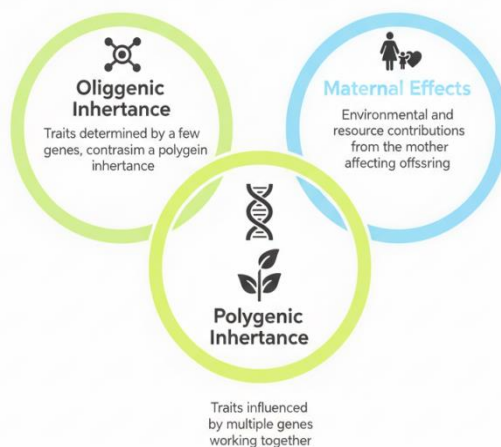
Examples:

Oligogene	Quality Trait	Crop	Remarks
hp	Provitamin A	Tomato	40% increase
Og ^c	Provitamin A	Tomato	40% decrease
ti	Trypsin inhibitor	Soybean	50% decline
O2	Lysine	Maize	Opaque endosperm
O7	Lysine	Maize	Opaque endosperm
F12	Lysine	Maize	Floury endosperm
Lys	Lysine	Barley	Shriveled endosperm

Polygenic Inheritance: Involves the action of multiple genes, each contributing a small effect to the expression of a trait, resulting in continuous variation in the population. Such traits are highly influenced by environmental factors and generally exhibit low to moderate heritability (Falconer and Mackay 1996).

e.g., Protein content in cereals, pulses and oil content in oilseed crops are governed by polygenes

Genetic Influences on Traits



Challenges and Significance

Quality traits in staple food crops are no longer optional refinements—they are essential pillars of modern agriculture. Enhancing nutritional value, processing suitability, consumer preference, and market competitiveness ensures that crops deliver not just calories, but true nourishment and economic value. While breeding for superior quality presents challenges—particularly in balancing yield performance and managing environmental sensitivities—scientific advancements continue to narrow this gap. Successful examples such as high-lysine maize and improved cooking-quality rice demonstrate that it is possible to combine productivity with enhanced nutritional and functional traits. These achievements highlight the power of genetics, innovation, and sustained research in reshaping our food systems.

As global populations rise and climate pressures intensify, the focus must shift from producing “more food” to producing “better food.” Breeding for quality traits is transforming staple crops into healthier, tastier, and more resilient sources of sustenance. The future of agriculture lies not only in feeding the world—but in nourishing it.

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Protecting Your Herd: A Guide to Livestock Insurance in India



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For millions of farmers in India, livestock is far more than just an asset—it is often the primary source of livelihood and financial security. A high-yielding buffalo, a productive dairy cow, or a flock of sheep and goats represents years of investment and care. However, unexpected events such as disease outbreaks, accidents, or natural disasters can cause sudden losses. In such situations, **livestock insurance** acts as an important financial safeguard, helping farmers recover losses and sustain their agricultural activities.

1. Understanding Livestock Insurance

Livestock insurance is a financial protection scheme designed to compensate farmers if their insured animal dies due to specified risks. Under this arrangement, the farmer pays a small **premium** to an insurance provider, and in return the company agrees to compensate the owner with the **sum insured**, which is usually the market value of the animal.

This compensation allows the farmer to replace the animal and continue the farming operation without severe financial hardship.

Livestock insurance schemes generally cover:

- Cattle:** Dairy cows and buffaloes, which form the backbone of India's dairy sector.
- Small ruminants:** Sheep and goats, commonly reared by rural and pastoral communities.
- Other livestock:** Pigs, horses, and poultry under certain commercial insurance schemes.

2. Government Support for Farmers

To encourage wider adoption of livestock insurance, the Government of India, through the **Department of Animal Husbandry and Dairying**, provides substantial financial assistance.

Key features include:

- Premium subsidy:** Farmers often receive a subsidy covering around **50% of the premium cost**, making insurance more affordable.
- Focus on milch animals:** Dairy animals receive particular attention because of their vital role in rural income and national milk production.
- State-level initiatives:** Several states, including Telangana and Andhra Pradesh, provide additional support. In some programs, subsidies for sheep and goat farmers can reach **up to 70% of the premium cost**.

Such initiatives aim to protect farmers from sudden economic shocks while strengthening the livestock sector.

3. Coverage Provided Under Livestock Insurance

Livestock insurance policies generally protect animals from a range of risks. However, certain exclusions also apply.

Risks commonly covered include:

- Death due to **diseases** occurring during the policy period
- Accidents**, such as lightning strikes, fire incidents, or vehicle collisions
- Natural calamities**, including floods, cyclones, and earthquakes
- Complications arising from necessary surgical procedures**

Risks generally not covered include:

- Intentional slaughter**, unless permitted by law
- Death caused by **negligence**, such as failure to provide proper food, water, or care
- Losses arising from **war or nuclear risks**

d. **Theft**, unless the policy includes a specific add-on for theft coverage
Understanding these terms is important for farmers before purchasing a policy.

4. Cost of Livestock Insurance

The premium for livestock insurance is usually calculated as a small percentage of the animal's market value. Due to government subsidies, the actual amount paid by farmers is often minimal.

Typical premium rates may include:

- a. **Cows and buffaloes:** Approximately 2–4% of the animal's value
- b. **Sheep and goats:** Around 4–6%
- c. **Pigs:** About 5–7%

A crucial step in this process is **proper valuation of the animal by a qualified veterinarian**. Accurate valuation prevents under-insurance and ensures fair compensation in case of loss.

5. Steps to Insure Livestock

Farmers can insure their animals through a simple procedure:

1. **Identification:** The animal is tagged with a unique ear tag or microchip, which serves as proof of identity.
2. **Health certification:** A veterinary doctor conducts a health examination and issues a health certificate.
3. **Valuation:** The veterinarian and insurance representative determine the animal's market value.
4. **Premium payment:** The farmer pays the premium to an authorized insurance provider such as the Agriculture Insurance Company (AIC) or New India Assurance.
5. **Policy issuance:** The insurance company provides policy documents that should be carefully preserved.

In the unfortunate event of an animal's death, the farmer must **inform the insurance company within 24 hours** and arrange for a **post-mortem examination** to verify the cause of death.

Why Livestock Insurance Matters

Livestock insurance is not merely a financial product—it is an important risk-management tool for rural livelihoods. By protecting farmers against sudden losses, it encourages them to invest in improved breeds, better feeding practices, and modern livestock management.

Ultimately, livestock insurance contributes to **economic stability in rural communities**, supports the growth of the dairy and livestock sectors, and helps ensure that a biological loss does not turn into a financial catastrophe for farming families.

Digital Agriculture: The Future of Farming



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A technological revolution is taking place in agriculture. Modern technologies like cellphones, drones, sensors, satellite imaging, and data analytics are rapidly supplementing traditional farming practices. Digital agriculture, also referred to as smart farming, is the incorporation of digital technologies into farming. It is a crucial route for agriculture's future since it has the ability to boost farmers' earnings, productivity, and resource efficiency. The use of data, digital tools, and information and communication technology (ICT) in agricultural management and production is known as "digital agriculture." These technologies assist farmers in making more informed decisions about marketing, irrigation, pest control, and crop management.

Mobile applications, remote sensing, artificial intelligence, precision farming technologies, and online agricultural marketplaces are examples of instruments used in digital agriculture. Farmers may increase productivity and reduce expenses by optimising inputs such as water, fertiliser, and pesticides using real-time data collection and analysis.

Key Technologies in Digital Agriculture

1. Mobile apps

Farmers can obtain market prices, crop advice services, weather forecasts, and pest control information using smartphone apps. These applications close information gaps and assist farmers in making prompt decisions.

2. Remote sensing and drones

The usage of drones for agricultural monitoring, pesticide spraying, and crop health assessment is growing. They offer precise aerial photos that aid in the identification of illnesses, nutrient deficits, and water stress.

3. Precision Farming

Precision agriculture applies inputs like fertilizer and irrigation in precise amounts using GPS technology, sensors, and data analytics. This lessens waste and its negative effects on the environment while increasing production.

4. The Internet of Things

Real-time data is gathered from farms via IoT devices like smart irrigation systems and soil moisture monitors. Farmers can better manage their resources and keep an eye on their land from a distance.

5. Online Marketplaces

Farmers can sell their goods directly to consumers through online channels, eliminating the need for middlemen. The goal of programs like the National Agriculture Market (e-NAM) in India is to establish a single digital marketplace for agricultural products.

The Government of India has launched several initiatives to promote digital agriculture and smart farming technologies. One of the main initiatives is the Digital Agriculture Mission, which uses tools like AgriStack, digital crop surveys, and decision-support systems that combine satellite, weather, and soil data to create an all-encompassing digital ecosystem for agriculture. The National Agriculture Market (e NAM), an online trading platform that links agricultural markets nationwide and enables farmers to sell their produce digitally with more price transparency, is another significant project. Additionally, the government launched the NaMo Drone Didi Scheme to encourage the use of drones in agriculture for precision spraying and crop monitoring while giving rural women jobs. Additionally, the Soil Health Card Scheme gives farmers scientific advice on nutrient management through digital soil testing.

Benefits of Digital Agriculture

Farmers and the agricultural industry can benefit from digital agriculture in a number of ways. First, it makes timely interventions and improved crop management possible, which boosts yield. Second, it increases resource efficiency by making the best use of pesticides, fertilizers, and water. Third, by putting farmers and buyers in direct contact and offering real-time pricing information, digital tools improve market access.

Climate resilience is further enhanced by digital agriculture. Farmers can modify their methods in response to shifting environmental conditions if they have access to climate data and weather forecasts.

Challenges in Adopting Digital Agriculture

Adoption of digital agriculture confronts a number of obstacles despite its potential. Many small and marginal farmers do not have access to digital literacy, smartphones, or the internet. Adoption may also be hampered by the high initial price of cutting-edge technologies like sensors and drones. To use digital instruments efficiently, farmers also require technical assistance and training. The advantages of digital agriculture could not be available to all farmers in the absence of adequate infrastructure and extension services.

The Way Forward

Governments and business organizations must make investments in rural digital infrastructure, enhance internet access, and offer farmers training programs in order to support digital agriculture. Affordable digital solutions can also be developed more quickly by fostering innovation and collaborations between IT firms and agricultural organizations.

Digital agriculture has the potential to revolutionize farming by increasing its productivity, sustainability, and profitability. Digital technologies can empower farmers and guarantee that agriculture is resilient in the face of increasing population demands and climatic issues with the correct policies and support systems.

Conclusion

The next frontier in agricultural development is digital agriculture. Farmers may increase output, lower hazards, and improve their standard of living by fusing ancient wisdom with contemporary technologies. Digital technologies will be vital in determining the direction of farming and guaranteeing the security of the world's food supply as they develop further.



Application of high-quality flavours and sweeteners in animal feeds: Impact on palatability, digestibility and performance of livestock



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Introduction

Feed is the single largest input in livestock production, accounting for 60–70% of the total cost in intensive systems. Achieving high productivity in animals whether it is growth rate, milk yield, reproductive performance or meat quality depends heavily on the quantity and quality of feed consumed. While nutritionists invest significant effort into formulating rations with the right balance of protein, energy, vitamins and minerals, feed intake itself is the first determinant of nutrient utilization. If animals do not consume the intended amount of feed, even the best-balanced ration will not meet its purpose.

Flavours and sweeteners have been strategically incorporated into animal feeds as feed additives to overcome feed intake limitations, mask undesirable tastes, improve palatability, enhance digestibility indirectly and consequently boost performance. In modern animal production systems, where efficiency is paramount, these additives play an increasingly important role. This popular article provides detailed scientific materials covering the application, mechanisms, advantages, palatability, digestibility and performance outcomes of using high-quality flavours and sweeteners in livestock feeds. The discussion spans poultry, swine, fish, companion animals and ruminants (cattle, buffalo, sheep, goats), with references to both scientific evidence and commercial practices.

Concept of feed palatability and need for flavours and sweeteners

Palatability refers to how pleasant and acceptable an animal perceives a feed to be, influencing its voluntary intake. It is a composite trait determined by:

- Taste (sweet, sour, bitter, salty, etc.)
- Smell (olfaction)
- Texture/mouth-feel
- Post-ingestive feedback (how the animal feels after consuming feed)

While energy density and nutrient balance are critical, feed refusal due to off-flavours, bitterness, or monotony in diet can significantly reduce intake.

Challenges in modern feed formulation

Inclusion of by-products (e.g., distillers dried grains, rapeseed meal, feather meal and fishmeal, etc.) that may impart bitterness or rancid notes,

Use of medications or minerals (zinc oxide, copper sulphate and coccidiostats) with metallic or bitter tastes,

Heat processing (pelleting and extrusion) that can generate burnt notes,

Consumer pressure to reduce antibiotics and chemical growth promoters, necessitating alternatives for sustaining intake and growth,

These factors highlight why flavours and sweeteners are vital to improve palatability, encourage feed intake and sustain performance.

High-quality flavours in animal nutrition

Feed flavours are formulations containing natural, nature-identical or artificial compounds that impart specific aromas or tastes to feed. They are usually blends of essential oils, aldehydes, ketones, alcohols, esters or botanical extracts.

Categories of feed flavours

1. Masking flavours: Conceal unpleasant odours/tastes from by-products or medications.

2. Enhancing flavours: Intensify natural aroma of feeds (e.g., vanilla, milk, fruit).

3. Novelty/conditioning flavours: Familiarize young animals with a consistent flavour, helping transition between diets (e.g., milk replacer to starter feed).

Mechanism of action

Stimulation of olfactory receptors: Attract animals to feed.

Positive association/conditioning: Animals recognize and accept flavoured feed more readily over time.

Improved feed uniformity perception: Flavours homogenize sensory cues in multi-ingredient feeds.

Application in different species

1) Swine

Piglets post-weaning face weaning anorexia due to stress and shift from milk to solid feed. Flavours such as vanilla, fruity, and milky notes improve feed acceptance. Trials show flavoured creep feed leads to higher feed intake and daily gain during the critical first 2 weeks post-weaning.

2) Poultry

Broilers are less sensitive to taste but respond to certain volatile compounds. Flavours help mask bitterness from amino acids or medications.

Layers benefit from improved consistency in feed intake, stabilizing egg production.

3) Ruminants

Calves transitioning from milk to starter feed respond well to dairy flavours (e.g., sweet cream, vanilla). However, adult cattle benefit less, but in situations of poor-quality silage or bitter forages, flavours enhance intake.

4) Aquaculture

Fish have acute chemosensory systems. Flavours (e.g., fish oil, krill extract) attract them to pelleted feeds.

High-quality sweeteners in animal nutrition

Concept

Sweeteners are additives that provide sweet taste to feed without necessarily adding calories. They are useful where bitterness or metallic tastes reduce intake.

Types of sweeteners

1. Natural sweeteners: Sucrose, glucose, fructose (limited due to cost/instability).

2. High-intensity sweeteners (HIS): Saccharin, sucralose, neohesperidindihydrochalcone (NHDC), stevia extracts.

3. Polyols: Xylitol, sorbitol (rare in animal feeds).

Mechanism of action

Activation of sweet taste receptors (T1R2/T1R3) located on tongue and intestinal tract. Sweet taste triggers cephalic-phase digestive responses, stimulating saliva, digestive enzyme secretion and appetite.

Application by species

1) Piglets

Have strong preference for sweet taste. Sweeteners improve acceptance of creep feed and weaner diets, reduce feed refusal and improve average daily gain.

2) Poultry

Chickens lack pronounced sweet receptors, but some sweeteners act through other mechanisms, helping to mask bitterness.

3) Ruminants

Calves respond well to sweeteners during pre-ruminant phase. Adult ruminants less responsive, but sweeteners may mask urea or mineral bitterness.

4) Aqua and companion animals

In fish, sweetness is less important than specific amino acid attractants. In pets, sweeteners enhance compliance with medicated diets.

Advantages of using high-quality flavours and sweeteners

Improved palatability and feed intake

Encourages young animals to start consuming solid feeds earlier,

Masks unpalatable tastes from by-products and medications,

Enhanced digestibility (Indirect effect)

Increased intake ensures better nutrient supply. Early stimulation of digestive enzyme activity through flavour conditioning improves feed efficiency.

Better growth and performance

Higher average daily gain, feed conversion ratio and body weight in pigs and broilers. Improved milk yield in dairy animals due to stable dry matter intake.

Reduced stress during transitions

Weaning, diet changes or medication periods become smoother with consistent flavours.

Economic advantages

Although flavours and sweeteners add to feed cost, improved feed efficiency and growth offset expenses. Reduced feed wastage,

Health benefits

Some natural flavours (e.g., essential oils, citrus extracts) have antimicrobial or antioxidant properties. Sweeteners like NHDC can enhance intestinal enzyme secretion.

Palatability, digestibility and conditioning effects

Palatability

Flavours directly influence feed preference tests,

Sweeteners particularly important in piglets,

Conditioning: animals develop preference for flavoured feed associated with positive post-ingestive feedback.

Digestibility

While flavours/sweeteners do not chemically alter digestibility, improved intake and enzyme stimulation increase nutrient utilization efficiency. Sweeteners acting on intestinal receptors may up-regulate digestive enzymes.

Feed-to-feed consistency

Animals exposed to consistent flavours across diets adapt more smoothly to feed changes (e.g., sow to piglet diets, milk replacer to calf starter).

Practical application and dosage considerations

Inclusion rate: Typically 100–500 g/ton for flavours, 50–200 g/ton for sweeteners (depending on product strength).

Stability: High-quality encapsulated flavours withstand pelleting/extrusion heat.

Uniform mixing: Ensure homogenous distribution to avoid over/under concentration.

Target species formulation: Piglet-specific flavours (sweet, milky) vs. ruminant (dairy/vanilla) vs. poultry (fruit/herbal).

Case studies and research evidence

Piglets: Studies show 8–12% increase in feed intake with flavoured creep feeds, translating to 5–7% higher weight gain.

Broilers: Flavours masking bitterness from canola meal improved feed conversion by 4–6%.

Dairy cows: Addition of anise or vanilla flavours increased dry matter intake by 0.5–1.2 kg/day, leading to improved milk yield.

Aqua feeds: Fishmeal replacement diets with krill flavour showed improved acceptance in shrimp and trout.

Limitations and challenges

Species variability: Not all animals respond equally.

Overuse risk: Excessive flavour can repel rather than attract animals.

Economic trade-off: In low-margin systems, additive cost must be justified.

Regulatory approvals: Some sweeteners are not approved for animal use in certain countries.

Future perspectives

Precision feeding: Tailor-made flavours/sweeteners for specific genetic lines or regions.

Natural and functional flavours: Combining palatability with bioactivity (antioxidant, gut health).

Neuro-nutrition approach: Exploiting gut–brain axis by targeting taste receptors in the intestine.

Sustainability: Flavours may enable higher inclusion of unconventional feed resources (by-products, insect meals) without intake penalties.

Conclusion

High-quality flavours and sweeteners in animal feeds serve as strategic tools to enhance feed intake, palatability and animal performance. They are particularly valuable during critical production stages such as weaning in piglets, milk-to-solid transition in calves and diet changes in poultry and aquaculture. While they do not directly increase nutrient digestibility, their effect on feed intake and digestive stimulation indirectly improves nutrient utilization and growth efficiency. Their advantages include improved productivity, reduced stress during dietary transitions, better economic returns and potential health benefits depending on the compounds used. Future innovations will likely focus on natural, multifunctional and species-specific solutions that align with consumer demand for safe, residue-free animal products. In modern livestock production, where efficiency, welfare and sustainability converge, the judicious use of high-quality flavours and sweeteners is not just optional but strategic.



Crop Residues - Techniques for Effective Utilization



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Introduction to Crop Residue Management

- In our state, crops like paddy, maize, cotton, pigeon pea, soybean, and groundnut are primarily cultivated.
- Observing drastic climate changes, farmers must adapt their agricultural technologies.
- They should conserve natural resources like soil, water, and air while increasing productivity and profits.
- Crops produce both grains and residues.
- By creating and selling valuable by-products and value-added products from these residues, farmers can achieve a high net income.
- Dairy, poultry, and sheep rearing are excellent allied activities to agriculture.
- By adopting integrated farming, crop residues can be processed using modern methods into value-added fodder.
- Nothing goes to waste in agriculture.
- The residues of our primary crops should be utilized effectively as detailed below.

1. Paddy (Rice)

- Paddy is a food crop cultivated across 22 lakh hectares in the state, producing 98.4 lakh tonnes.
- Milling this grain yields 9 lakh tonnes of rice husk, 4.5 lakh tonnes of bran, and 31 lakh tonnes of rice.

Utilization of By-products:

- **Rice Bran:** Rich in proteins, fats, crude fibre, and Vitamin B. Therefore, 10-23% high-quality cooking oil can be extracted from it. This oil is also used in cosmetics. By diversely mixing bran with other materials, it is used as feed for cattle, sheep, and poultry.
- **Rice Husk:** A hard material containing silica and lignin; the heat generated from burning it can be used to dry grain. It is used as fuel to burn brick kilns. Husk is made into briquettes and blocks to be used as an alternative to fossil fuels. It is also used to generate electricity. Rice husk ash is used to reclaim problematic soils and as an additive in cement and steel manufacturing.
- **Broken Rice:** Fermented to make beer and its flour is used to make idli, dosa and noodles.
- **Paddy Straw:** Yields about 6-7.5 tonnes of straw per hectare. Burning paddy straw in states like Punjab and Haryana increases pollution. Instead of burning, it should be enriched with urea to increase its nutritional value and used as cattle feed. Ploughing it back into the field increases soil fertility. When ploughed into the soil, the carbon-to-nitrogen ratio increases, which reduces nitrogen availability to the crop. Therefore, 25% more nitrogen than the recommended dose should be applied. Over the long term, this practice increases soil organic carbon by 14-27%. It also increases the availability of micronutrients like zinc, copper, iron, and manganese. Crops like maize, sorghum, and others can be sown using a "Happy Seeder" drill machine without removing the straw from the field. The straw can be baled using machines to generate electricity. It is used in mushroom cultivation and as bedding in cattle sheds to improve cattle health and milk production. Waste straw can be converted into vermicompost.

2. Maize

- After harvesting maize, the stalks, leaves and decobbed cobs remain.
- The starchy sugars from these can be fermented to produce ethanol as an alternative fuel to petrol.

- It can be pulped to make paper.
- It can be burned to generate electricity.
- The residues can be powdered and mixed with concentrated feed in a 75:25 ratio to prepare dry TMR (Total Mixed Ration) feed.
- Similarly, the powder is used as filler in the manufacturing of plastics, adhesives, vinegar, and artificial leather.
- Waste stalks can be used as mulch, bedding in animal yards, or vermicompost.
- If the crop dries up during the flowering stage due to drought or other reasons, such stalks can be converted into "silage".
- By finely chopping the remaining plants of millet crops like maize, sorghum, and ragi immediately after harvesting the ear heads, and making silage in drums, high-quality fodder can be efficiently fed to cattle without wastage.

3. Cotton

- After extracting the cotton fibre, the remaining stalks, leaves, and bark yield about 3 tonnes per hectare.
- Immediately after picking cotton in November, the leaves and squares/buds should be fed to goats and sheep.
- Afterward, the plant bases should be removed to reduce the incidence of the "pink bollworm".
- The stalks can be used in small quantities as firewood, and in large quantities for the wood, cardboard, and paper industries.
- Cotton stalks contain 68% cellulose, 26% lignin, and 7% ash.
- 1000 tonnes of cotton stalks are sufficient to run five 100 KV capacity power plants for a year.
- When cotton stalks are chopped into small pieces using a recently introduced tractor-driven multicrop bio-shredder and incorporated into the soil, they decompose quickly.
- One acre of cotton stalks provides 10 kg of nitrogen and 27 kg of potash to the soil.
- Ploughing the cotton crop residues into the soil increases organic carbon content.
- It improves soil physical properties.
- It benefits beneficial microorganisms.

4. Pigeon Pea (Red Gram)

- Residues include stalks, leaves, pod shells, and split waste, yielding 6-10 tonnes per hectare.
- Pigeon pea stalks are widely used for baskets, huts, fences, timber, firewood, and other weaving applications.
- The pulp is utilized in the paper industry.
- In countries like China, Thailand, Vietnam, and states like Bengal and Assam, shellac is produced from the pulp.
- The leaves are used as an alternative to alfalfa fodder and in poultry feed for carotene and other essential nutrients.
- The pod shells contain protein and fibre, making them a good nutritional feed for ruminant animals.
- Pigeon pea chunni contains 25-35% broken bits, acting as a good concentrated feed and supplying protein.
- Leaves that fall during the maturity stage add about 40 kg of nitrogen per hectare to the soil.

Conclusion

- Entrepreneurs and farmers should recognize the benefits of using crop residues and collaborate to establish regional industries.
- Similarly, brother farmers should adopt integrated farming practices, rear cattle and poultry, and efficiently utilize crop residues.
- Preventing environmental pollution is everyone's responsibility.
- Farmers have a significant responsibility to protect the environment while earning high profits.

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GROW OUT CULTURE OF LOACHES & FUTURE PROSPECTS



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Introduction

Loaches are diverse group of freshwater fishes that belongs to Cobitidae and Botiidae families respectively which are spread worldwide. Loaches are in both ornamental and economical important food fish sectors due to their small size, bright colors, peaceful nature, hardiness, compatibility, and ability to live their entire lifespan in aquariums (Mercy *et al.*, 2007; Zaidi, *et al.*, 2018; Goswami *et al.*, 2022). Loach is a small freshwater fish, reaching a maximum length of about eight centimetres. It has a slender, cylindrical body with several barbels around its mouth. Most loaches have vibrant patterns, featuring black and yellow stripes or a pale yellow body with black spots (Pethiyagoda, 1991; Perdices *et al.*, 2016; Nelson *et al.*, 2016; Keskar *et al.*, 2018). Loaches are fish that live in shallow freshwater areas like streams, swamps, and paddy fields all over the India, often partially buried in the sandy bottom. In western India, some appear in rice fields during the monsoon, earning the name "rice field loach" (Liu and Wang, 2017; Luo *et al.*, 2021; Zang *et al.*, 2022). Loaches are a rich source of proteins, amino acids, fatty acids, minerals (like calcium and iron), and vitamins A, D, E, and K (Manoharan *et al.*, 2019; Mohanty *et al.*, 2019). Loach is valued for its medicinal and culinary benefits, because this fish is in high demand in the market (Gao *et al.*, 2012). Loaches are freshwater fish from the Cypriniformes order, found in Asia, Europe, and Africa. They live in rivers, streams, and ponds and are popular in aquariums for their unique appearance and adaptability (Dey, A., Verma, R., Singh, M. and Barat, S., 2015). Loaches are distributed in Asia: Bangladesh (Rahman, 1989 and 2005), India and Myanmar (Talwar and Jhingran, 1991), peninsular Thailand, and Mekong basins (Kottelat, 1992) with many species worldwide.



Some important indigenous loaches

Scientific Name	Common Name(s)	Conservation Status
<i>Botia dario</i>	Queen Loach, Rani Mach	Vulnerable
<i>Botia rostrata</i>	Ladder Loach	Vulnerable
<i>Botia almorhae</i>	Almorha Loach	Endangered
<i>Botia lohachata</i>	Y-Loach, Tiger Loach, Lohachata	Endangered
<i>Lepidocephalichthys thermalis</i>	Indian spiny loach- Meen Ayirai	Threatened

Indian spiny loach is locally referred as

State	Local Name
Tamil Nadu	Aiyrai / Asaree / Pallimeen
Andhra Pradesh	Asira
Maharashtra	Chikani / Mura
Odisha	Jubbi Cowri
Bihar	Bulu

(Hossain *et al.*, 2015) (Acharjee *et al.*, 2014)



Source - A lateral view image of *Botia almorhae* is presented in the article "Lateral views of: a. *Botia almorhae*, UMMZ 244844, 44.3 mm SL" on ResearchGate.

The characteristics of this fish that make it a desirable cultivar include high market value, eurythermal nature, omnivorous food habit, rapid growth, tolerance of high stocking density. (Xu and Pan, 2005).

These two exotic loaches are also very dominant over the Indian ornamental fish.

Scientific Name	Common Name(s)	Conservation Status	Distribution
<i>Botia macracanthus</i> or <i>Chromobotia</i>	Clown loach	Endemic, Not Evaluated	Indonesia
<i>Botia modesta</i>	Blue loach	Threatened	Vietnam, Cambodia, Laos, Thailand



(Chaudhari et al., 2022)

Understanding the behavior of loaches:

Loaches are Peaceful and most adaptable fish for community tanks these are non-aggressive in nature which makes them popular among the fish keepers, they lead a nocturnal life and remain buried in the sand or silt for most of the time. Loaches are bottom dwellers and omnivores in nature, loaches feed on algae, detritus, and small invertebrates, and plant material in the wild. In aquariums, they accept pellets, flakes, and live or frozen food (Dey, A., Verma, R., Singh, M. and Barat, S., 2015). During feeding, loaches may come to the surface to take feed and then return to the bottom immediately. Loaches can survive in low-oxygen water by taking in air from the surface. They absorb oxygen through their intestines and release the extra air through their anus.

Sexual dimorphism and Sexual Maturity in loaches

Loach species shows sexual dimorphism such as the females can be easily distinguished by the abdomen which is prominent in female than that of male, generally the males are smaller in size and have slender body and are generally more pigmented than that of females. Females are generally bigger in size and less attractive than that of male. In some of the species other distinctive characters are found such as in males 7th and 8th ray of pectoral a thin layer (ossified fin rays) with milky whitish while in female there is no modification is found and pale whitish in color (Velmurugan and Somu, 2024). Loaches fish attains sexual maturity at the size of 4.5 cm, 1.24 g (male); year (1+), 1.38 g (female) year (2+) and the minimum size at first maturity is 3.3-3.5 cm respectively.

Sex ratio & Spawning Season

To carry out the breeding process the loaches have to be released in sex ratio of 1:1(male: female) is for better breeding performance. As the loaches are biannual spawner, they spawn twice in a year which lies from June to August & December to October generally to initiate the spawning when the water temperature exceeds 18.5°C, with optimal temperatures around 21-24°C in flowing water (Juchno *et al.*, 2006).

Fecundity

It is the egg laying capacity of the female during its breeding cycle in loaches fecundity ranges in between loach 869 to 3371 eggs per female, and the relative fecundity lies between 378 to 782/gram body weight of female (Kumari and Nair, 1979). the fecundity is determined by various factors such as such as food and environment.

Tank Setup

The tank setup for loaches mainly preferred outdoor fiberglass or FRP tanks with optimal water parameter, a substrate layer of fine sand and gravel at the bottom can be given to create a more please and comfortable environment the water depth should be maintained at least 25cm (Hossain *et al.*, 2022). In the tanks, rear the aquatic plants for hiding and to maintain the water temperature 26 °C or below therefore, a suitable substratum such as sand, gravels and plants, needs to be provided (Chaudhari A., Felix S., Swain, S.K., Uma, A., 2022)

Grow-out Culture & Development of Broodstock

In every culture broodstock development is the most important which decide the quality and quality of the seeds therefore proper broodstock development is required. The brood should be stocked at density of 150-200 individual per square meter. Generally, the brood or juvenile are collected from the wild such as canal or riverine areas and can be easily acclimatized to captivity condition. The water parameter are managed by maintaining pH (7.0-7.5) and adjust temperature from 26°C to 22°C to promote faster maturation. (Rizki *et al* 2020). The broodstock are provided good quality water with mild aeration to support optimal health and maturation (Bai and Yu, 2010). During the brood stock development, the natural feeds are more preferred which promote maturation therefore they are feed with frozen bloodworms is provided, with nutritional content including 57.5% protein, 13.5% fat, 2.04% crude fiber, 3.6% ash, and 87.19% moisture This feed is given daily twice at 8:00 and 16:00 (Rizki *et al* 2020). they are provided with slow sinking feed or bottom sinking pellets with 30-35%protein content. during the rearing of the broodstock 20% water exchange has to be performed in every fortnight to maintain optimal water quality. During the bloodstock management period the feed conservation ratio(FCR) was 1.2, indicating efficient feed utilization

Grow out culture of loaches (Juvenile Rearing)

For grow out culture of loaches we have to do some of the management in order to maximize the production and to minimize the loss at first the pre-stocking management is carried out in pre stocking management of loaches their various preparatory steps are carried out such as at first the tank should be cleaned after that spread a layer of properly washed sand of height 5cm on the tank bottom. Gently fill the tank up to 25-30cm of water (minimum 400 liters) with maintaining free board area of 10-20cm the stock fish after 3 days of filling it. Use floating plants like Azolla and Lemna to cover up to 20% of the water surface, helping to stabilize temperature and provide shade. (Bai and Yu, 2010). After this rearing of early fry of loaches is carried out in prepared tank the stocking is done optimal stocking density for loach 3-4 fish/L of water gives best results. Fry measuring 0.5- 1 cm are stocked (Rizki *et.*, al 2020).in the whole rearing process the feeding plays a most important role promoting good growth and maximizing the output, in feeding diet is Rice bran mixed with groundnut oil cake (GNOC) or copepod larvae that promote good growth and development. During the rearing period regular growth monitoring is important,

the fry should reach approximately 4 cm. Once the target size is achieved, fry can be used for grow-out rearing, (Chaudhari et., al 2024) during the rearing the water quality parameter should be maintained such as temperature 26–28°C, dissolve oxygen 5mg, pH 6.5-7.5, alkalinity ranges between 64-120ppm, hardness 60-125ppm, Ammonia should be less than <0.05 ppm. (Budiardi et., al 2022) respectively.

Loach Fish Harvesting and Yield

After the completion of rearing period which lasts 90 days. when they attain the optimum size the harvesting is done as the loaches burrow into the sand substrate, necessitating complete tank drainage for collection. During this process, the sand is gathered to retrieve the fish, and then the sand is returned to the tank. (Dong et al. 2002). At harvest, loaches average 4.9 cm in length and 3.3 g in weight, yielding approximately 1,005 g from 400 liters of water. The vertical tanks platforms in limited spaces can further boost profits. Loaches fetches good market value and can be sold live at local markets, potentially earning a profit of Rs. 1,500 to 2,000 per kilogram (Shaji et al.,2000).

Various cultural approaches

Culture of the clown loach *Chromobotia macracanthus* in Sumatra and Borneo Islands, (Indonesia).

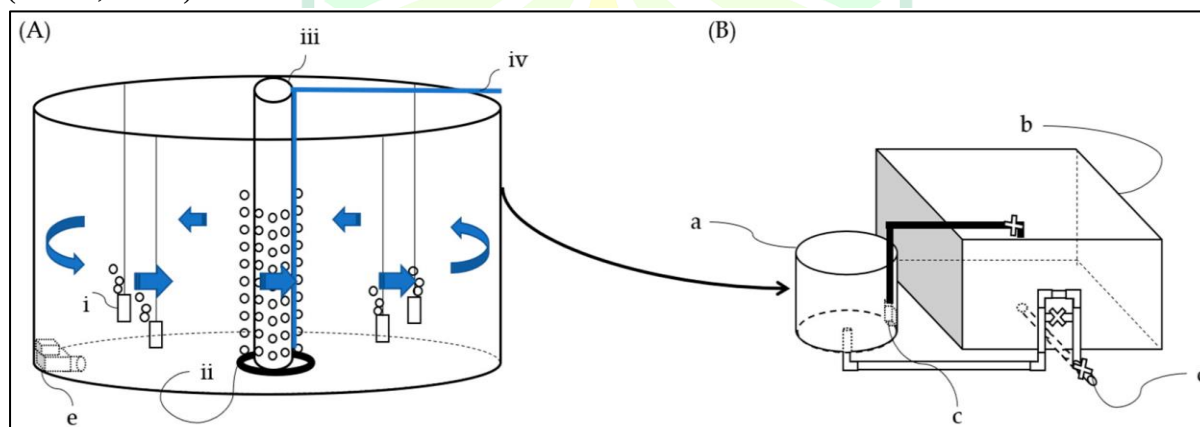
Broodfish of *C. macracanthus* were caught with cast nets by fishermen in the Musi River, Sumatra, between September and December, which is assumed main reproductive season. After capture, the fish were kept in wooden cages (0.5 m³) attached to a floating house & immersed in the river. (Legendr et al.,2012) Induced breeding trials took place in the floating house in October and November. At other times, fish were transported in plastic bags with water and oxygen. (Satyani et al., 2012)

Loach culture in south China as rice-cum-fish farming

Places like South China where the loach been raised in rice field in Stocking densities of loach fingerling with total length of 2–3 cm, it ranges from 20,000 to 25,000 fish per 1,000 m², with annual yields of above 70 kg, and the rice production were higher than that without stocking loach (Xu and Pan 2005). Reliable, cultured fry production necessary even in south China where environmental degradation has reduced wild fry yields (Beveridge et al. 1997; Li 1999). Only a few reports are available on larval rearing of loach (Shao and Tong YEAR).

Floc Ponics (FP) Technology in grow out culture of loaches in Korea

Aqua Ponics system based on biofloc technology (BFT) called Floc Ponics (FP) (J Hwang.,et al 2024) , the Floc Ponics system can provide a large amount of nutrients and improve the growth performance of both fish and crops (Park et.,al 2024)



(Park et al., 2024)

Future prospects of Loaches

Loaches are one of the versatile fishes which are having various aspects in maintaining the ecosystem and for humans because of their various benefits such as Loach fish are known for their good biochemical composition, minerals, antioxidants, and polyunsaturated fatty acids (PUFAs) (Vishwanath et al., 1998). In some of the places loaches used as traditional Chinese medicine in folk remedies for treatment of inflammation and cancer (Qin, Huang & Xu 2002); Some active substances obtained from loach have proved to be of high medical value (Kimura

et al. 1994; Park et al. 1997). Indian spiny loach has a greater market demand in Indian local market due to its delicious and nutritious meat. Tamil Nadu Dr. J. Jayalalithaa Fisheries University has initiated induced breeding and seed production of Indian spiny loach. Loach, supporting commercial farming to ensure sustainable use and conservation of the species. (Larsen et al., 2000). Queen loach, *Botia dario* has the highest potential for export fish in North eastern states highly praised & increasing annually market demand because of its attractive colour pattern (orange-reddish, broad black bars) (Kottelat et al. 1995).

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Management of Saline and Alkaline Soils



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Introduction

In our state, lakhs of hectares of land are not suitable for agriculture. In these lands, crops either do not grow properly or do not yield as much as they should. Such soils that create problems for farmers are called "problematic soils". In our state, approximately 5.5 to 6 lakh hectares of land consist of problematic soils. A large percentage of these are white and black saline/alkaline soils. Farmers often abandon these lands as crops do not grow properly in them. However, by identifying and reclaiming them, and following proper cultivation techniques, good yields can undoubtedly be achieved. These white and black saline soils have been identified in a small area in our district. By following the management practices mentioned below, farmers can achieve good yields in these soils as well.

(Note: The original document includes reference images of cracked and saline soil)

Causes for the Formation of Saline Soils

- These soils generally form in areas with low rainfall and high temperatures, lands lacking proper drainage facilities, coastal lands, and lands with a shallow groundwater table.
- Apart from this, problematic soils can also form due to our management practices. They include:
- Relying entirely on chemical fertilizers without using organic manures.
- Irrigating with poor-quality water.

White Saline Soils (Pala Choudu)

Identification

- During the summer, the top layer of the soil contains white salt.
- Some types of soils absorb moisture from the air and have the characteristic of always remaining wet.
- In some places, the land swells up into a soft powder. When stepped on, you can also notice the soil sinking.
- Salt-tolerant weed plants grow in these soils. Their leaves are dark green and feel soft and sticky like wax when touched.
- Even if a crop is sown, the plants are only sparsely distributed across the field. The crop does not grow properly.
- The growth is uneven. The leaves remain folded, and the tips are dried up. Based on these characteristics, white saline soils can be identified in the field.

Reclamation and Prevention

- The main problem with white saline soils is the presence of excess salts. Reclaiming these soils means bringing the excess salts down to a limited/acceptable level.
- For this, good quality irrigation water is required. There must be a proper drainage facility.
- The field should be levelled, divided into plots of about 20-25 cents, and bunds should be formed.
- The first time, apply about 9 inches of water, puddle it well, let it settle for the whole day, and drain the water out through the drainage canal the next day.
- For the second time, four to five inches of water is sufficient. Puddle the field and drain the water the next day. Doing this 4 or 5 times will reduce the salt content. The soil will return to its normal state.
- Separate canals should be arranged so that irrigation water flows directly into the plot and drainage water flows out. Water from one plot should not be allowed to flow into another plot.

- Drainage canals should be at least 18 inches deep. Utmost care must be taken in draining out the excess water.
- This improved state must be maintained through good management practices so that the salt levels do not rise again.

Cultivation Practices

- Organic manures should be used abundantly in the reclaimed field. Green manure crops like Dhaincha (Jeeluga) should be grown and ploughed back into the soil.
- Allow it to decompose for up to two weeks, drain the water, apply fresh water, and sow paddy as the first crop.
- Fertilizers should be applied 25 per cent more than the usual dosage. 20 kg of zinc sulphate per acre should be applied either during the last ploughing or before transplanting.
- Micronutrient deficiencies on the crop should be monitored constantly and corrected.
- Fertilizers like Urea, Ammonium Sulphate, Super Phosphate, DAP, and NPK complex fertilizers can be applied. Ammonium chloride and Murate of Potash should not be applied.

Black Saline or Highly Alkaline Soils (Karu Choudu)

Identification

- When the soil dries, it becomes so hard like a rock that even a crowbar cannot penetrate it.
- When there is sufficient water and moisture, it turns into a soft, thick mud. If you step on it, your foot sinks.
- The water never clears up and remains muddy. Water does not percolate for days. Air and water infiltration capacity is very low.
- The physical properties of the soil are degraded. Due to the organic matter and humus combining with the alkalinity, the black alkaline soils and the stagnant water in them acquire a kind of blackish colour.
- Generally, plants do not germinate in these soils; even if they do, they are sparse and do not show adequate growth.
- In such lands, the exchangeable sodium percentage exceeds 15. This condition is seen in red soils with a pH greater than 8.5 and in black soils with a pH greater than 9.0.
- However, water-soluble salts remain at low, normal levels.
- As a result of the black alkaline characteristics, the nutritional balance required by the plant is disrupted. Some necessary nutrients become unavailable, while some unnecessary nutrients become excessively available, causing harm to the plant.
- The physical properties of the soil, especially soil structure, degrade and become unfavourable. Favourable soil structure is of great importance, especially in dry land and irrigated dry crops, as it plays a key role in achieving high yields.

Reclamation and Prevention

This takes place in two stages:

1. Converting exchangeable sodium into water-soluble salts.
2. Flushing out the dissolved salts through drainage water.

Key Steps:

- The crucial aspects in these soils are bringing the sodium percentage below 15 and reducing the pH to a favourable level. To achieve this, necessary soil amendments must be applied to the soil.
- Chemicals like gypsum, sulphuric acid, aluminium sulphate, sulphur, and calcium chloride can be used as soil amendments.
- However, among these, the most important is Gypsum (Calcium Sulphate), which is cheaply and widely available. It contains 24% calcium and 18% sulphur. Calcium helps in reducing the exchangeable sodium percentage in the soil, while sulphur helps in reducing the pH.
- To reclaim black alkaline soils, adequate irrigation facilities and drainage systems must be available along with gypsum.
- The quantity of gypsum to be applied per acre depends on the severity of the soil alkalinity, i.e., the amount of exchangeable sodium. This is determined through laboratory tests.
- The field should be levelled well, divided into plots of about 20-25 cents, and proper bunds should be formed.

- Finely powdered gypsum should be broadcasted evenly over the soil, ploughed, and watered so that it percolates. After it completely percolates, water should be applied again to let it soak in.
- Initially, the percolation of water will be slow, which may take 3-4 days or even longer. Since gypsum dissolves slowly and to a lesser extent in water, the reaction also occurs slowly.
- As the chemical reaction of the applied gypsum progresses in the soil, water begins to percolate faster.
- After applying and percolating water 3-4 times in this manner, finally, apply excess water, puddle the soil, let it settle, and drain the water out through drainage canals the next day.
- In this process, the calcium in the gypsum infiltrates the soil, converting the exchangeable sodium element into sodium sulphate. This gets flushed out through the drainage water.
- As a result, the exchangeable sodium percentage decreases. Along with this, the pH level also drops, and the soil returns to its normal state.

Cultivation Practices

- After reclaiming the soil, grow Dhaincha (Jeeluga) as a green manure crop and plough it into the soil at the flowering stage.
- Apply water well, allow it to decompose for 2 weeks, and then drain the water. Apply fresh water and transplant paddy for the first time.
- Chemical fertilizers should be applied 25% more than the usual dosage. Apply 20 kg of zinc sulphate per acre.
- If any other nutrient deficiencies are observed on the crop, they should be identified and corrected immediately.
- The seedlings should be planted densely to ensure an adequate plant population. In these soils, older seedlings establish themselves more easily than younger ones.
- It is advisable to apply shallow irrigations more frequently. Generally, all chemical fertilizers can be used.
- After growing the first paddy crop, other crops can be cultivated. Crops that are tolerant to black alkalinity should be selected.
- A higher seed rate than usual should be used to ensure the plant population does not decrease. Good management practices must be strictly followed.

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Strengthening Farmer Knowledge through Agricultural Extension Services



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Abstract

Agricultural extension services play an essential role in strengthening farmers knowledge and improving agricultural productivity. In many developing regions, farmers rely heavily on extension services to gain access to modern technologies, improved farming practices, and information related to climate change, pest management, and market opportunities. Agricultural extension acts as a bridge between research institutions and farmers by translating scientific knowledge into practical applications that farmers can adopt in their fields. Over time, extension systems have evolved from simple information dissemination models to participatory and technology-driven approaches that emphasize farmer engagement and capacity building. This article examines how agricultural extension services contribute to enhancing farmer knowledge and improving rural livelihoods. It discusses the historical development of extension systems, the various approaches used in knowledge dissemination, and the role of modern digital technologies in extension delivery. The article also highlights the challenges faced by extension systems, including resource limitations, inadequate training, and weak institutional linkages. Finally, it proposes strategies to strengthen agricultural extension services through improved capacity building, digital innovations, and participatory approaches that place farmers at the center of the learning process.

Keywords: Agricultural Extension, Farmer Education, Knowledge Transfer, Rural Development, Sustainable Agriculture, ICT In Agriculture.

1. Introduction

Agriculture continues to be one of the most important sectors for ensuring food security, generating employment, and supporting rural livelihoods across the world. In many developing countries, a large proportion of the population depends directly on agriculture for their income and sustenance. Smallholder farmers in particular contribute significantly to food production, yet they often face numerous challenges that limit their productivity and profitability. These challenges include limited access to improved technologies, insufficient knowledge about modern farming practices, unpredictable weather patterns, soil degradation, pest outbreaks, and fluctuating market conditions.

In order to address these challenges, agricultural extension services have been developed as a key mechanism for delivering knowledge, innovations, and technical support to farmers. Agricultural extension is essentially an educational and advisory system that facilitates the transfer of scientific research and technological advancements from research institutions to farmers in a practical and accessible manner. Through training programs, demonstrations, workshops, and advisory services, extension agents help farmers adopt improved agricultural practices that enhance productivity and sustainability.

Over the years, agricultural extension has evolved significantly. Earlier extension models primarily focused on the one-way transfer of technology from scientists to farmers. However, modern extension systems recognize that farmers themselves possess valuable indigenous knowledge and experience. As a result, contemporary extension approaches emphasize participation, collaboration, and knowledge exchange between farmers, researchers, and extension professionals.

Strengthening farmer knowledge has become increasingly important in the context of global challenges such as climate change, environmental degradation, and population growth. Farmers need continuous access to reliable information in order to make informed decisions about crop production, resource management, and market participation. Agricultural extension services therefore play a critical role in empowering farmers with the knowledge and skills required to adapt to changing agricultural conditions and to ensure sustainable food production.

2. Understanding Agricultural Extension Services

Agricultural extension services can be understood as organized systems that facilitate the dissemination of agricultural knowledge and technologies to farmers. These services aim to improve farming practices, increase agricultural productivity, and enhance the socio-economic well-being of rural communities. Extension activities are typically carried out by government agencies, universities, research institutions, non-governmental organizations, and private sector organizations.

The primary function of agricultural extension is to bridge the gap between agricultural research and practical farming. Research institutions continuously develop new crop varieties, farming techniques, and agricultural technologies. However, these innovations can only benefit farmers if they are effectively communicated and demonstrated in the field. Extension agents play a crucial role in translating scientific knowledge into practical guidance that farmers can easily understand and implement.

Extension services involve a variety of activities, including farmer training programs, field demonstrations, advisory visits, farmer meetings, and distribution of informational materials. These activities are designed to provide farmers with opportunities to learn new skills, exchange ideas with other farmers, and experiment with innovative practices in their own fields.

In addition to technical knowledge, extension services also provide information related to market access, financial management, and value addition. By supporting farmers in these areas, extension systems contribute not only to increased agricultural production but also to improved livelihoods and rural development.

3. Role of Agricultural Extension in Strengthening Farmer Knowledge

Agricultural extension services play a vital role in enhancing farmers' knowledge and skills. One of the most significant contributions of extension systems is the transfer of agricultural technologies and innovations. Through field demonstrations and practical training sessions, farmers are introduced to improved crop varieties, modern irrigation techniques, integrated pest management practices, and efficient soil management strategies. These technologies enable farmers to increase productivity while minimizing environmental impacts.

Extension services also promote continuous learning among farmers. Agriculture is a dynamic sector where new challenges and opportunities emerge regularly. Changes in climate patterns, the introduction of new crop varieties, and fluctuations in market demand require farmers to constantly update their knowledge. Extension agents facilitate this learning process by providing timely information and technical guidance.

Another important aspect of agricultural extension is the development of farmers' problem-solving abilities.

Instead of simply providing ready-made solutions, modern extension approaches encourage farmers to analyze problems and experiment with different solutions. This participatory learning process enhances farmers' confidence and decision-making capabilities.

Extension services also contribute to improving farmers' awareness of sustainable agricultural practices. Issues such as soil degradation, water scarcity, and excessive use of chemical inputs have become major concerns in many agricultural regions. Extension agents promote environmentally friendly practices such as organic farming, crop diversification, and conservation agriculture, which help protect natural resources while maintaining productivity.



Fig 1: Agricultural Extension Training in the Field

4. Extension Approaches Used to Disseminate Knowledge

Different approaches have been developed to deliver extension services effectively. One widely known approach is the Training and Visit system, which was introduced in several countries during the twentieth century. Under this system, extension agents received regular training from agricultural specialists and then visited farmers periodically to share new information and technologies. While this approach improved the flow of information, it was later criticized for being highly centralized and costly.

In response to these limitations, participatory extension approaches were developed. These approaches emphasize collaboration between farmers, researchers, and extension agents. Farmers actively participate in identifying problems, testing new technologies, and sharing knowledge with other farmers. This participatory process ensures that extension activities are more relevant to farmers' needs and local conditions.

Another important extension method is the Farmer Field School model. Farmer Field Schools provide a platform where farmers meet regularly during the crop growing season to observe crop development, analyze field conditions, and learn about pest management and soil health. These schools encourage experiential learning, allowing farmers to gain knowledge through observation and experimentation rather than through lectures alone.



Fig 2. Farmer Field School Learning Session

5. Role of Digital Technologies in Agricultural Extension

The rapid development of digital technologies has significantly transformed agricultural extension services. Information and communication technologies have made it possible to deliver agricultural information to farmers more quickly and efficiently than traditional extension methods.

Mobile phones are among the most widely used tools in digital extension. Farmers can receive SMS alerts about weather forecasts, pest outbreaks, fertilizer recommendations, and market prices. These messages help farmers make timely decisions that improve productivity and reduce risks.

Mobile applications have also become valuable tools for agricultural knowledge dissemination. Many agricultural apps provide step-by-step guidance on crop cultivation, disease identification, irrigation management, and post-harvest practices. Farmers can access these resources at any time, making learning more flexible and accessible. In addition to mobile technologies, radio and television programs continue to play an important role in agricultural education. These platforms reach a large number of farmers simultaneously and provide practical advice in local languages.

Applications of Digital Technologies in Agricultural Extension

Technology	Use in Extension	Impact
Mobile SMS	Weather and pest alerts	Timely farming decisions
Mobile apps	Crop management guidance	Easy knowledge access
Radio programs	Farmer education	Large outreach
Online training	Skill development	Flexible learning

6. Challenges Facing Agricultural Extension Services

Despite their importance, agricultural extension services face several challenges that limit their effectiveness. One of the most common challenges is the shortage of trained extension personnel. In many countries, the ratio of extension workers to farmers is extremely low, making it difficult to provide regular support to all farmers.

Another challenge is inadequate funding and infrastructure. Extension agencies often lack the financial resources required to conduct training programs, field demonstrations, and technology dissemination activities. This limits the reach and impact of extension services.

In some cases, farmers may also be reluctant to adopt new technologies due to financial constraints, cultural beliefs, or lack of trust in extension agents. Building strong relationships between extension workers and farming communities is therefore essential for improving technology adoption.

Furthermore, weak linkages between research institutions and extension agencies can slow down the dissemination of innovations. Effective communication and collaboration between researchers and extension agents are necessary to ensure that farmers receive updated and relevant information.



Fig 3. Digital Agricultural Advisory System

7. Strategies for Strengthening Agricultural Extension

Strengthening agricultural extension systems requires a combination of policy support, institutional collaboration, and technological innovation. One important strategy is the continuous training of extension workers to ensure that they remain updated with new agricultural technologies and research findings.

Another key strategy is the promotion of farmer participation in extension programs. Farmers should be actively involved in identifying problems, testing solutions, and evaluating the effectiveness of new technologies. Participatory approaches not only improve the relevance of extension activities but also increase farmers' sense of ownership.

The integration of digital technologies can also significantly enhance the efficiency of extension services. Governments and development organizations should invest in digital platforms that provide farmers with easy access to agricultural information.

Collaboration between universities, research institutions, private sector organizations, and farmer groups is equally important. Such partnerships can strengthen knowledge sharing and ensure that extension services reach a larger number of farmers.

Key Outcomes of Effective Agricultural Extension

Extension Activity	Outcome
Farmer training	Improved knowledge and skills
Technology demonstrations	Adoption of innovations
Advisory services	Better farm management
Digital platforms	Faster information access

8. Conclusion

Agricultural extension services play a crucial role in strengthening farmer knowledge and improving agricultural productivity. By providing education, training, and access to modern technologies, extension systems empower farmers to adopt innovative and sustainable farming practices. Over time, extension approaches have evolved from traditional technology transfer models to participatory and technology-driven systems that emphasize collaboration and knowledge exchange.

However, several challenges continue to hinder the effectiveness of extension services, including limited resources, shortage of trained personnel, and weak institutional coordination. Addressing these challenges requires increased investment in extension systems, improved capacity building for extension workers, and stronger partnerships among stakeholders.

The integration of digital technologies offers new opportunities for expanding the reach and efficiency of agricultural extension services. By combining traditional extension methods with digital innovations, extension systems can provide farmers with timely and reliable information that supports better decision-making. Ultimately, strengthening agricultural extension services is essential for enhancing farmer knowledge, promoting sustainable agriculture, and ensuring food security in a rapidly changing world.

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WHITHER SELF-RELIANCE IN THE COUNTRY'S EDIBLE OIL FRONT? GROUND REALITIES AND THE WAY FORWARD



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The rapid retreat of the domestic edible oil sector from one of self-reliance in mid 90s to the world's largest importer today is not only surprising but a matter of grave concern. According to the latest data, the country's annual imports of edible fats and oils in oil year 2024-25 skyrocketed to an all-time high of 16MT involving huge foreign exchange outgo of Rs. 161000 crores. What are the factors which plunged the country into such progressively widening and burgeoning demand-supply gaps and the resultant unsustainable and chronic import dependency (2024-25: 60%) in the aftermath of economic liberalisation? Stagnation on domestic production front or its failure to cope up with rising demands for edible oils on account of increasing population, rising incomes, improvements in lifestyles, changing dietary habits and/or unrealistic year -year projections of demand or resort to open and liberal import policy regime pursued consequent upon WTO trade agreement with zero or very low basic customs duties and/or weak farmer supportive policy interventions!

1. DOMESTIC EDIBLE OIL SUPPLY SCENARIO POST-LIBERALISATION OF TRADE

Contrary to the widespread scepticism in the country on the available technologies and their realisable production potentials under real farm situations, country's aggregate production of oilseeds more than doubled by 2024-25 (42.99 MT) as compared to 1994-95 (=24MT). Interestingly, area under oilseeds registered only marginal improvement (=17%) over the above period. Equally striking if not remarkable are the overall improvements in per hectare productivity levels of oilseeds. from 797 kg of early 90s to as high as 1412 kg in 2023-24. The above improvements in production and productivity of oilseeds are no mean achievements when viewed against the hostile conditions under which oilseeds continue to be cultivated even today across diverse geographies in the country (rainfed=75%) with poor management. Concurrently, domestic availability of edible oils also shot up from 5.5 MT in 1994-95 to as high as 12.6 MT by 2023-24 i.e., an increase of 111 per cent. Quite obviously, lack of breakthroughs in domestic supplies cannot be the prima-facie reason for such alarming situation in such a commodity of mass consumption.

2. PER CAPITA CONSUMPTION LEVELS OF EDIBLE OILS TODAY VIS-A-VIS RECOMMENDED DIETARY INTAKE RATES OF NIN/ICMR:

According to the recommended daily intake rates of edible oils and fats of NIN/ICMR(2024) , a moderate adult male with an energy requirement of 2730 Kcal per day hardly requires 30gms/day/capita of visible oils and fat .As against an average requirement of 12 kg /year of NIN/ICMR, our current per capita consumption levels of visible edible oils in the country already shot up from 7.5 kg of 1994-95 to close to the level of developed countries of west (excluding USA) i.e., 25 kg/year by the end of oil year, 2024-25. Given the current growth trend and the liberalised imports, we may even hit the USA's current per capita consumption of 45kg sooner or later. Do our country men really require such excessively high daily consumption levels of fats and oils which are reported to be highly detrimental to the health and are known to predispose to high incidence of fatty liver, obesity, triglycerides, cholesterol thereby posing to high risks of cardiovascular diseases and strokes? Certainly not. Neither the country needs to be in such an unhealthy rat race with the west nor does it warrant exposure of the later to the recurrent unsustainable drain of it's valuable foreign exchange reserves on account of imports. The above situation, therefore calls for a serious introspection on the part of country's policy makers and administrators.

3. NITI AYOGE'S DEMAND-SUPPLY PROJECTIONS FOR 2030 & VIKSIT BHARAT (2047)

The latest report of NITIAYOG (2024) "Pathway and strategies for accelerating growth in edible oils towards the goal of atmanirbharata" projects a total demand of 38.9 MT and 41.9 MT of edible oils by 2030 and 2047 based on prevailing *per capita* consumption levels of developed countries (25kg) excluding USA. The above demand is reported to touch staggering levels of 45.5 (2030) and 66.8 MT (2047) if one adopts USA consumption levels of 45 kg *per capita* per year as a benchmark. It's well nigh impossible for the country to meet such humongous demands, given a multitude of factors namely (a) overwhelming dependence of bulk of country's oil crops to the vagaries of wayward monsoons, (b) near stagnation in the area under sesame as well as progressive decline in the acreage of not only one of the major oil crop, groundnut but many a other oil crops such as sunflower, safflower, Niger once considered to offer attractive opportunities for vertical as well as horizontal growth in their nich areas of cultivation, (c) increasing disenchantment of farmers with oilseeds on account of rising costs of cultivation and their increasingly unpredictable and unremunerative market, (d) growing preference of farmers to more remunerative crops with assured market support such as wheat, rice, sugarcane under irrigation even in hitherto drylands, thanks for 24*7 free electricity in many a states and (e) widespread opposition from within the country not only to GM crops but also to genome edited crops involving no alien genes which otherwise holds the key for overcoming many an intractable barriers such as undesirable nutritional concerns, vulnerability to one or the other biotic and abiotic stresses for want of availability of durable and desirable sources from within the available plant genetic resources, (f) Negligible contribution of oil palm and other secondary sources namely rice bran, cottonseed, tree based oilseeds *vis-a-vis* their projected potentials even after more than 3 decades. What is then the realisable pathway to speedy self-reliance in edible oils under the country's twin on-going national missions on edible oils namely NMEO-Oilseeds and NMEO-Oil palm.

4. THE WAY FORWARD TOWARDS SUSTAINABLE SELF-RELIANCE

The various constraints and ground level realities highlighted above, therefore, call for a re-visit not only to the way demand projections are made today for future based on CAGRs of past *per capita* consumption levels which have long back crossed the pro health threshold limit of 12 kg of NIN/ICMR but also a host of other key policy interventions including pro oil crop supportive initiatives. As per Niti Ayog's (2024) own report, the country's total consumption needs of edible oils dropped to as low as 15.87 and 17.35 MT by 2030 and 2047, respectively once the consumption benchmarks were switched from developed west to that of NIN/ICMR i.e., 12 kg/capita/year. Quite interestingly, domestic supplies of edible oils in oil year, 2024-25 (=12.5 MT) are not very far from the above demand projections and hence very well within the realms of realisation notwithstanding highly unfavourable ecosystem of country's annual oilseeds barring rapeseed and mustard (83% irrigated). Keeping in view the above constraints in the way of major breakthroughs in annual oilseed production in near future as well as the wide gaps between actual potentials of oil palm and various secondary oil sources (rice bran, cotton seed, tree based oilseeds) *vis-a-vis* what has been achieved since the time of technology mission on oilseeds (TMO), there is an urgent need to tweak the currently adopted processes/policy interventions, farmer support systems if the country is to be freed from chronic imports and the associated recurrent foreign exchange outgo and attain the hitherto elusive self-reliance in edible oils sooner than later. The suggested pro farmer and pro-consumer measures inter alia include (a) Dispense immediately with the present system of relying on CAGRs of *per capita* consumption of edible oils based on past data for arriving at future demand projections as the latter already breached the NIN/ICMR recommended dietary intake levels of visible oils and fat and freeze immediately the latter at least at 120 or 140% of NIN/ICMR recommended 12 kg/capita/year i.e., 14 or 16.5 kg of visible fats and oils/year as a pro health measure in the larger interest of public health and discourage excessive consumption; (b) Restriction of zero or very low basic customs duty only to bridge the estimated shortfalls based on frozen *per capita* consumption levels and thereafter de-incentivise excessive and unhealthy consumption thru calibrated high tariff structure taking advantage of the options available under WTO to levy tariff levels upto a maximum of 45% in soybean oil and 300% in other oils; (c) Distribution of edible oils to marginalised sections as per dietary needs or 150 or 160% of recommended *per capita* consumption level through PDS in order to protect the latter from the inflationary impact; (d) Declaration of MSPs to oilseeds based on C2 plus 50% rather than the current A2 plus FI backed up with 100 per cent procurement as a special incentive to oilseed growers; (e) Disbursal of import

savings to oil crop farmers as an incentive bonus per every additional quintal procured; (f) Discourage irrigation water intensive crops in drylands areas and promote instead crops like oilseeds, pulses with inherently very low water requirements and (e) Launching a nationwide education drive thru regional multi-media to create awareness about ill effects of excessive consumption of visible fats and oils on health, permissible consumption levels, choice of oils *vis-a-vis* cooking styles, dos and don'ts, etc.



Integrated farming systems for enhancing productivity and livelihood of small farmers



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MP 482004

Abstract

Integrated Farming System (IFS) offers a viable solution by integrating multiple enterprises. The by-products of one enterprise serve as valuable inputs for another, thereby fostering resource recycling, labour use efficiency, and reduced market dependency. By promoting year-round productivity, IFS significantly improves livelihood security. IFS minimize risks from crop failures, market fluctuations, and impacts of climatic variability. Thus, IFS is a resilient and farmer-centric model, particularly suited to the needs of small and marginal farmers in India. Despite challenges of investment, management, and market linkages, the long-term economic, nutritional, and ecological benefits establish IFS as a cornerstone for sustainable agriculture in India

Keywords: Enhanced income and livelihoods, Enterprise diversification, Integrated farming systems, Nutrient cycling

The rapid growth of the global population has placed unprecedented pressure on the agricultural sector, compelling a paradigm shift in food production systems. Traditionally, agricultural research and technologies were tailored for large, mechanized farms, often leaving smallholders at a disadvantage. This technological divide has widened the gap between large landowners and small and marginal farmers. Globally, more than 80% of farmers fall into the smallholder and marginal category, who struggle to achieve livelihood security despite significant progress in global food security. India alone contributes nearly one-fourth of the world's small and marginal holdings, with the majority cultivating less than 2.0 hectares of land. For these farmers, raising income and ensuring sustainable livelihoods remain persistent challenges for researchers, policy makers, and governments. Given that land resources are finite and further horizontal expansion of cultivated area is practically impossible, focus must shift towards vertical intensification through diversification. The Integrated Farming System (IFS) offers a viable solution in this direction by integrating multiple farming enterprises such as crops, dairy, poultry, fisheries, horticulture, and others within a single farm unit. The by-products of one enterprise serve as valuable inputs for another, thereby fostering resource recycling, labour use efficiency, and reduced market dependency. By promoting year-round productivity, optimal resource utilization, nutrient recycling, and income diversification, IFS significantly improve livelihood security. Furthermore, the diversity embedded in IFS minimizes risks from crop failures, market fluctuations, and climatic variability. As such, IFS represent a sustainable, resilient, and farmer-centric model, particularly suited to the needs of small and marginal farmers in India and across the globe.

Need of IFS

The urgency of adopting IFS arises from multiple socio-economic and ecological challenges faced by smallholder agriculture.

- Declining landholdings: Fragmentation of agricultural land continues to rise. Presently, approx. 85% of Indian farmers fall under the small and marginal category, collectively operating just 44.6% of the total cultivated area.
- Self-sufficiency: IFS promotes self-reliance among small and marginal farmers by producing food, fodder, fuel, and income within the farm boundary.
- Year-round employment: By integrating multiple components, IFS generates continuous employment opportunities for farm families throughout the year.
- Efficient resource utilization: The system ensures optimal use of available natural, human, and financial resources without diminishing the overall farm value.

- **Curbing rural-urban migration:** By improving profitability and livelihood security at the village level, IFS helps reduce distress migration of smallholders to urban centers.
- **Sustainability and risk management:** The multi-enterprise approach enhances ecological balance, reduces dependency on external inputs, and builds resilience against climate and market uncertainties.

Components of IFS in India IFS in India incorporates both basic and supplementary components, tailored to regional resources, farmer needs, and agro-climatic conditions. Basic components (Core enterprises found in most systems):

- **Cropping system:** The foundation of all farming systems, present in almost every model.
- **Dairy:** The second most important component, integrated in nearly 83% of farming systems.
- **Horticulture (fruits and vegetables):** Enhances dietary diversity, nutritional security and higher returns.
- **Fisheries:** Vital in water-rich and coastal regions.
- **Poultry:** Provides quick returns and supplements household earnings.

Supplementary Components (value-adding enterprises):

- **Apiculture (Beekeeping):** Enhances pollination and provides honey.
- **Vermicomposting:** Ensures organic manure for crops and reduces input costs.
- **Boundary plantation:** Strengthens ecological services and adds income.
- **Biogas units:** Convert animal waste into renewable energy while supplying nutrient rich slurry for enhancing soil fertility.

Across India, nearly 25 types of farming systems have been documented, developed through various permutations and combinations of farming enterprises. Among these, seven major systems account for nearly 76% of the total share nationwide. The most dominant and widely adopted system is the crop + dairy combination, practiced by approximately 42% of farmers. This is followed by crop + dairy + horticulture, which contributes 11%, while crop + dairy + goatry accounts for 7%. A more diversified model, crop + dairy + goatry + poultry, represents about 5% of the systems.

Crop diversification in IFS for higher income and nutritional security

Crop rotation is one of the basic principles of the IFS. IFS encourages the cultivation of multiple crops, including cereals, pulses, oilseeds, vegetables, and fruits. This diversification reduces the risk of crop failure due to climatic uncertainties and ensures a continuous supply of food. In an IFS model, cereals such as wheat, rice, maize, and millets form the backbone of staple food production, ensuring household food security. These are strategically combined with pulses like pigeon pea, chickpea, mung bean, urd bean, etc. which contribute significantly to dietary protein intake and improve soil fertility through biological nitrogen fixation. Oilseed crops such as mustard, groundnut, sunflower, and sesame enhance dietary diversity and market opportunities while helping to disrupt pest and disease cycles in rotations. Fodder crops such as Napier-Bajra hybrid, berseem, and sorghum are integrated to support livestock units and reduce dependency on external feed purchases. Proper crop sequencing and intercropping not only maximize land use efficiency but also improve soil health through diverse root architectures and residue incorporation.

Horticulture: Fruits and vegetables

Horticultural crops significantly enhance both income and nutritional security. Incorporating seasonal vegetables such as tomato, brinjal, okra, cucurbits, and leafy greens into the IFS ensures a steady cash flow and dietary diversity. Perennial fruit crops like mango, guava, jackfruit, papaya, and banana contribute to long-term income stability while improving farm biodiversity. Vegetables grown in sequence—kharif, rabi, and summer seasons, ensure year-round production and market availability. The integration of protected cultivation, micro irrigation, and improved hybrids further boosts productivity, while market-oriented varieties help smallholders capture better prices.

Livestock and fisheries enterprises

Livestock rearing and fisheries are vital components of IFS, especially in the Indo-Gangetic Plains (IGP) where protein deficiency is widespread. Dairy is the corner stone enterprise, providing regular income through daily milk sales. Regionally suited high-yielding crossbred cows, buffaloes, or indigenous breeds are selected, and their productivity is enhanced through balanced ration, mineral supplementation, and hygienic housing. Poultry, whether backyard or semi-intensive, offers quick returns, supplying eggs and meat for both household use and market sales. Goat rearing and duckery can also be integrated where grazing lands and water bodies are available. These enterprises efficiently recycle crop residues, weeds, and kitchen waste efficiently, reducing feed costs while contributing to nutrient recycling via manure. Fisheries complement IFS wherever water resources exist. Farm ponds or reservoirs can be stocked with species such as rohu, catla, mrigal, and tilapia under

polyculture systems. Integrating aquaculture in waterlogged or low-lying areas enhances productivity of marginal lands. Fish farming not only supplies high-quality protein but also optimizes resource use by utilizing farm wastewater and enabling integration with duckery or horticulture along pond embankments. Composite fish culture maximizes ecological niche utilization, improving yield per unit area.

Nutrient recycling and vermicomposting

A critical strength of IFS lies in internal nutrient cycling. Crop residues, livestock manure, poultry droppings, and agro-wastes are recycled into compost or vermicompost, reducing reliance on costly chemical fertilizers. Vermicomposting using species like *Eisenia fetida* produces nutrient-rich organic manure that improves soil structure, water-holding capacity, and microbial activity. Similarly, farmyard manure (FYM) and enriched compost supply macro- and micronutrients, ensuring sustainable soil fertility management. These organic inputs promote nutrient recycling, minimize environmental pollution and support a closed-loop farming system

Boundary plantation

Planting fruit-bearing and multipurpose species along farm boundaries optimizes land use while providing ecological and economic benefits. Karonda (*Carissa carandas*), jackfruit (*Artocarpus heterophyllus*), and guava (*Psidium guajava*) are well-suited for boundary plantations in many agro-climatic zones. These species offer seasonal fruits for home consumption and sale, provide shelterbelts against wind, and support pollinator diversity. The perennial nature of these plants ensures long-term income without compromising the primary cropping area.

Mushroom production

Mushroom cultivation is an emerging component in IFS with high returns from a small area. Species like oyster (*Pleurotus* spp.), button (*Agaricus bisporus*), and milky mushroom (*Calocybe indica*) can be grown using crop residues such as wheat straw, paddy straw, and maize cobs. Besides being a nutrient-rich food source, mushroom cultivation creates employment opportunities for family members, especially women. Post-harvest spent mushroom substrate can be used as organic manure, further enriching the nutrient cycle within the farm.

Multilayer vegetable farming

Multilayer farming involves growing compatible vegetable crops at different canopy levels to maximize sunlight interception and land productivity. For instance, creepers like bitter melon or bottle melon can be trained on trellises above shorter crops like okra or maranthus, with root vegetables like radish or carrot underneath. This system ensures higher yields per unit area, diversified income sources, and efficient utilization of space and resources. In IFS, multilayer farming is particularly effective in homestead gardens and peri-urban areas where land is limited.

IFS as a pathway to nutritional well-being

While food security ensures availability and access to food, nutritional security focuses on dietary quality and diversity. In IGP despite high agricultural output, malnutrition remains due to limited dietary diversity and over-reliance on staples like wheat and rice. IFS bridge this gap by delivering a balanced food basket rich in proteins, vitamins, minerals, and other essential nutrients.

Diversifying the farm, diversifying the plate

IFS integrates cereals (supply carbohydrates), pulses (provide proteins and micronutrients), vegetables, and fruits (offer vitamins, antioxidants, and dietary fiber) to create a nutrient-rich diet. This crop diversity ensures farming families and communities enjoy balanced meals throughout the year.

Organic practices for healthy and safe produce

By using farmyard manure, crop residues, and compost from livestock waste, IFS promotes organic farming. This reduces chemical residues in food, safeguards consumer health, and enhances soil fertility for long-term productivity.

Combating hidden hunger through nutrient-dense crops

Micronutrient deficiencies ("hidden hunger") are a major concern in rural IGP. Inclusion of crops such as millets, leafy greens, and fruits in IFS helps tackle this. For instance, iron-rich spinach and vitamin C-rich citrus fruits grown alongside staples can reduce anaemia and micronutrient deficiencies.

Implementation on a small scale

High implementation costs limit the direct replication of IFS models. However, the Indian Institute of Farming Systems Research (IIFSR), through its scheme AICRP-IFS-OFR, has demonstrated that strategic, region-specific interventions can significantly enhance smallholders' livelihoods. By focusing on limited yet targeted interventions tailored to specific modules and local conditions, the programme showcases the potential for scalable solutions that improve productivity and profitability of small farms across diverse agro-climatic zones. Under the AICRP-IFS-OFR on-farm research component, IFS interventions were refined with farmer participation. These refinements were based on location-specific, module-based, low-cost practices designed to strengthen food security, nutrition, environmental sustainability, and income for small and marginal farmers. The refinements covered four key modules:

1. **Benchmarking:** Recording baseline data on crops, livestock, other farm components, and the household as a whole.
2. **Cropping system diversification/improvement:** Introducing efficient cropping systems suited to farmers' resources, preferences, and market opportunities, while improving existing practices.
3. **Livestock diversification/improvement:** Promoting year-round fodder production, mineral mixture supplementation, deworming, and integration of low-cost, location-specific components such as backyard poultry, duckery, piggery, and goat rearing.
4. **Product diversification:** Supporting value addition through preparation of mineral mixtures, processing of market surplus products, and promotion of kitchen/roof gardens

Economic advantages of IFS

1. **Enhanced and stable farm income:** Diversification through IFS ensures multiple and complementary Promising interventions at farmer's field (A) Azolla for animal feeding (B) Bundur Sheep (C) Duplex for backyard poultry (D) Improved shed for goatry (Photo courtesy: AICRP-IFS-OFR)ACBD
2. **Income reducing farmers' vulnerability to market volatility and climatic uncertainties.** For instance, earnings from livestock, aquaculture, or high-value horticultural produce can buffer losses from staple crop failures, ensuring year-round revenue flow.
3. **Rural employment and livelihood security:** The multifaceted nature of IFS demands skilled and unskilled labour for activities such as animal husbandry, fish rearing, and intensive crop management. This not only generates substantial on-farm employment but also curbs rural-to-urban migration by creating sustainable livelihood opportunities within villages
4. **Reduction in production costs:** Efficient recycling of crop residues, livestock manure, and other farm by-products within the IFS framework significantly minimizes dependence on external inputs such as synthetic fertilizers and pesticides. This integrated resource-use strategy lowers input costs while maintaining soil fertility and ecological balance.

Environmental benefits of IFS

IFS contribute not only to food and nutritional security but also to environmental sustainability through the following pathways:

- **Building living soils:** Inclusion of legumes, agroforestry components, and organic inputs improves soil fertility, stimulates microbial activity, and reduces risks of land degradation.
- **Securing every drop:** Practices such as rainwater harvesting, efficient irrigation, and tree-based systems minimize water losses and enhance groundwater recharge.
- **Locking away carbon:** Agroforestry and organic management increase carbon sequestration potential in IFS, thereby mitigating climate change impacts.

Challenges in IFS adoption

Despite its potential, IFS adoption faces several challenges. Initial investment in infrastructure for multiple enterprises can be high for resource-poor farmers. Management complexity increases as multiple components require knowledge, labour, and timely interventions. Market access for perishable produce, lack of extension services, and absence of integrated value chains often limits profitability. Climatic uncertainties, pest pressures,

and fragmented landholdings further hinder adoption. Addressing these challenges require targeted policy support, capacity building, and farmer-to-farmer learning models.

SUMMARY

Integrated farming systems offer a resilient pathway for small and marginal farmers to achieve higher productivity, diversified income, and enhanced livelihood security. By integrating crops, livestock, fisheries, horticulture, boundary plantations, mushrooms, and multilayer vegetable farming with efficient nutrient recycling, farmers can optimize resource use and ensure year-round returns. Although challenges remain in terms of investment, management, and market linkages, the long-term economic, nutritional, and ecological benefits establish IFS as a cornerstone for sustainable agriculture in India.



GREEN HYDROGEN: INDIA'S NEXT CLEAN ENERGY REVOLUTION

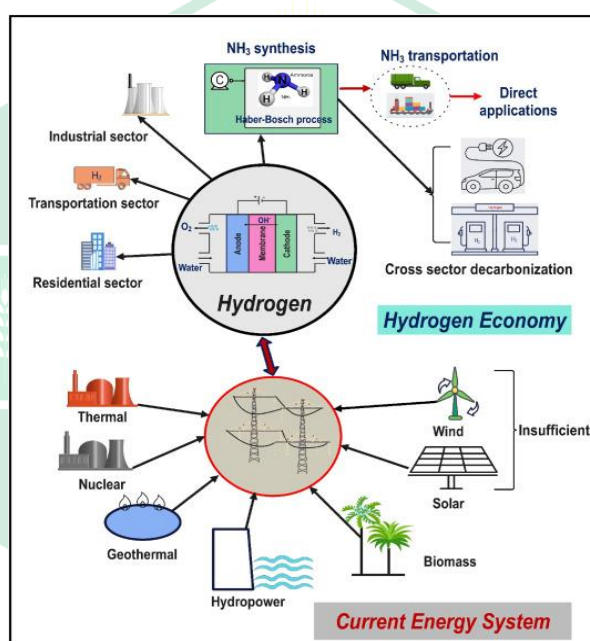


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As the world searches for clean alternatives to fossil fuels, hydrogen produced from renewable energy is emerging as one of the most promising solutions for a sustainable energy future. With rising concerns about climate change, air pollution, and energy security, countries across the world are searching for sustainable alternatives to fossil fuels. Renewable energy technologies such as solar and wind power are already playing a crucial role in this transition. However, renewable electricity alone cannot fully solve the global energy challenge. Many sectors including heavy industry, aviation, and long-distance transport require high-energy fuels that electricity alone cannot easily provide.



One promising solution is **green hydrogen**, a clean energy carrier produced using renewable electricity. When hydrogen is generated using solar energy, the process becomes completely sustainable and environmentally friendly. Solar-powered hydrogen production has the potential to revolutionize energy systems by providing clean fuel for transportation, industry, and electricity generation.

A number of large-scale green hydrogen projects are already being developed around the world. One of the most notable examples is the **NEOM Green Hydrogen Project in Saudi Arabia**, which aims to produce about **650 tons of green hydrogen per day** using renewable energy from solar and wind power. The hydrogen produced will be converted into green ammonia and exported globally as a clean fuel. In India, companies such as **NTPC and Reliance Industries** are also investing in solar-powered hydrogen production plants as part of the country's **National Green Hydrogen Mission**. These projects demonstrate how renewable energy can be integrated with hydrogen production to create sustainable energy systems.

For countries like India, which receive abundant sunshine throughout the year, the combination of **solar energy and hydrogen production** presents a powerful opportunity to build a low-carbon and energy-secure future.

Researchers and engineers are also developing advanced technologies to improve hydrogen production efficiency. For example, experimental systems using solar photovoltaic panels combined with intelligent control algorithms such as Maximum Power Point Tracking (MPPT) can enhance energy conversion efficiency during electrolysis. Such systems allow solar energy to be utilized more effectively even under changing weather conditions, improving hydrogen production efficiency. These innovations highlight the importance of integrating renewable energy, power electronics, and smart control systems for the future hydrogen economy.

Understanding Hydrogen as an Energy Carrier

Hydrogen is the lightest and most abundant element in the universe and has a very high energy content, making it an attractive clean fuel. It contains a high amount of energy per unit mass and can be used as a fuel in many applications. When hydrogen is used in a fuel cell or burned as a fuel, the only by-product produced is water, making it one of the cleanest energy carriers available.

However, hydrogen rarely exists freely in nature. It is usually bound with other elements such as oxygen in water or carbon in hydrocarbons. Therefore, hydrogen must be produced through chemical or electrochemical processes before it can be used as fuel.

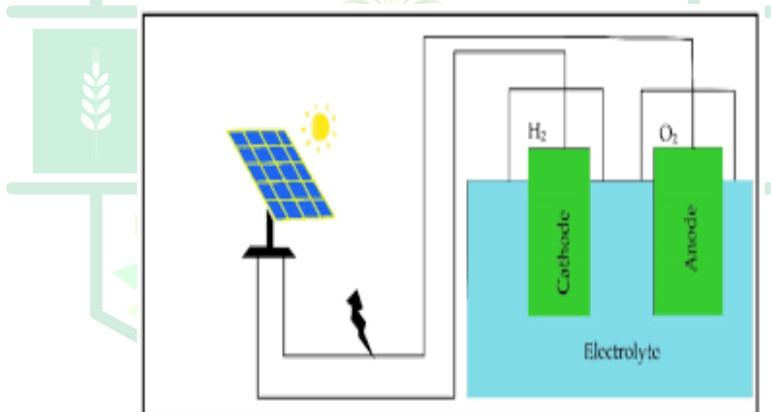
Hydrogen production methods are commonly classified by colours based on their environmental impact:

- **Grey hydrogen** - produced from natural gas with high carbon emissions
- **Blue hydrogen** - produced from fossil fuels with carbon capture technology
- **Green hydrogen** - produced using renewable electricity and water electrolysis

Among these options, green hydrogen is considered the most sustainable and environmentally friendly.

How Solar Energy Produces Green Hydrogen

The production of green hydrogen using solar energy typically involves a process called water electrolysis. In this process, electricity generated by solar photovoltaic (PV) panels is used to split water into hydrogen and oxygen.



The basic process consists of four main steps:

1. Solar Energy Conversion

Solar photovoltaic panels capture sunlight and convert it into electrical energy. This renewable electricity serves as the power source for hydrogen production.

2. Water Electrolysis

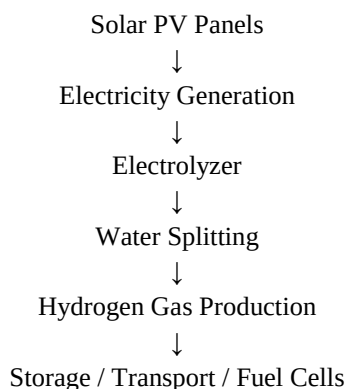
The electricity produced by the solar panels is supplied to an electrolyzer, a device that splits water molecules into hydrogen and oxygen gases. The reaction occurs in an electrochemical cell where water molecules are separated using electrical energy.

3. Hydrogen Collection and Storage

The hydrogen gas produced during electrolysis is collected, purified, and stored in pressurized tanks or specialized storage systems.

4. Energy Utilization

The stored hydrogen can later be used as fuel in fuel cells, industrial processes, or power generation systems. This process allows renewable energy to be stored in the form of hydrogen, which can be transported and used whenever energy is required.



Applications of Green Hydrogen

Green hydrogen is attracting global attention because it can support decarbonization across multiple sectors.

Clean Transportation

Hydrogen fuel cells are being developed for buses, trucks, trains, and even ships. In these systems, hydrogen reacts with oxygen inside a fuel cell to generate electricity, which powers the vehicle. The only emission produced is water vapor. Several countries are already testing hydrogen-powered buses and trains, demonstrating the potential of this clean transportation technology.

Industrial Applications

Many industries require hydrogen for chemical processes. For example:

1. Ammonia production for fertilizers
2. Petroleum refining
3. Steel manufacturing

Currently, most industrial hydrogen is produced from fossil fuels. Replacing this with green hydrogen could significantly reduce industrial carbon emissions.

Renewable Energy Storage

Renewable energy sources such as solar and wind are intermittent because they depend on weather conditions. Hydrogen provides an effective solution for storing excess renewable energy. When solar power generation exceeds demand, the surplus electricity can be used to produce hydrogen. This hydrogen can later be converted back into electricity when energy demand increases.

Power Generation

Hydrogen can also be used to generate electricity through fuel cells or hydrogen turbines. This makes it useful for backup power systems and remote energy applications.

Advantages of Solar-Based Green Hydrogen

Combining solar energy with hydrogen production offers several important advantages.

1. Environmentally Friendly

Green hydrogen production produces no greenhouse gas emissions, making it one of the cleanest energy solutions available.

2. Renewable and Sustainable

Solar energy is abundant and renewable. When solar power is used to produce hydrogen, the entire energy cycle becomes sustainable.

3. Energy Storage Capability

Hydrogen allows large amounts of renewable energy to be stored for long periods, solving one of the major challenges of solar power.

4. Energy Security

Countries can produce hydrogen locally using renewable energy resources, reducing dependence on imported fossil fuels.

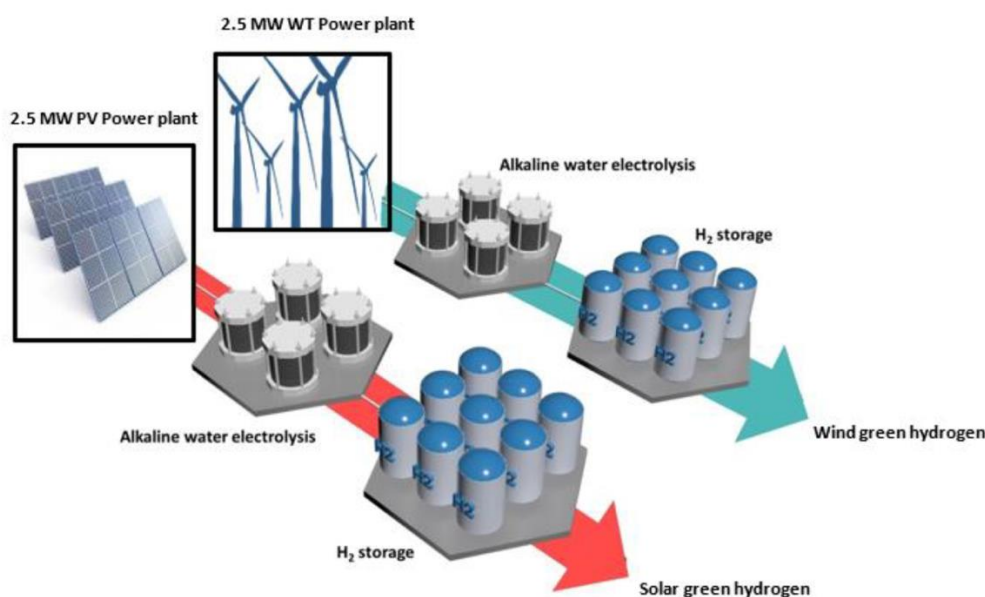
5. Versatile Energy Carrier

Hydrogen can be used in multiple sectors including transportation, electricity generation, and industrial applications.

Green Hydrogen Opportunities in India

India is uniquely positioned to become a global leader in green hydrogen production due to its abundant solar resources. Many regions of the country receive high levels of solar radiation throughout the year, making solar power one of the most promising renewable energy sources. Recognizing this potential, the Government of India launched the **National Green Hydrogen Mission**, which aims to:

- Promote domestic hydrogen production
- Reduce dependence on fossil fuel imports
- Encourage development of hydrogen infrastructure
- Support clean energy innovation



The mission seeks to establish India as a **global hub for green hydrogen production and export**.

Green hydrogen can also benefit the agricultural sector by supporting **fertilizer production, rural energy systems, and decentralized renewable power solutions**.

Challenges in Green Hydrogen Development

Despite its promise, several challenges still need to be addressed before green hydrogen becomes widely adopted.

1. High Production Cost

Currently, electrolyzers and hydrogen infrastructure remain expensive. However, costs are expected to decrease as technology advances and production scales increase.

2. Storage and Transportation

Hydrogen is a very light gas, which makes storage and transportation technically challenging. Specialized storage systems and pipelines are required.

3. Infrastructure Development

A large-scale hydrogen economy requires new infrastructure including production plants, pipelines, storage systems, and fueling stations.

4. Technology Advancement

Further research and development are needed to improve electrolyzer efficiency and reduce system costs.

Despite its promise, green hydrogen faces several challenges. The cost of electrolyzers and renewable electricity remains relatively high compared to conventional hydrogen production methods. Hydrogen storage and

transportation also require advanced infrastructure and safety systems. Additionally, large-scale deployment of renewable energy systems is necessary to ensure continuous hydrogen production.

Future Outlook

The future of green hydrogen looks highly promising. As renewable energy capacity continues to grow worldwide, hydrogen is expected to play a major role in the global energy transition. Advances in solar technology, electrolysis systems, and hydrogen storage methods are likely to reduce costs and improve efficiency. Governments, industries, and research institutions are investing heavily in hydrogen technologies, accelerating innovation and deployment. In the coming decades, solar-powered hydrogen production could become a cornerstone of sustainable energy systems, helping the world achieve climate goals while ensuring reliable and clean energy for future generations.

Conclusion

Green hydrogen produced using solar energy represents one of the most promising developments in the global transition toward sustainable energy. By harnessing abundant sunlight to generate clean hydrogen fuel, nations can significantly reduce carbon emissions, strengthen energy security, and support long-term economic growth.

For countries like India, the integration of solar energy with hydrogen production offers immense opportunities for clean energy expansion, industrial decarbonization, and technological innovation. With supportive government policies, increasing investments, and continued research, solar-powered green hydrogen has the potential to become a cornerstone of India's clean energy strategy and an important pillar of the global low-carbon future.

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AGRO-TEXTILES' SIGNIFICANT CONTRIBUTION TO AGRICULTURAL USES



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ABSTRACT

For thousands of years, the agricultural industry has employed agro-textiles, which are a visually appealing method of protecting crops throughout their whole life cycle. Among the technical textile sectors, it is one that is expanding. "Agro-textile" is the term used to describe technical fabrics used for agricultural purposes. India is the world's largest producer, consumer, and exporter of agro-textiles. The agro-technological application area determines the choice of fibres for agro-textiles. Fibres such as hemp, sisal, jute, and coir are used extensively in agro-textiles. Agro textiles such as mulch mats, bird nets, sunscreen, harvesting nets, hail protection nets, and windscreens are becoming more and more popular these days. In essence, agro textile encompasses various industries, including horticulture, fisheries, animal husbandry, and more. Regardless of the climate, the use of agro-textile goods has produced a wide range of favourable results and has a beneficial effect on the growth and production of different crops and vegetables. This paper's primary goal is to provide an overview, highlight the significance of agrotiles, their functions and product and highlight their future prospects.

Keywords- Textile industry, Agro textiles, non-conventional fibers, application, Textile Product

INTRODUCTION

One of humanity's oldest professions, agriculture continues to be a significant global industry. The ongoing global population growth has resulted in a significant increase in the strain on agricultural food output. With limited land resources, the current situation necessitates high yield and quality agro-products to meet the growing demands of the people. To meet this strict requirement, the conventional method of applying pesticides and herbicides is challenging. Additionally, these techniques are costly and have long-term ecological effects on soil, living things, and agricultural goods (Bhavani *et al.* 2017).

The use of textile fibres in agriculture has received a lot of attention as a result of technological advancements and a notable rise in environmental consciousness. Among the many industries worldwide, the textile industry is regarded as one of the biggest since it is essential to the growth and flow of the global economy. The textile industry is revolutionising textile processing through the use of biotechnology. Many cellulose fibres that have applications in anything from biomedicine to agriculture have been synthesised as a result of textile processing. Because they are non-toxic and biodegradable, agro-textile products (such as mulch mats, harvest nets, and shade nets) can benefit agriculture by shielding crops from inclement weather and undesirable pests without having an adverse effect on the environment (Sharma *et al.* 2022).

With 1.3 billion people, India is the second most populous country in the world. By 2030, India is predicted to surpass all other countries in terms of population. Due to overexploitation by the populace, this population growth is placing pressure on land use and deteriorating water and forest resources. Crop management and food scarcity are major problems in India. The latest development in crop management and climate control is agro textiles (Mandle *et al.* 2019).

STRATIFICATION OF FIBERS UTILIZED IN AGRICULTURE

As seen in Figure 1, textile fibres are divided into two categories: natural and synthetic. Natural agro-textiles are made from fibre materials derived from plants or animals and are environmentally beneficial. The most common type of natural fibres are plant-based fibres, which come from a variety of plant parts, including seeds, stems, leaves, and fruit. Plant fibres have a long history in human civilisation and are biodegradable and renewable.

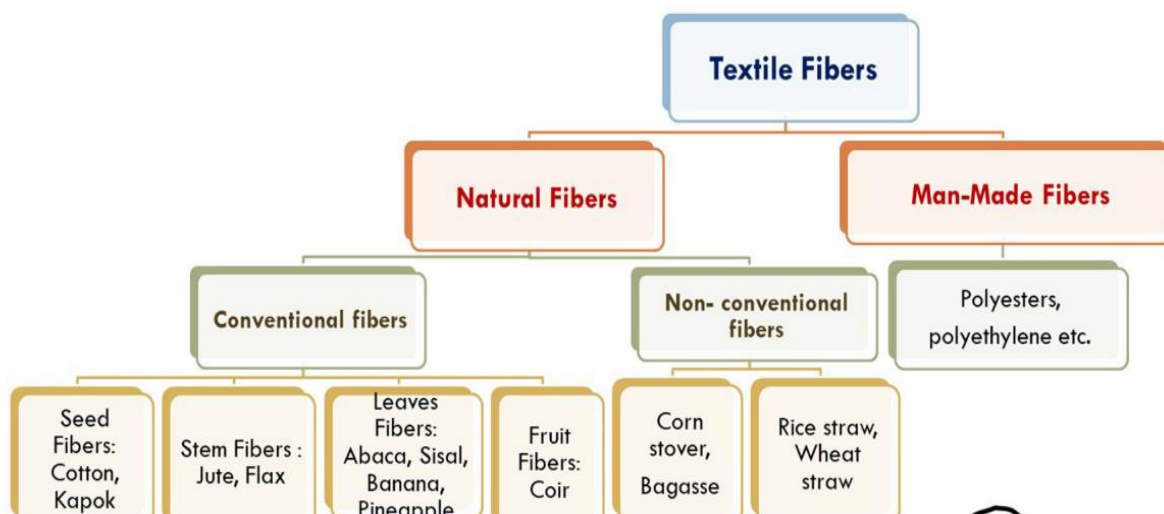


Figure. 1- Classification of Textiles Fibers (Bhavani *et al.* 2017)

NON-CONVENTIONAL PLANT FIBERS FOR AGRO-TEXTILES

Crop improvement may benefit from the use of unconventional plant fibres derived from maize stover, bagasse, bananas, wheat straw, rice straw, pineapple leaves, etc. Because of their intrinsic chemical and physical characteristics, non-conventional fibres, which are generated from lignocellulosic agricultural by-products, have the potential to be used in the textile and paper sectors. The chemical makeup of lignocellulosic-based fibre, its origin, and the methods used for extraction all affect its characteristics. Cellulosic waste derived from crop residues and other agricultural wastes typically has 12–28% lignin, 11–38% pentosans, and 31–60% cellulose (Bhavani *et al.* 2017).

PROPERTIES REQUIRED IN AGRO TEXTILES

The agro textiles must have the following properties:

1. They must be able to endure sun radiation.
2. They should have the ability to endure UV rays.
3. Textiles should be bio-degradable.
4. They should have a great ability to retain water.
5. Textiles should have good protective characteristics.
6. They should have a long service life (Bhavani *et al.* 2017) (Kapila *et al.* 2020)

FIBRES USED TO PRODUCE AGRO TEXTILES

Elongation, stiffness, biodegradation, strength, and resistance to sunlight and harmful environments are characteristics of agro-tech textiles. Textiles used in agriculture include anti-bird netts, sunlight screening, wind shield packing for storing grass, crop protection and erosion prevention, and layer separation in fields (Aldalbahi *et al.* 2021). Both natural and synthetic fibres can be used to create agro textiles. Because they degrade after a few years, agro textiles made of natural fibres are less effective than those made of man-made fibres. Conversely, agro-based textiles manufactured by men are sturdy, long-lasting, and portable. The different fibres used to make agro textiles are listed below (Dorugade *et al.* 2023).

- Coir
- Flax
- Jute
- Nylon
- Polyester
- Polyethylene
- Polypropylene
- Wool

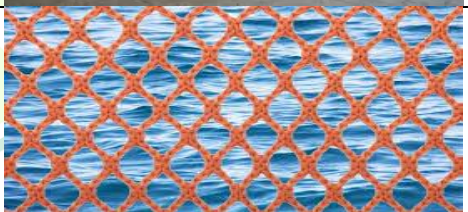
Methods of Agro Textiles Production with their Agro-textiles Product

Fabric type/Method	Classification				
	Crop Production and packing	Horticulture & Floriculture	Forestry	Animal Husbandry	Fishing & Aquaculture
Woven	Sunscreen, Packing sack, Insect meshes, Cold and frost control fabrics, Nets for covering pallets, Tape nets, Ground cover.	Sunscreen, Root ball net	Soil protection fabric	Tape net, Mats for animals	Anti fouling nets
Non-woven	Mulch mat	Mulch mat, mixed bed for mushroom	Weed control fabric	Underlay for reducing mud, Filter for milking	Anti fouling nets
Knitted	Plant net, Bird protection net, Shade cloth, Wind shield, Anti hailstone nets, Support nets, Monofil nets.	Plant net, Bird protection net, Shade cloth, Windshield, Anti hailstone nets, Harvesting nets, Insect meshes		Udder protection nets, mosquito protection nets, tape nets	Fishing nets, Aquaculture nets, Anti fouling nets.
Plastic Sheets	Ground cover, Cherry cover	Ground cover, Greenhouse cover, Rain protection fabric			Ultraviolet radiation protection sheets
Braided & Twisted				Baler twine, belt	Fishing line

Table 1. Methods of agro textiles production with their agro-textiles product (Chowdhury *et al.*2017)
Different Agro-textile Product and their Functions

Name	Function	Picture
Sunscreen	Sunscreen gives plants a regulated quantity of shade and sunlight. The mesh size affects the shadow proportion. (Azam <i>et al.</i> 2020)	

Mulch Mat	Mulch mats are used to cover the soil and prevent sunlight, which inhibits the growth of weeds. (Restrepo-Osorio <i>et al.</i> 2019)	
Harvesting Nets	This nett can safeguard fruits that are vulnerable to mould infections, discoloured kernels, and insect and beetle invasion because they are lying on the ground. Harvesting is made simpler, cleaner, and more sustainable using this nett. It also cuts down on fruit collection time. (Azam <i>et al.</i> 2020)	
Ground cover	Ground cover is a simple option for long-term weed control, moisture retention, and separation. They are employed in horticulture and landscaping. (Azam <i>et al.</i> 2020)	
Anti hailstone net	These nets are suitable to protect cultivations from hail damages. (Azam <i>et al.</i> 2020)	
Udder protection nets	These guard against udder injury in crowded barns and pastures. Additionally, it is perfect for preventing step injuries to the udder. (Basuk <i>et al.</i> 2025)	
Porous tube for localized irrigation	The entire field is connected by a porous tube with a watering pipe. It regulates consistent watering in the garden and field. (Restrepo-Osorio <i>et al.</i> 2019)	
Support nets	These netts help flowers flourish and support vertically growing plants and climbing vines. It helps plants support their enormous fruit. (Basuk <i>et al.</i> 2025)	

Insect meshes	Pollinating insects are kept inside this nett. They keep dangerous insects out of tunnels and greenhouses. Without the use of insecticides, this finely woven screen provides insect protection. (Marasovic <i>et al.</i> 2019)	
Cold and frost control fabrics	By creating a favourable microclimate, Frost Protection Fabric helps retain more heat during the day and lessens the amount of heat that is lost from the soil at night. Consequently, the fabric cools to the lowest possible temperature without harming the plants. (Basuk <i>et al.</i> 2025)	
Mosquito protection nets	It protects cattle from mosquito and harmful insects. (Marasovic <i>et al.</i> 2019)	
Root ball net	It is a biodegradable substance that shields root balls from damage while they are being stored and transported. Additionally, it keeps soil from adhering to the roots. (Restrepo-Osorio <i>et al.</i> 2019)	
Anti fouling nets	It offers a physical defence against biofouling. This nett lasts a long time. Compared to regular fishing nets, they are more resistant to deterioration in saline water. (Marasovic <i>et al.</i> 2019)	
Bird protection net	It guards against harm from birds and other pests to seeds, crops, and fruit. However, the mesh size is sufficiently large to for bee mobility. (Restrepo-Osorio <i>et al.</i> 2019)	
Weed control fabric	This kind of fabric is used to suppress weed growth. Typically, they are non-woven, needle-punched fabrics. (Restrepo-Osorio <i>et al.</i> 2019)	

Packing material for agricultural goods	A variety of agricultural items are packed using these netts. It could be tubular packing netts or packing sacks. (Marasovic <i>et al.</i> 2019)	
Fishing nets	Fishing nets are knitted fabrics. They are used for fishing. (Restrepo-Osorio <i>et al.</i> 2019)	
Windshield	Plants, small trees, and crops are shielded from severe winds by windscreens. If trees are shielded from severe winds, they will appear healthy. (Marasovic <i>et al.</i> 2019)	
Aquaculture net	Several fish species are raised in the same pond using this nett. For example, raising predatory fish with regular fish or raising fish of various sizes in a single pond or lake. (Marasovic <i>et al.</i> 2019)	

ROLE OF AGRO-TEXTILES IN CROP IMPROVEMENT

Numerous researchers have demonstrated the impact of jute agrotexiles on increasing broccoli yields; 800 g/m² of jute agrotexile produced a noteworthy outcome with an average broccoli weight of 1.2 kg and length of 29.5 cm. The moisture-holding capacity was 49.05%, and the yield was approximately 4.44 tons/ha. The natural jute bast fibre product that makes up the jute agro-textile is biodegradable and environmentally benign, and it promotes plant growth by supplying vital nutrients through the breakdown of lignin (Sarkar *et al.*, 2018).

The impact of non-woven ramie fibre film on the root zone environment of rice seedlings was examined in another study. The film had a direct effect on the growth of the seedlings since it was utilised as a pad on the bottom surface of the seedling tray, which tended to improve the oxygen supply that encouraged root respiration. The study's findings demonstrated a markedly increased concentration of inorganic nitrogen in the soil and a decrease in organic matter, which improved the growth and development of rice seedlings (Zhou *et al.* 2020).

In order to shield radish seeds from spit germination and low temperatures, a team of scientists employed non-woven agro-textiles with masses of 10 g m⁻² and 17 g m⁻² per unit area. Compared to the uncovered control plot, both agro-textile covers increased the temperature during the day, tended to promote germination by around 19%, and shortened the germination time (Rekika *et al.* 2008).

MAJOR AGRO-TEXTILE PROJECTS

Agrotexiles, a subset of technical textiles, are essential for increasing agricultural sustainability and productivity. Globally, major agro textile projects concentrate on advances that minimise the need for agrochemicals, increase crop output, and use less water. Among the noteworthy projects is the AGROTEX programme, which is financed by the European Union and investigates the use of biodegradable mulching textiles and shadow netts to maximise plant growth microclimates (European Commission, 2021). Large-scale field tests of agrotexile applications, including mulch mats, insect netts, and shade netts, have been carried out in India by the Ministry of Textiles and

the Indian Council of Agricultural Research (ICAR) in a variety of climatic zones, showing improved crop productivity and decreased pest infestation (ICAR, 2022). The creation of smart agrotexiles with sensors to track crop health and soil moisture is another area of focus for research from organisations such as the Textile Research Institute of Sweden (Andersson, Berglund, & Nilsson, 2020). These initiatives highlight how agrotexiles can be used to address issues of global food security by promoting sustainable farming methods.

CONCLUSION AND FUTURE PERSPECTIVES

There are possible uses for agrotexiles in agricultural settings, where they aid in the faster germination and growth of crops. Additionally, it affects the general morphology of the plant, resulting in increased leaf areas and plant heights. As they break down, a range of agro-textile fibres tend to improve soil conditions and contribute organic carbon to the soil. Eco-friendly and biodegradable materials derived from farms or agriculture appear to be preferred in next-generation agro-textiles. Therefore, lignocellulosic-based agro-textiles could be a blessing for agriculture and an affordable, eco-friendly substitute.

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MADS Box Gene Family: Master Regulators of Plant Development and Floral Organ Identity



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MADS BOX GENE

MADS box genes are transcription factors that are present nearly in all major eukaryotic groups. MADS box genes are a family of genes that encode MADS domain proteins that bind to specific DNA sequences to regulate the expression of other genes. They can also regulate the flowering time, seed and fruit development, and stress response. The term MADS box gene was coined later after four subsequently characterized 'founding family members': MINICHROMOSOME MAINTENANCE 1 (MCM1) from *Saccharomyces cerevisiae*, AGAMOUS (AG) from *Arabidopsis thaliana*, DEFICIENS (DEF) from *Antirrhinum majus* and SERUM RESPONSE FACTOR (SRF) from *Homo sapiens*.

There are two type of MADS box gene 1) Type I MADS box gene and 2) Type II MADS box gene (also called MIKC type). These two types are distinguished on the basis of sequence dissimilarity and also differ in sequence specificity in DNA binding and the amount of DNA bending that they induce. Type I MADS box gene are simpler in structure and found in both plants and animals. Usually have only the MADS domain and work in reproductive processes like seed and embryo development. Type I MADS box gene has three subclasses **Ma** (M-alpha) **Mβ** (M-beta) **Mγ** (M-gamma). While type II MADS box gene are plant specific and have four domain (MADS domain, I domain, K domain and C domain). Type II MADS box gene have two subclasses **MIKC^C** (classical type) and **MIKC*** (star type).

Type	Subtype	Structure	Function	Example
Type I	Mα, Mβ, Mγ	Only MADS domain	Reproductive/seed development	AGL62, AGL80 etc.
Type II	MIKC ^C	M + I + K + C	Flower organ identity	AG, AP1, SEP etc.
Type II	MIKC*	M + I + K + C	Pollen/gametophyte development	AGL66, AGL104 etc.

All the well characterized MADS box genes contributing to plant development and all genes for which mutant phenotypes are known are type II genes. Type I and type II MADS box gene have different gene structure. In type I MADS box gene there is an absence of introns while in type II introns are present.

There are major clades of MIKC-type genes reported in angiosperms, some are as below with their respective function.

AGAMOUS-like: Reproductive organ development.

SOC1: Integrates flowering signals, promotes flowering.

SQUAMOSA: Specific transcription factors that play important roles in plant life cycle.

FLC: Represses two genes that promote flowering *FT* and *SOC1*.

AGAMOUS: Controls reproductive organ development, specifically stamens and carpels.

PISTILLATA: Works with *AP3* to specify petal and stamen identity during flower development.

SHORT VEGETATIVE PHASE: A critical inhibitor of flowering.

DEFICIENS: Control of flower morphogenesis in *Antirrhinum majus*.

Characteristics of MADS box proteins

MADS domain is around 174 nucleotide residues of DNA encoding about 58 amino acid residues in MADS protein. MADS domain proteins bind to DNA in a sequence specific way as homodimers or heterodimers or multimers. N-terminal is important for sequence-specific binding. C-terminal is part of a dimerization surface it means involved in the protein's ability to form multi-protein complexes (Fig 1).

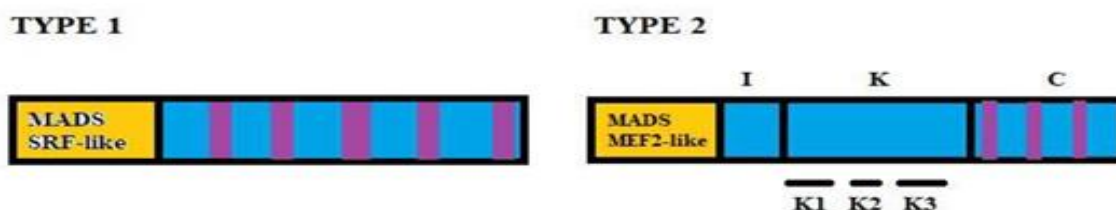


Fig 1: Domain structure of type-I and type-II MADS domain proteins.

Type I proteins do not have other conserved domains only the SRF-like MADS domain whereas in type II (MIKC-type) proteins of plants MEF-2 like MADS domain is followed by the intervening (I), the keratin-like (K) and the C-terminal (C) domains. Orange part have a role in DNA binding, blue portion in protein-protein interaction, and purple in transactivation (regulating gene expression). The three subdomains of the K domain, K1, K2 and K3, are indicated by black lines. I domain less conserved and determine the specificity of dimeric protein-protein interactions. K domain highly conserved, approx 70 amino acid long and further divided into K1, K2 & K3 domains. C domain least conserved, protein multimer formation and involved in recruiting other regulatory proteins or activating transcription.

Functions of MADS Box

The MADS box genes play a crucial and multi faceted role in the development and regulation of plant life. Their primary functions include controlling flower development and determining floral organ identity, which is essential for reproduction. Beyond flowering they also integral to the process of fruit development and seed development. Furthermore MADS box genes contribute to overall vegetative development and are involved in complex regulatory pathways modulating hormone signalling and enabling the plant's response to environmental signals.

Applications of MADS Box

MADS box genes serve as master regulator tool in biotechnology and research. Primarily used to optimize crop yields and plant architecture by controlling grain size and leaf positioning. In agricultural breeding they are targeted to enhance stress resilience such as cold and drought tolerance and to improve nutrient efficiency reducing the need for chemical fertilizers. These genes also allow for the finetuning of flowering schedules to match specific climates and the manipulation of fruit ripening to extend shelf life. Beyond food security they are essential in horticulture for creating unique ornamental flower shapes and in evolutionary biology as a "genetic blueprint" to understand how complex plant structures first evolved.

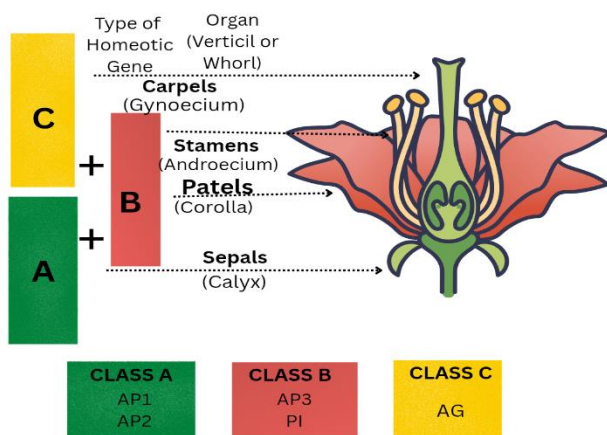
Advantages of MADS Box

MADSbox genes offer a distinct conceptual advantage by serving as evolutionary "master switches". Their primary strength lies in combinatorial control where a relatively small number of genes can form diverse protein complexes (like the ABCDE quartet model) to specify distinct organ identities such as petals or seeds with high precision. Conceptually this family provides plants with developmental plasticity acting as an environmental sensor that integrates external signals like temperature and light to finetune critical life events like flowering and root growth. By bridging the gap between genetic potential and environmental survival, MADSbox genes function as a versatile "genetic toolkit" that drives the immense morphological diversity and stress resilience observed across the plant kingdom.

Future prospects of MADS Box

MADS box genes engineering especially using precise tools like CRISPR/Cas9 will allow for finetuning the expression of these genes. Target specific MADS box genes could lead to improved vase life (longevity) and increased tolerance to post harvest stress significantly benefiting the floral industry. Engineering gene expression can allow precise control over when a plant blooms which is crucial for commercial floriculture enabling growers to schedule harvests and it can also be used to speed up breeding cycles. Future research will continue to discover and functionally characterize MADS box genes in non-model species, this knowledge can be applied to diversify reproductive traits in crop plants.

ABC model of floral development



Here we see that A B C which represent the class of regulatory gene. These genes are homeotic gene and have role in different whorl formation. The identity of an organ is determined by the specific combination of active gene classes in that region.

Class A: Active alone in Whorl 1 to produce Sepals

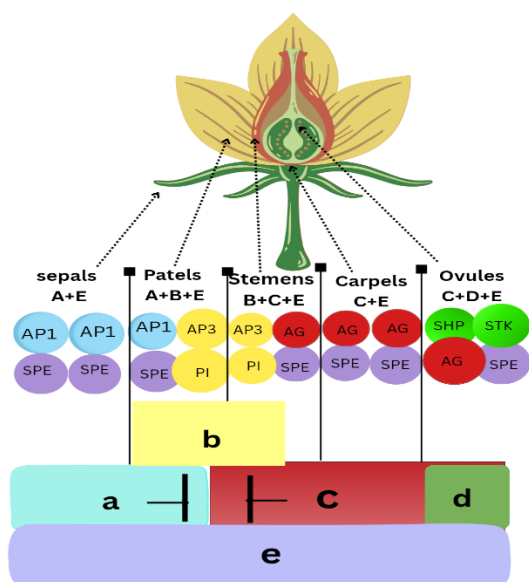
Class A + Class B: Active together in whorl 2 to produce petals

Class B + Class C: Active together in whorl 3 to produce stamens

Class C: Active alone in whorl 4 to produce carpels

Here Class A and Class C are antagonistic with each other when class A is active Class C is off and vice versa. Means class A inhibits the class C function in whorl 1 and 2 while class C inhibits class A function in whorl 3 and 4.

ABCDE model of floral development



It expands on the classic ABC model by including two additional classes of genes, D and E. This model explain the identity of the five floral structures (sepals, petals, stamens, carpels, and ovules) through the combine action of five classes of genes (A, B, C, D, and E).

ABC could not explain all the experimental observation, there is some limitation of ABC model, when all ABC genes were mutated resulting in cauline like leaves, so this showed that alongside of A B & C gene there is some missing factor. Which make organ floral and later study showed that inside the carpel the formation of ovules regulate by some separate gene which is D class gene and Class E required in all whorl formation.

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Women oriented Marketing Programmes Supporting Women Entrepreneurship



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Women oriented marketing programmes are designed to support women entrepreneurs, self-help groups, and women producers by providing marketing assistance, financial support, training, and market linkages. These programmes help women to sell their products effectively and increase their income.

Central government programmes for promoting women entrepreneurs in India

1. Pradhan Mantri MUDRA Yojana, 2015

Pradhan Mantri MUDRA Yojana (PMMY) is a scheme launched by the Hon'ble Prime Minister on April 8, 2015 for providing loans up to 20 lakh (for those entrepreneurs who have availed and successfully repaid previous loans under the 'Tarun' category) to the non-corporate, non-farm small/micro enterprises. These loans are classified as MUDRA loans under PMMY. These loans are given by Commercial Banks, RRBs, Small Finance Banks, MFIs and NBFCs.

Features of Pradhan Mantri MUDRA Yojana

- ✓ **Collateral-Free Loans:** To provide easy access to loans to small entrepreneurs to start or expand their business.
- ✓ **Support to non-agricultural enterprises:** Providing financial assistance for activities in manufacturing, trading and service sectors (truck drivers, shopkeepers, artisans, etc.).
- ✓ **Promotion of self-employment:** Encouraging new entrepreneurs, especially women and young workers, to set up their own businesses.
- ✓ **Employment Generation:** To increase employment opportunities in the country by providing loans to micro enterprises.

Loan Categories:

Shishu: Loans up to ₹50,000.

Kishor: Loans from ₹50,001 to ₹5 lakh.

Tarun: Loans from ₹5 lakh to ₹10 lakh.

Tarun Plus: Loans from ₹10 lakh up to ₹20 lakh.

The funding support from MUDRA are of two types:

- ✓ Micro Credit Scheme (MCS) for loans up to 1 lakh finance through MFIs.
- ✓ Refinance Scheme for Commercial Banks / Regional Rural Banks (RRBs) / Small Finance Banks / Non Banking Financial Companies (NBFCs).

MUDRA Card is a debit card issued against the MUDRA loan account, for working capital portion of the loan. The borrower can make use of MUDRA Card in multiple drawals and credits, so as to manage the working capital limit in cost-efficient manner and keep the interest burden minimum. MUDRA Card also helps in digitalization of MUDRA transactions and creating credit history for the borrower. MUDRA Card can be operated across the country for withdrawal of cash from any ATM / micro ATM and also make payment through any 'Point of Sale' machines.

Application Process: Applications can be made directly from public or private banks, rural banks, NBFCs and Micro Finance Institutions (MFIs) or online through this portal www.udyamimitra.in.

2. Stand-Up India, 2016

A scheme by Ministry of Finance for financing SC/ST and/or Women Entrepreneurs by facilitating bank loans for setting up a greenfield project enterprise in manufacturing, services, trading sector and activities allied to agriculture. The programme facilitate bank loans between Rs. 10 lakh and Rs. 1 Crore to at least one Scheduled

Caste (SC) or Scheduled Tribe (ST) borrower and at least one woman borrower per bank branch for setting up a greenfield enterprise. In case of non-individual enterprises, at least 51% of the shareholding and controlling stake should be held by either an SC/ST or Woman entrepreneur.

Benefits:

- ✓ Facilitation of composite loan (inclusive of term loan and working capital) between ₹10 Lakhs and ₹100 Lakhs. Rupay debit card to be issued for convenience of the borrower.
- ✓ The web portal by SIDBI provides hand-holding support through a network of agencies engaged in training, skill development, mentoring, project report preparation, application filling, work shed / utility support services, subsidy schemes etc.

Application Process: Either approach your nearest bank branch to or through the Lead District Manager (LDM), or apply through portal: www.standupmitra.in

3. Kalyani Scheme, 2013

The Cent Kalyani Scheme, launched by the Central Bank of India, is a, flagship, collateral-free loan initiative designed to support women entrepreneurs in starting new projects or expanding existing micro/small-scale manufacturing or service enterprises. It provides up to ₹1 Crore in financing (term loans/working capital) with concessional interest rates.

Services under Kalyani Scheme:

- ✓ **Target Beneficiaries:** Women entrepreneurs (MSMEs, self-employed, professionals like doctors/engineers, artisans).
- ✓ **Loan Amount:** Up to ₹100 Lakhs (₹1 Crore).
- ✓ **Collateral Requirement:** No collateral or third-party guarantee is required, as the loan is covered under the Credit Guarantee Fund Trust for Micro and Small Enterprises (CGTMSE).
- ✓ **Interest Rates:** Concessional rates of MCLR + 0.25% to 0.5%.
- ✓ **Margin:** 20%.
- ✓ **Purpose:** To start new units or expand/modernize existing ones (e.g., in manufacturing, handloom, food processing, beauty, transport).
- ✓ **Not Covered:** Retail trade, educational institutions, and self-help groups are generally not covered.
- ✓ **Application process:** Interested applicants can apply through Central Bank of India branches or through the MSME online application portal.

4. TREAD (Trade Related Entrepreneurship Assistance and Development)

TREAD scheme, launched by India's Ministry of MSME, empowers women, particularly those who are illiterate or semi-illiterate by providing financial loans (up to 30% of project cost as a grant) through NGOs for non-farm, self-employment ventures. It combines credit, training, and counseling to enhance women's economic independence.

Services under TREAD:

- ✓ **Financial Assistance:** The Government of India (GoI) provides a grant of up to 30% of the total project cost to NGOs for lending to women entrepreneurs, while the remaining 70% is financed by lending institutions/banks.
- ✓ **Training & Capacity Building:** The scheme offers up to ₹1 lakh per program to training institutions/NGOs for training women, provided the institutions bring a 25% (or 10% for North Eastern Region) share.
- ✓ **Scope:** It supports non-farm activities, including products and services, aiming to foster self-reliance.
- ✓ **Institutional Framework:** The scheme is implemented through partnering banks and NGOs to facilitate credit delivery and counseling.

5. Women Entrepreneurship Platform (WEP), 2018

The **Women Entrepreneurship Platform (WEP)** is a flagship initiative by NITI Aayog, launched on March 8, 2018, to create a unified ecosystem for both budding and existing women entrepreneurs in India. It functions as an aggregator platform that transitions from a government-led project into a **public-private partnership (PPP)** to provide a continuum of support.

Core Pillars of WEP:

The platform is built on three central pillars designed to guide an entrepreneur's journey:

- ✓ **Ichha Shakti:** Focuses on motivating aspiring entrepreneurs to start their ventures.
- ✓ **Gyaan Shakti:** Provides essential knowledge and ecosystem support.
- ✓ **Karma Shakti:** Delivers hands-on support in setting up and scaling businesses

Services under WEP: WEP offers free services across **six strategic areas** to address common bottlenecks:

- ✓ **Funding & Finance:** Facilitates access to financial resources, grants, and credit-linked subsidies like the Stand-Up India Scheme.
- ✓ **Mentorship:** Features a digital WEP Mentorship Platform using AI/ML for smart matchmaking between mentors and mentees.
- ✓ **Incubation & Acceleration:** Connects entrepreneurs with over 500 incubators and accelerators to scale innovative ideas.
- ✓ **Skilling & Training:** Provides industry-relevant training, including specialized programs like the "EmpowHER Biz" for the retail sector.
- ✓ **Compliance & Tax Assistance:** Offers guidance on legal requirements, IP protection, and tax regulations.
- ✓ **Marketing Assistance:** Helps build market linkages and provides exposure to global trade requirements through partners like DP World.

6. Mahila Coir Yojana, 1994

Mahila Coir Yojana (MCY) is a 100% women-centric scheme under the Coir Board Ministry of Micro, Small and Medium Enterprises (MSME) aimed at providing training and skill development to rural women in coir (coir coir) processing. The scheme provides 75% subsidy for purchasing motorized spinning ratts, thereby creating self-reliance and employment opportunities for women.

Regions Covered: Primarily active in major coir-producing states such as Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, Telangana, Odisha, Lakshadweep, Maharashtra, Gujarat, Goa, Puducherry, Andaman & Nicobar Islands, West Bengal, and the North Eastern Region.

Services under MCY:

- ✓ **Subsidy on Machinery:** 75% subsidy (₹7,500 per rat or more, depending on the type of equipment).
- ✓ **Stipend:** Women receive a stipend ranging from ₹1,000 to ₹3,000 per month during the training period.
- ✓ **Equipment:** Motorized/traditional ratchets, spinning/weaving equipment.
- ✓ **Training:** 2 months training, conducted through Coir Board's training centres.

7. Mahila Samridhi Yojana, 1993

The Mahila Samridhi Yojana (MSY) provides loans ranging from ₹1 lakh to ₹1.25 lakh at low interest rates (around 4-6%) for self-employment to Scheduled Caste/minority women, primarily through the National Safai Karamcharis Finance and Development Corporation (NSFDC) and the National Minorities Development and Finance Corporation. The scheme helps women become financially self-reliant through occupations such as tailoring and handicrafts.

Features of MSY:

- ✓ **Eligibility:** The female applicant must be between 16 and 45 years of age, and the annual family income must be below the prescribed limit
- ✓ **Loan amount:** Project cost usually from ₹1,00,000 to ₹1,25,000.
- ✓ **Interest Rate:** Loans at very low interest rates (up to 4% for SC women) through NSFDC.
- ✓ **Repayment period:** The loan has to be repaid in installments within 3 to 3.5 years, which may also include a moratorium period of 3-6 months.
- ✓ **Skill development:** This scheme often involves providing skills training to women and helping them form self-help groups (SHGs).

Application process: Eligible women can apply online through the official website of NSFDC, the respective development corporation of their state or through the myScheme portal.

8. Mahila Udyam Nidhi Scheme, 1987

The Mahila Udyam Nidhi Scheme was set in motion by the Indian government to encourage more women to take up entrepreneurship. It offers financial assistance and credit facilities at concessional interest rates. It is an initiative by the Small Industrial Development Bank of India (SIDBI). It was first launched by Punjab National Bank (PNB) under SIDBI's guidance. Owing to its success and nationwide impact in supporting women entrepreneurs, the scheme has since expanded to other lending and financial institutions. Beneficiaries can avail a loan up to INR 10 lakhs. The funds can be used for projects and businesses engaged in manufacturing, production and service-related activities.

Features of Mahila Udyam Nidhi Loan:

- ✓ **Loan Amount:** Beneficiaries of this scheme can avail of a loan up to INR 10 lakhs.
- ✓ **Collateral-Free:** Under this scheme, women entrepreneurs are not required to pledge any collateral or security against the loan.
- ✓ **Interest Rates:** Women entrepreneurs are given loans at concessional interest rates. This depends on your credit score, project cost, location and business type. Rates can vary for different lending institutions and other financial institutions.
- ✓ **Repayment Tenures:** This scheme offers flexible repayment tenures of up to 10 years with a provision for extending the loan moratorium for up to 5 years.
- ✓ **Flexible Usage:** These funds can be used for business functions like manufacturing, production and service-related activities. They can also be used to upgrade existing manufacturing facilities and technology.
- ✓ **Loan Limit:** The scheme allows you to avail of up to 25% of the total project cost with a maximum amount of INR 2.5 lakhs per project.
- ✓ **Service Charges:** Loans under this scheme charge you a service fee of 1% per annum. This fee can vary or be waived at the discretion of the lending authority.
- ✓ **Disbursal of Funds:** SIDBI sanctions the loan amount, which is disbursed through traditional lending institutions, microfinance institutions, and NBFCs.

9. Support to Training and Employment Programme for Women (STEP), 1986 - 87

The Support to Training and Employment Programme for Women (STEP) Scheme, administered by the Ministry of Women & Child Development, is a Central Sector Scheme aimed at providing skills to marginalized women (aged 16+) to enhance employability and foster self-employment/entrepreneurship. It provides financial assistance to NGOs, cooperatives, and organizations for training in diverse sectors like agriculture, handicrafts, IT, and hospitality.

Features of STEP:

- ✓ **Implemented Sectors:** Agriculture, Horticulture, Food Processing, Handlooms, Tailoring, Embroidery, Handicrafts, Computer & IT services, Travel & Tourism, and Hospitality.
- ✓ **Funding:** Provided directly to eligible implementing agencies, including NGOs, after approval by the Project Sanctioning Committee of the Ministry.

Services under Step:

- ✓ **Sector-Specific Skill Training:** Training is provided in traditional and non-traditional sectors, including Agriculture, Horticulture, Food Processing, Handlooms, Tailoring, Stitching, Embroidery, Zari, Handicrafts, Computer & IT-enabled services, Gems & Jewellery, Travel & Tourism, and Hospitality.
- ✓ **Employability & Entrepreneurship Skills:** Beyond technical skills, the programme imparts soft skills, workplace training, and skills needed to become self-employed.
- ✓ **Support Services:** The program includes components designed to enable women to attend training, such as ensuring access to necessary resources.
- ✓ **Project-Based Assistance:** The scheme funds projects with a maximum duration of 18 months, usually supporting up to 90% of the project cost, with the implementing agency bearing the remaining 10%.

Table showing Beneficiaries and Objectives of the programmes

S. No.	Programme	Beneficiaries	Objectives
1.	Pradhan Mantri Mudra Yojana	✓ Women: Especially women entrepreneurs, who are a big part of the scheme. ✓ Small entrepreneurs: Those engaged in small manufacturing, processing and agriculture allied non farm activities. ✓ Service Sector: Small shops, salons, gyms, beauty parlors, repair shops, etc. ✓ Traders: Street vendors, hawkers and small traders.	✓ Funding the Unfunded: To provide easy access to credit for micro-enterprises and small businesses that lack traditional collateral. ✓ Employment Generation: To boost self-employment and generate jobs within the non-farm sector, including small manufacturing units, trading, and service sectors.. ✓ Regulating Microfinance: To monitor and regulate Microfinance Institutions (MFIs) and last-mile financiers to support grassroots institutions.
2.	Stand Up India	✓ Women Entrepreneurs: At least one woman borrower per bank branch. ✓ SC/ST Entrepreneurs: At least one SC or ST borrower per bank branch. ✓ Requirements: In non-individual enterprises, at least 51% of the shareholding and controlling stake must be held by an SC/ST or woman entrepreneur. ✓ Age Requirement: > 18 years old	✓ Access to Credit: To provide bank loans ranging from ₹10 lakh to ₹1 crore to underserved, marginalized sections. ✓ Promotion of Entrepreneurship: To enable SC/ST and women to set up their own enterprises. ✓ Greenfield Focus: Exclusively supports new ventures, not existing ones. ✓ Support System: The scheme aims to create a supportive environment for business, including access to loans. ✓ Economic Empowerment: To enable beneficiaries to become job creators rather than job seekers.
3.	Kalyani Scheme	✓ Women entrepreneurs engaged in manufacturing and service sectors. ✓ Self-employed professionals (doctors, artists, engineers, chartered accountants, etc.). ✓ Small businesses like salons, beauty parlors, tailoring, and boutiques.	✓ To provide financial support to women entrepreneurs for starting new projects or expanding/modernizing existing ones. ✓ To promote women-owned micro and small enterprises (MSME). ✓ To provide collateral-free, third-party guarantee-free loans up to ₹1 crore.
4.	TREAD (Trade Related Entrepreneurship Assistance and Development)	✓ Target Audience: Women entrepreneurs, especially those in rural and urban areas with limited access to resources. ✓ Focus Area: Primarily focuses on Self Help Groups (SHGs) and women engaged in, or wanting to start, non-farm activities.	✓ Empowerment through Training: To provide trade-related training, counseling, and information to women to encourage self-employment. ✓ Financial Assistance: Delivering credit to women-led MSME ventures by providing a GoI grant up to 30% of the loan amount to NGOs, with the remaining 70% financed as a loan. ✓ Capacity Building: Assisting NGOs and institutions with grants up to ₹1 lakh per program for training women.
5.	Women Entrepreneurship Platform (WEP)	✓ Aspiring Women Entrepreneurs: who are looking to start new businesses. ✓ Established Women Entrepreneurs: Women seeking to scale or grow their existing businesses. ✓ Women-Led Startups: Companies founded or co-founded by women. ✓ Self-Help Groups (SHGs) & Individuals: Grassroots entrepreneurs and salon/beauty parlour owners.	✓ Ecosystem Building: To create a supportive, inclusive environment for women to pursue business ideas. ✓ Financial Access: To provide monetary assistance, including seed capital, growth capital, and loans. ✓ Skill Development & Mentorship: To bridge skill gaps through training and provide mentorship for entrepreneurial growth. ✓ Capacity Building & Support: To offer incubation, acceleration, marketing, and legal compliance services. ✓ Networking: To connect entrepreneurs with stakeholders, industry leaders, and potential partners.

6.	Mahila Coir Yojana	✓ Target Group: Rural women artisans in coir-producing regions. ✓ Training Requirement: Women must have successfully completed a training program in spinning coir yarn/processing. ✓ Household Limit: Not more than one artisan/ household.	✓ Empowerment of Rural Women: To provide self-employment opportunities to rural women artisans by providing them with spinning equipment at subsidized rates. ✓ Skill Development: To train women artisans in the spinning of coir yarn and other coir processing activities to improve their skill levels. ✓ Modernization & Productivity: To replace traditional, labour-intensive methods with mechanized equipment enhancing productivity, quality and income.
7.	Mahila Samridhi Yojana	✓ Target Group: Women belonging to Backward Classes, SC/ST, or, in state-specific versions, low-income groups (BPL). ✓ Income Limit: The annual family income of the applicant should generally be up to ₹3.00 Lakh. ✓ Age Limit: Primarily women between 21 - 60 years. ✓ Structure: Women can apply directly or as part of a Self-Help Group (SHG).	✓ Empowerment: To foster financial independence and overcome social stigma for women from economically backward, SC, ST, or, in specific cases, minority or nomadic communities. ✓ Micro-financing: To provide accessible, low-interest micro-credit for setting up micro-enterprises. ✓ Entrepreneurship Development: To encourage an entrepreneurial mindset and create self-employment opportunities. ✓ Skill Training: To enhance vocational skills by providing training and stipends for craft activities. ✓ Capacity Building: To support Self-Help Groups (SHGs) in managing finances and expanding businesses.
8.	Mahila Udyam Nidhi Scheme	✓ Ownership Structure: Women entrepreneurs must hold a minimum of 51% of the financial holding in the enterprise. ✓ Business Sector: New or existing Micro, Small, and Medium Enterprises (MSMEs). ✓ Types of Business: Tailoring, beauty parlors, daycare centers, small manufacturing units, and similar ventures.	✓ Empowering Women Entrepreneurs: To support women for initiating new projects in the small-scale sector. ✓ Bridging the Equity Gap: To provide financial aid to cover the gap in equity for small business projects. ✓ Rehabilitation of Small Units: To assisting in the revival of viable, sick Small Scale Industry (SSI) units run by women. ✓ Modernization and Diversification: To provide funds for the expansion, modernization and technological upgradation of existing businesses.
9.	Support to Training and Employment Programme for Women (STEP)	✓ Age Limit: Women aged 16 years and above. ✓ Focus Groups: Special focus is given to SCs, STs, OBCs, minorities and women with disabilities. ✓ Employment Status: Unemployed or underemployed ✓ Beneficiaries include wage labourers, unpaid daily workers, and female-headed households.	✓ Skill Upgradation: To provide training in both traditional and modern sectors to make women employable. ✓ Self-Employment: To enable groups of women to take up employment-cum-income generation programmes. ✓ Support Services: To provide essential services for improving the training and employment conditions of women, including childcare and health check-ups. ✓ Market Linkages: To promote entrepreneurship and facilitate access to credit and market linkages.

Conclusion

These programmes provide financial assistance, training, and marketing support to women entrepreneurs and self-help groups. Overall, the schemes play an important role in promoting women's entrepreneurship, self-employment, and economic empowerment by improving their access to markets and income opportunities.

Origin of Epstein File and Adrenochrome: The Story, the Facts, the Science, and the Myth



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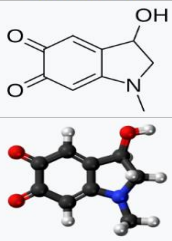


Julie Brown, the fearless female journalist who brought the Epstein file to the world



What Adrenochrome Really Is

At its core, **adrenochrome** is a *real chemical compound* formed by the **oxidation of adrenaline (epinephrine)**, a hormone your body produces during stress or excitement. The name comes from “adrenaline” + the suffix “-chrome” referring to its color. In pure form, adrenochrome appears reddish and is **chemically unstable**, breaking down quickly in solution. Adrenochrome has been studied in biochemical contexts and can be synthesized easily in laboratories through simple oxidation reactions. It is not controlled or rare, and laboratory-made adrenochrome is commercially available for research purposes.

Adrenochrome	
	Names
	IUPAC name 3-Hydroxy-1-methyl-2,3-dihydro-1H-indole-5,6-dione Other names Adraxone; Pink adrenaline
Properties	
Chemical formula	C ₉ H ₉ NO ₃
Molar mass	179.175 g·mol ⁻¹
Appearance	deep-violet ^[1]
Density	3.785 g/cm ³
Boiling point	115–120 °C (239–248 °F; 388–393 K) (decomposes)

Historical & Scientific Context

In the **1950s and 1960s**, some psychiatrists like Abram Hoffer and Humphry Osmond speculated that adrenochrome might be linked to schizophrenia and brain chemistry. They suggested large doses of vitamins could counteract its effects, but this idea **was never validated and was eventually discarded** by mainstream medicine.

The only stable derivative of adrenochrome that ever saw niche medical use is **carbazochrome**, which has been explored as a **hemorrhage-controlling agent**, though its effectiveness remains inconclusive.

Scientifically, *adrenochrome has no established role in anti-aging, longevity science, or human enhancement*. Real aging research today focuses on molecular pathways like **cellular senescence, DNA repair, and metabolic regulation**, not on compounds like adrenochrome.

Origins of the Myth

The idea that adrenochrome is a **secret youth elixir** or *hallucinogenic drug harvested from humans* originates not from science, but from **literature and pop culture**:

- **Aldous Huxley's *The Doors of Perception* (1954)** mentioned adrenochrome analytically in discussions about altered consciousness.
- **Hunter S. Thompson's *Fear and Loathing in Las Vegas* (1971)** exaggerated the substance in a fictionalized drug narrative, claiming it was extracted from living people - a detail the author later indicated was purely fanciful.

These fictional portrayals were **never scientific claims**, yet they were later taken literally by online communities and conspiracy theorists.

Modern Conspiracy Theories & Misinformation

In the 2010s and 2020s, fringe movements like **QAnon** and themes from the **Pizzagate** conspiracy began circulating the claim that *elites harvest adrenochrome from children to remain youthful or gain special powers*. These stories often draw on age-old fears like *blood-libel myths* and sensational narratives about secret cabals.

However:

- There is **no credible evidence** that adrenochrome is harvested from human subjects, willingly or not.
- No verified biological mechanism supports its use as a *rejuvenation* or *anti-aging* agent.
- The compound's instability and ease of *laboratory synthesis* contradict claims that it must come from rare or violent sources.

In fact, experts have repeatedly stated that these conspiracy narratives are **misinformation**, merging fictional storytelling with modern political and cultural anxieties.

Why the Myth Persists

Conspiracy theories around adrenochrome combine:

- **Fictional and dramatic portrayals** from literature and film.
- **Online amplification** via social networks, message boards, and fringe forums.
- **Symbolic associations** with fear, youth, and power.

These elements make the story compelling - but not factual.

It's important to distinguish **cultural mythology** from **scientific fact**: adrenochrome is a simple chemical with no proven role in anti-aging or secret human-harvesting practices.

Conspiracy theories

Adrenochrome is the subject of several conspiracy theories, including QAnon and Pizzagate, in which the chemical plays a similar role to Satanic ritual abuse stories.^[22]

Fear and adrenochrome

The conspiracy theory right is addicted to crazy ideas about a drug

'Adrenochrome is a drug that the elites love,' says gossip columnist-turned-conspiracy-theorist Liz Crokin. 'It comes from children. The drug is extracted from the pituitary glands of tortured children. It's sold on the black market. It's the drug of the elites. It is their favorite drug. It is beyond evil. It is demonic. It is so sick.'

When I read this, I wondered where I had heard of adrenochrome before. Of course - *Fear and Loathing in Las Vegas*, when Hunter S. Thompson is given a taste of the drug by his half-mad attorney:

"Where'd you get this?" I asked. "You can't buy it." "Never mind," he said. "It's absolutely pure." I shook my head sadly. "What kind of monster client have you picked up this time? There's only one source for this stuff." He nodded. "The adrenaline glands of a living human body," I said. "It's no good if you get it out of a corpse."

This passage bubbled beneath the surface of American popular culture for decades. In 2009, Mark Dice, who is Alex Jones without the charm, referred to it in *The Illuminati: Facts & Fiction*, which implied that Thompson was some kind of Satanist pedophile. Adrenochrome also featured in the bizarre *Matrix* series - the esoteric books, not the films starring Keanu Reeves - as the preferred snack of extraterrestrials.

In 2018, rumors spread online that a video was circulating on the dark web showing Hillary Clinton and her staffer Huma Abedin mutilating a girl in order to harvest adrenochrome from her terrified body. No such video ever came to light, of course, but a meme had taken hold. Remember Pizzagate? Fervid elements of Donald Trump's base convinced themselves that leaked emails between Democratic operatives contained some kind of

code for the operations of an elite child-abuse ring centered on a DC pizza restaurant. The idea convinced one man to fire a gun in the restaurant and another to attempt to burn it down.

These fringe Trumpers have convinced themselves that the President is fighting an elite cabal of pedophiles and the 'deep state' apparatus that protects them. A purported insider named 'Q' has left cryptic posts on the message board Chan that detail Trump's alleged plans for an event called 'the Storm' in which hundreds of his depraved opponents will be arrested. Somehow President Trump has never got around to doing this after more than three years in office.

The epithet 'the Storm' is derived from the time Trump informed the White House press pool in 2017 that he was 'the calm before the storm'. The statement baffled journalists at the time, though Trump later expanded by saying 'I am the storm.' I think the simplest explanation is that he was running his mouth, not dropping occult references to some kind of millenarian apocalypse.

We must remember that secretive elite sex criminals do exist. There was Jeffrey Epstein and his international exploitative enterprises. There was Ed Buck, the wealthy Democrat donor, with his bizarre fondness for injecting black men with crystal meth. There were the Hollywood pedos exposed in the film *An Open Secret*. There were depraved men as diverse as Michael Jackson and Marcial Maciel, the Mexican priest who founded the Legion of Christ.

So there is nothing wrong with theorizing about elite sex criminals *per se*. But theories about elite sex criminality tend to inflate its scale and organization while defying epistemic standards. For example, when celebrities started being diagnosed with coronavirus, a reasonable person might have concluded that this was predictable: they do a lot of traveling and hand-shaking and have above-average access to testing. Not the QAnon crowd, though. They thought quarantined celebrities were being secretly arrested. Their excitement was dampened when Tom Hanks left his quarantine in Australia and returned to LA, but they soon devised a theory that the pilots of his plane were actually federal agents.

The role of adrenochrome in recent events is harder to fathom. Ms Crokin modishly suggests that pro-Trump patriots have 'tainted the adrenochrome supply with the coronavirus'. Tommy G, the QAnon-supporting, Twitter blue-tick- sporting host of the *No Mercy Podcast*, posits that drug-crazed celebrities are 'running out' of adrenochrome. A depleted adrenochrome stash, Mr G suspects, might explain why Madonna has been making weird videos about roses and fried fish. The diminishing number of rational observers, I think, assume it is because Madonna is an attention-starved eccentric with no taste.

QAnoners are also big fans of comparing flattering and unflattering photos of celebrities. This is supposed to illustrate the devastating effects of adrenochrome withdrawal, but instead it illustrates the aging process and the possibility that people look different without make-up and an expensive hairdo.

The broader adrenochrome theory is based on two strange ideas. One, which is ubiquitous in QAnon circles, is that 800,000 kids go missing every year in the US. This is true but misleading. More than 99 percent of these children are reported missing but found. Of course, even one permanent disappearance is a tragedy. But this is not quite the startling statistic the QAnon crowd imagines.

The idea of extracting adrenochrome from a living body comes not from science or history but, as mentioned before, from Hunter S. Thompson. Given that Thompson created the literary form 'gonzo journalism', which explicitly prioritizes atmosphere and emotion over facts, trying to do this seems inadvisable. In fact, just as you can create testosterone without extracting it from the testicles or ovaries, you can synthesize adrenochrome in a lab.

Opinions are mixed on its psychoactive properties. In the 1960s, Abram Hoffer suggested that adrenochrome was a neurotoxic and might account for schizophrenia. True or not, I am not sure that a drug which makes you feel 'changes in thinking...similar to those observed in schizophrenia' would be such an attractive one, especially among people whose drug of choice is generally cocaine. I wanted to try it out myself, of course, but ran into objections from *The Spectator's* lawyers and accountants.

Adrenochrome fascinates the QAnoners less as a drug than for its role in ritual: drug-crazed Luciferian elites sacrificing young children on an altar. Any aspect of this nightmare would be horrifying, but never so memorably

as when child abuse, drugs, Satanism and secret societies are mixed together. In this aspect, the fantasies of QAnon are little more than an online echo of the Sixties counterculture at its most depraved.

The idea of Satanic ritual abuse, a bundling of everything awful in the psychological shadows, is not new. Tearing like wildfire through the 1980s, it led to appalling miscarriages of justice like the McMartin preschool case, in which the hapless owners and employees of a daycare center in Manhattan Beach, California, were accused of being depraved Aleister Crowley-like abusers. Satanic ritual abuse does occur - in 2010, a cult was discovered in Kidwelly, Wales, for example. But the imaginative power of the concept leads to exaggerated claims of its practice. And we might wonder whether the proliferation of false claims gives the actual practitioners a script for their depravities.

Americans are especially attracted to conspiracy theories. The ideas in Richard Hofstadter's 1964 essay 'The Paranoid Style in American Politics' are widespread, but it is longer on examples than explanation. Feeling robbed of an Edenic home by a dark conspiracy might be more attractive to a nation young enough to be that idealistic, and whose origins included fantasies of malign 'arbitrary power' and 'Popery'.

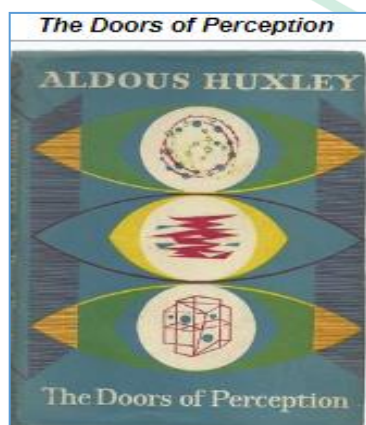
The presidency of Donald Trump has added a radical edge to the QAnoners. This is not due to extremism in his administration's actions - but because of their moderation. He egged on chants of 'lock her up', but Hillary Clinton is still on Twitter insulting his policies. He encouraged 'build that wall' but the wall does not exist. A truly radical administration would contain radical followers. The increasingly dramatic and esoteric fantasies of Trump's militant fringe are an attempt to rationalize the mundane reality.

I would like to suggest that there is hope for people who think Donald Trump has arrested Tom Hanks on charges of torturing children to harvest adrenochrome, but there is not. Their passions are so intense and their beliefs so elastic that if each claim were patiently disproven, they would twist the rest into newly preposterous shapes. The way to stop people from sliding down the long slope to fantasy is to teach them how to evaluate fact claims, to educate them about historical contexts, and also to encourage a vital sense of comic absurdity.

The theories commonly state that a cabal of theistic Satanists rape and murder children, and harvest adrenochrome from their victims' blood as a recreational drug or as an elixir of youth, similar to children's blood infusions. In reality, adrenochrome has been produced by organic synthesis since at least 1952, is synthesized for research purposes by biotechnology companies, who will then sell it to anyone; as it is not a controlled substance, any medical or recreational use of the chemical is effortless to access.

In popular culture

- In his 1954 book *The Doors of Perception*, Aldous Huxley mentioned the discovery and the alleged effects of adrenochrome, which he likened to the symptoms of mescaline intoxication, although he had never consumed it.



First edition, published in 1954

Author Aldous Huxley

Language English **Subject** Philosophy. Psychology

Published 1954 Chatto & Windus (UK), Harper & Row (US)

Publication place UK

Media Type Print (hardback & paperback)

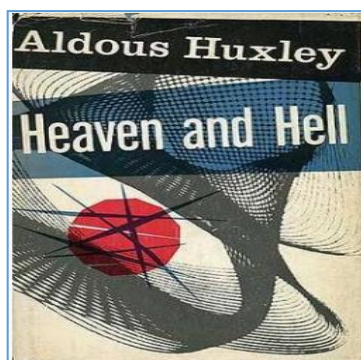
Pages 63 (hardcover, first edition; without the accompanying 1956 essay *Heaven and Hell*)

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First US edition

Author Aldous Huxley

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Harper & Brothers (US)

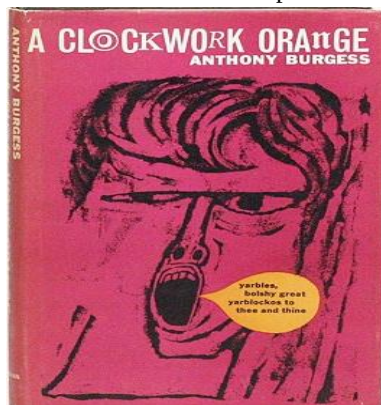
Publication date 1956

Publication place United Kingdom

Media type Print (Hardback & Paperback)

Pages 126

- Anthony Burgess mentions adrenochrome as "drencrom" at the beginning of his 1962 novel *A Clockwork Orange*. The protagonist and his friends are drinking drug-laced milk: "They had no license for selling liquor, but there was no law yet against prodding some of the new veshches which they used to put into the old moloko, so you could peet it with vellocet or synthemesc or drenchrom or one or two other veshches. This book is based on the three pillars such as, nihilism, anarchy, and moral philosophy.



First US edition

Author Anthony Burgess

Language English

Subject Philosophy

Publisher Chatto & Windus (UK)

Harper & Brothers (US)

Publication date 1962

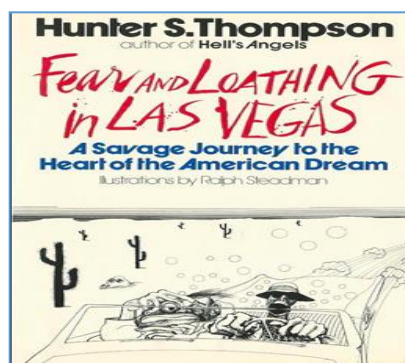
Publication place United Kingdom

Media type Print (Hardback & Paperback)

Pages 192 & 176

ISBN 978-0-434-09800-2

- Hunter S. Thompson mentioned adrenochrome in his 1971 book *Fear and Loathing in Las Vegas*.^[30] This is the likely origin of current myths surrounding this compound, because a character states that "There's only one source for this stuff ... the adrenaline glands from a living human body. It's no good if you get it out of a corpse." The adrenochrome scene also appears in the novel's film adaptation.^[29] In the DVD commentary, director Terry Gilliam admits that his and Thompson's portrayal is a fictional exaggeration. Gilliam insists that the drug is entirely fictional and seems unaware of the existence of a substance with the same name. Hunter S. Thompson also mentions adrenochrome in his book *Fear and Loathing on the Campaign Trail '72*. In the footnotes in chapter April, page 140, he says: "It was sometime after midnight in a ratty hotel room and my memory of the conversation is hazy, due to massive ingestion of booze, fatback, and forty cc's of adrenochrome."



First US edition

Author Hunter S. Thompson

Language English

Subject Philosophy

Publisher Random House

Publication date 1971

Publication place US

Media type Print (Hardback & Paperback)

Pages 204

ISBN 0-679-78589-2

- In 2025, electronic music producer Juelz released an EP titled *ADRENOCHROME*.

In Summary

Adrenochrome:

- ✓ A real chemical compound produced by oxidation of adrenaline.
- ✓ Found in small amounts in the body and synthesized in labs.

Not an anti-aging drug or longevity serum.

- Not harvested from humans for mystical effects.
- Not supported by credible scientific evidence outside of basic biochemical research.

Disclaimer: The magazine does not assume responsibility for the opinions expressed by authors in their articles.



Organic Farming as a Tool to Restore Dead Soils: Restoring soil health through ecological practices backed by science



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ABSTRACT:

Soil degradation is also called as dead soils results from overuse of chemical inputs, erosion and loss of biological activity threatening agricultural productivity and ecosystem services .it is more recognized as a sustainable alternative to conventional farming because of its positive effects on soil health and ecosystem services. This is used in natural and ecological management practices to improve soil quality and long term productivity. Evidence from long-term field experiments, meta-analyses and studies shows that organic farming soil physical, chemical and biological properties. Physically organic soils have better structure, higher aggregate stability, lower concentration and improved water infiltration. chemically organic practices increase soil organic matter, maintain balanced soil pH and enhance nutrient availability through compost application and biologically, organic farming supports greater microbial biomass, enzyme activity and soil organism diversity which are needed for nutrient cycling, carbon sequestration and natural pest control.

These improvements in soil health contribute to important ecosystem services such as sustainable food production, climate regulation, water purification and biodiversity conservation even organic farming generally produces yields that are about 10 – 20% lower than conventional systems these yields gaps often offset by improved energy efficiency, reduced environmental impacts and enhanced long term soil fertility. However, challenges such as yield variability, certification requirements and region-specific performance limitation remain, overall scientific evidence indicates that organic agriculture has strong potential to restore degraded soils and support resilient, climate- smart food systems when combined with long-term research, appropriate technologies and supportive policies.

KEYWORDS: Organic farming, soil health, ecosystem services, carbon sequestration, biodiversity, sustainability.

INTRODUCTION:

Soil is a living ecosystem essential for food production water regulation and climate stability. Intensive farming has degraded soils globally, reducing organic carbon disrupting soil structure and diminishing biological activity. practices such as composting, crop rotation, green manures and reduced tillage aim to mimic natural ecosystems, fostering soil restoration and sustainability.

Why Organic Farming Is Needed for Dead Soils

1. Soil Degradation Is Widespread

- Agriculture soils currently facing declines in organic carbon and fertility due to conventional farming practices and erosion worldwide.
- Degrading soils lose water-holding capacity and biological function, making them less productive and more vulnerable to drought and flood.



2. Chemical Inputs Can Harm Soil Biology

- Usage of fertilizers and pesticides can reduce soil microbial diversity and degrade the soil structure.

3. Organic Farming Builds Long-Term Soil Health

Focuses on ecological processes that :

- Increase soil organic matter
- Enhances nutrient cycling
- Promote microbial diversity
- Improve physical soil structure
- These elements are crucial to reversing soil degradation and restoring productivity.

How Organic Farming Restores Dead Soils

1. Increasing Soil Organic Matter (SOM):

This meta- analysis studied how best management practices (BMPs) improve soil health in organic farming systems. Practices such as organic amendments, conservation tillage and cover cropping were evaluated using soil organic carbon (SOC) and microbial biomass carbon (MBC) as indicators. Overall, BMPs increased SOC by 18% and MBC by 30% compared to organic systems without these practices . Organic amendments and conservation tillage showed clear benefits, while cover cropping improved SOC only after long-term use. The results show long-term adoption of BMPs is essential for improving soil health and achieving sustainable organic farming.

2. Boosting Microbial Diversity And Activity:

Organic farming is sustainable approach to meet food production challenges caused by population growth and climate change. It relies on natural soil processes, especially soil microorganisms, to support nutrient cycling and plant health. a global meta-analysis of 56 studies showed that organic farming systems had 32-84% higher soil microbial biomass and enzyme activity than conventional systems. practices such as crop rotation, legumes and organic inputs played a key role in improving soil microbial health. Overall, organic farming enhances soil biological activity and supports healthier, more resilient soils worldwide.

3. Improving Soil Chemical and Physical Properties:

Organic soil exhibits :

- Higher nutrient content
- pH balance
- greater aggregate stability
- enhanced water infiltration

4. Reinforcing Resilient Soil Ecosystems:

Long-time scales, organic farming fosters complex microbial networks and soil food webs that stabilize soil functions, making degraded soils more resilient to environmental stress

CONCLUSION:

Organic farming is a viable tool to restore dead or degraded soils, supported by robust scientific research. by enhancing organic matter, boosting soil microbial life and improving physical and chemical soil properties, organic systems rebuild soil fertility and ecological function over time. While transition to organic agriculture requires investment and adaption, its long-term benefits for soil health, productivity and environmental sustainability are increasingly evident in scientific literature.

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Response of Cauliflower to Different Microbial Inoculants under Field Conditions



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Abstract

Cauliflower is an important vegetable crop for both family nutrition and farm income, especially in intensive vegetable-growing areas. At the same time, repeated cropping and heavy chemical use have raised concerns about soil health, input costs, and long-term sustainability. This article discusses how microbial inoculants can support more balanced and resilient cauliflower production under field conditions. These eco-friendly products contain beneficial fungi or bacteria that help plants develop stronger roots, use nutrients more efficiently, and maintain better overall growth. Commonly used microbial inoculants, such as *Trichoderma*, *Bacillus*, and *Pseudomonas*, are highlighted for their roles in improving plant vigour, supporting soil life, and contributing to healthier cauliflower crops. The focus is on practical field experiences and simple recommendations that farmers and extension workers can apply in their own situations. The article encourages the thoughtful use of microbial inoculants as part of an integrated, sustainable approach to cauliflower cultivation.

Keywords: cauliflower, microbial inoculants, *Trichoderma*, *Bacillus*, *Pseudomonas*

Introduction

Cauliflower is widely grown and profitable in India, valued for its nutritional value and its contribution to farm income. Despite its importance, farmers increasingly face challenges such as declining soil health, rising fertiliser and pesticide costs, and persistent soil-borne diseases. To sustain yields under these pressures, heavy reliance on chemical inputs has become common. While effective in the short term, this practice often leads to nutrient imbalances, reduced soil fertility, and environmental degradation, ultimately compromising long-term productivity.

In this context, microbial inoculants are emerging as sustainable alternatives in cauliflower-based production systems. Beneficial microbes improve nutrient availability, suppress soil-borne pathogens, and enhance overall soil health, thereby reducing dependence on chemical fertilisers and pesticides (Kumar et al., 2021; Li et al., 2022). This article examines the field-level effects of microbial inoculants, including *Trichoderma*, *Bacillus*, and *Pseudomonas*, on cauliflower growth, yield, and overall performance under practical farming conditions.

What Are Microbial Inoculants?

Healthy soils are living systems, rich in microscopic organisms that interact closely with plant roots. Among these are beneficial microbes that support plant growth and help protect roots from disease. Microbial inoculants are formulations of selected fungi or bacteria applied to seeds, seedlings, or soil to improve crop performance and plant health.

Unlike chemical fertilisers that supply nutrients directly, microbial inoculants act through biological processes. They improve the availability of soil nutrients and promote stronger root development, allowing plants to use water and nutrients more efficiently. In simple terms, they function as natural “farm helpers” within the soil.

With continued use, microbial inoculants help maintain soil fertility, reduce dependence on chemical inputs, and support more sustainable farming practices. As a result, microbes such as *Trichoderma*, *Bacillus*, and *Pseudomonas* are increasingly used in vegetable crops, including cauliflower, where they improve yield, enhance soil health, and reduce disease pressure (Kumar et al., 2021; Poveda & Eugui, 2022).

Role of Microbial Inoculants in Cauliflower Cultivation

Microbial inoculants play an important role in supporting cauliflower growth from the early seedling stage through curd formation. When applied at planting or during transplanting, these beneficial microbes help seedlings establish more quickly by improving root development and protecting young roots from soil-related stress. A well-developed root system enables plants to absorb water and nutrients more efficiently, giving the crop a healthier start in the field.

As the crop grows, microbial inoculants continue to improve nutrient availability, particularly nitrogen and phosphorus, in the root zone. Rather than supplying nutrients directly, they mobilise and release nutrients already present in the soil, allowing cauliflower plants to use applied fertilisers more efficiently and reducing nutrient losses (Kumar et al., 2021). Active microbial populations around the roots also contribute to better soil structure by increasing porosity and moisture retention, which is particularly beneficial in sandy or intensively cultivated soils (Sarkar et al., 2020). The association of beneficial microorganisms with the cauliflower root zone and their functional roles are illustrated in Figure 1.

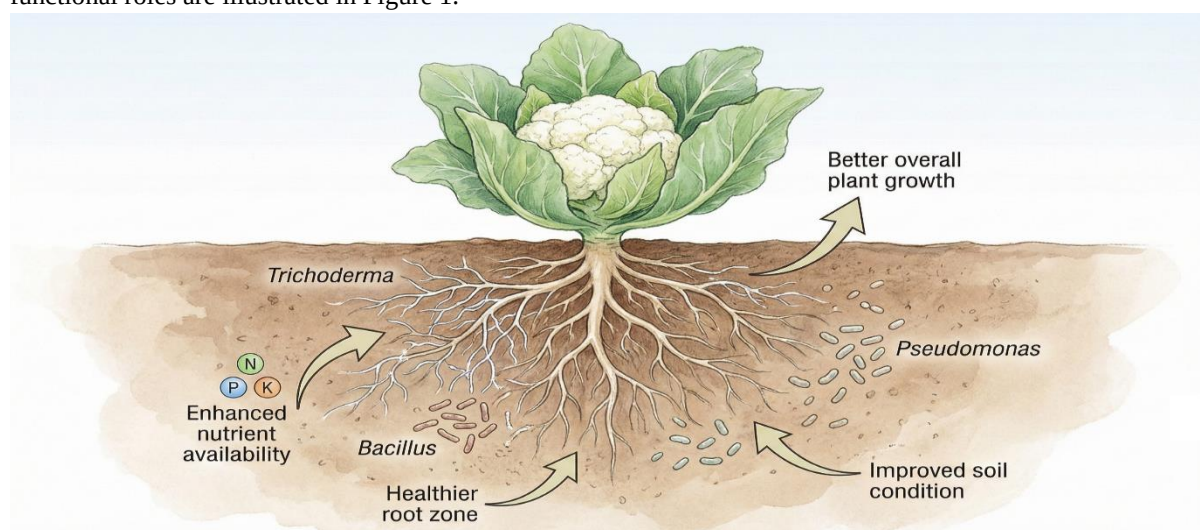


Figure 1. Conceptual diagram illustrating the association of beneficial microorganisms such as *Trichoderma*, *Bacillus*, and *Pseudomonas* with the cauliflower root zone.

In addition to improving nutrition, microbial inoculants help maintain a healthy balance of soil organisms. This balanced microbial environment limits the buildup of harmful pathogens and supports the development of more vigorous, disease-tolerant cauliflower plants. Healthier crops are better able to cope with environmental stress and produce firm, well-sized curds (Poveda & Eugui, 2022; Choudhary et al., 2019).

For best results, microbial inoculants should be used alongside recommended cultivation practices such as proper fertilisation, irrigation, and crop rotation. They are not substitutes for good farm management but act as supportive partners that enhance the efficiency of other inputs.

Today, an increasing number of farmers are adopting microbial inoculants as a natural and straightforward approach to improving cauliflower production. By strengthening soil fertility, supporting healthy root systems, and promoting stable yields, these products are becoming an important component of sustainable and eco-friendly vegetable farming systems (Li et al., 2022).

Major Microbial Inoculants Used in Cauliflower Fields

Trichoderma

Trichoderma is a beneficial fungus commonly present in agricultural soils and widely used in cauliflower nurseries and main fields. It colonises the root zone rapidly and helps young plants establish well after transplanting. Farmers usually apply *Trichoderma* through nursery bed treatment, seedling root dip, or soil application mixed with well-decomposed farmyard manure.

In cauliflower, *Trichoderma* is valued for improving root health and early crop establishment under field conditions. Treated fields often show stronger root systems, better plant stand, and fewer problems related to poor

soil conditions. Its ability to suppress soil-borne pathogens in the root zone helps reduce plant stress, supporting uniform growth and curd development. With repeated use, *Trichoderma* also contributes to a more active and balanced soil microbial environment in intensive vegetable systems (Choudhary et al., 2019; Poveda & Eugui, 2022).

Bacillus

Bacillus is a genus of beneficial bacteria well known for their ability to survive under varying field conditions, making them popular biofertilizers for vegetable crops. These bacteria colonise the rhizosphere and help release nutrients already present in the soil, improving their availability to cauliflower plants. Farmers commonly apply *Bacillus* through soil application mixed with compost or farmyard manure, or by treating seedlings before transplanting.

Under field conditions, *Bacillus* supports vigorous vegetative growth by enhancing nutrient availability and improving fertiliser-use efficiency. This results in sturdy plants with healthy foliage, which is essential for supporting curd formation later. *Bacillus*-based inoculants integrate easily with regular fertiliser schedules and fit well within recommended nutrient and water management practices (Kumar et al., 2021; Li et al., 2022).

Pseudomonas

Pseudomonas is a beneficial bacterium known for its active growth around plant roots and its role in promoting plant vigour and stress tolerance. In cauliflower fields, it supports healthy root activity and helps maintain balanced microbial populations in the soil. Farmers generally apply *Pseudomonas* as a nursery treatment, a seedling root dip, or a soil application, along with organic manures.

Proper use of *Pseudomonas* can lead to better root function, greener plants, and improved recovery from environmental stress. Fields with regular application often show healthier cauliflower crops that progress smoothly towards curd formation. Its role in maintaining a diverse and competitive rhizosphere also helps keep disease pressure under check, particularly under continuous vegetable cultivation (Poveda & Eugui, 2022; Sarkar et al., 2020).

No single microbial inoculant can address all challenges in cauliflower cultivation, and their performance depends heavily on sound agronomic practices, such as balanced fertilisation, proper irrigation, and timely intercultural operations. Even so, the increasing use of *Trichoderma*, *Bacillus*, and *Pseudomonas* reflects their growing importance as key components of integrated and sustainable cauliflower production systems under field conditions.

Field-Level Response of Cauliflower to Microbial Inoculants

Field observations show that cauliflower responds well under practical conditions when microbial inoculants are used as part of the cultivation package. Farmers commonly report faster seedling establishment, reduced transplant shock, and a more uniform crop stand. During early growth, plants in inoculated fields generally appear sturdier than those in uninoculated plots.

As the crop develops, inoculated fields often exhibit stronger root systems and more active root zones, along with better leaf development and healthier green foliage. This growth response is usually linked to improved nutrient use and a more favourable soil environment around the roots. In many cases, soils remain more friable and easier to manage, supporting timely intercultural operations (Kumar et al., 2021; Sarkar et al., 2020).

During curd formation, microbial inoculants are frequently associated with better crop vigour, more uniform curd development, and even maturity, which helps in harvest and marketing planning. A higher proportion of marketable heads with well-filled, compact curds is commonly reported in inoculated plots compared with uninoculated fields (Li et al., 2022; Munish Sharma & Suryavanshi, 2020). These effects are summarised in Table 1, while visual differences between treatments are shown in Figure 2.

In terms of plant health, inoculated crops generally show greater resilience under field conditions, with healthier root systems and improved tolerance to routine stresses such as minor soil constraints or short dry spells. Although disease pressure may still occur, many growers observe quicker recovery and longer maintenance of active growth (Poveda & Eugui, 2022).

At the same time, responses vary with soil type, climate, and management. Microbial inoculants support crop performance but do not replace good agronomic practices. When combined with balanced fertilisation,

proper irrigation, and timely crop care, they contribute to healthier, more uniform crops and help stabilise cauliflower yields under field conditions (Li et al., 2022).

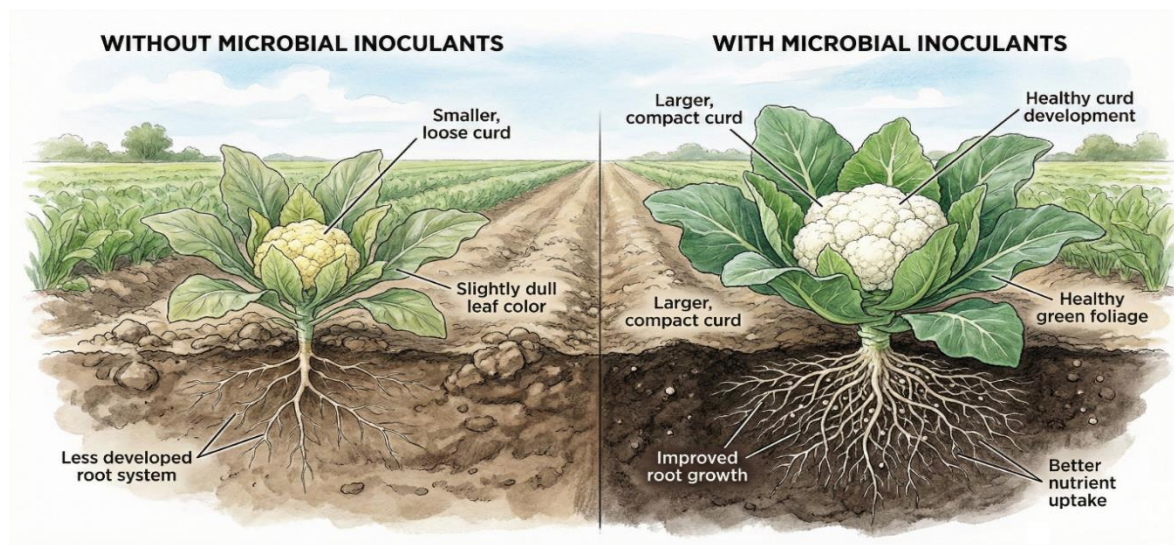


Figure 2. Comparative illustration showing the general differences in plant growth, root development, and curd formation in cauliflower grown with and without microbial inoculants under field conditions.

Table 1. General response of cauliflower to different microbial inoculants under field conditions

Microbial inoculant	Major role in soil–plant system	Visible field response in cauliflower
<i>Trichoderma</i> spp.	Root colonization, disease suppression	Vigorous root system, healthier plants
<i>Bacillus</i> spp.	Nutrient solubilization, growth promotion	Improved vegetative growth, uniform curds
<i>Pseudomonas</i> spp.	Stress tolerance, plant protection	Better plant vigor and reduced disease symptoms

Practical Considerations for Farmers

When using microbial inoculants, farmers should treat them as careful investments rather than quick-fix products. Since these inputs contain living organisms, they require more attention than most chemical fertilizers or pesticides.

Products should be purchased from reliable or government-approved sources, with close attention to manufacturing and expiry dates. Packets that are wet, caked, or damaged should be avoided. Proper storage in a cool, shaded place away from direct sunlight and heat is essential, and opened packets should not be stored for long.

The application should follow the crop stage and method recommended on the label or by extension workers. Standard practices include seed treatment, root dip of seedlings, and soil application mixed with compost or farmyard manure. Correct timing helps ensure that microbes reach the active root zone. Care is needed when using microbial inoculants alongside fertilisers and pesticides, as potent pesticides or highly saline fertilisers can reduce their effectiveness (Sarkar et al., 2020).

Overuse should be avoided, as higher doses do not guarantee better results and only increase costs. Microbial inoculants support crop growth and soil health but cannot compensate for poor land preparation, imbalanced fertilisation, inadequate irrigation, or weak pest management (Kumar et al., 2021). A gradual introduction, combined with field observations and guidance from extension workers, helps farmers effectively integrate these products under local conditions (Li et al., 2022).

Conclusion

Microbial inoculants provide cauliflower growers with a practical way to enhance plant vigour, root development, and nutrient use under field conditions. When applied correctly, they support better crop establishment, sustained

vegetative growth, and the formation of healthier, more uniform curds. Inoculants based on *Trichoderma*, *Bacillus*, and *Pseudomonas* are increasingly used as complementary inputs in cauliflower production. They function alongside fertilisers, irrigation, and sound agronomic practices, rather than replacing chemical inputs. In intensive vegetable systems, where repeated cropping puts pressure on soil quality, these inoculants improve soil biological activity, long-term soil health, and more resilient, sustainable cauliflower production.

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Seaweeds: Emerging Sources of Bioactive Metabolites



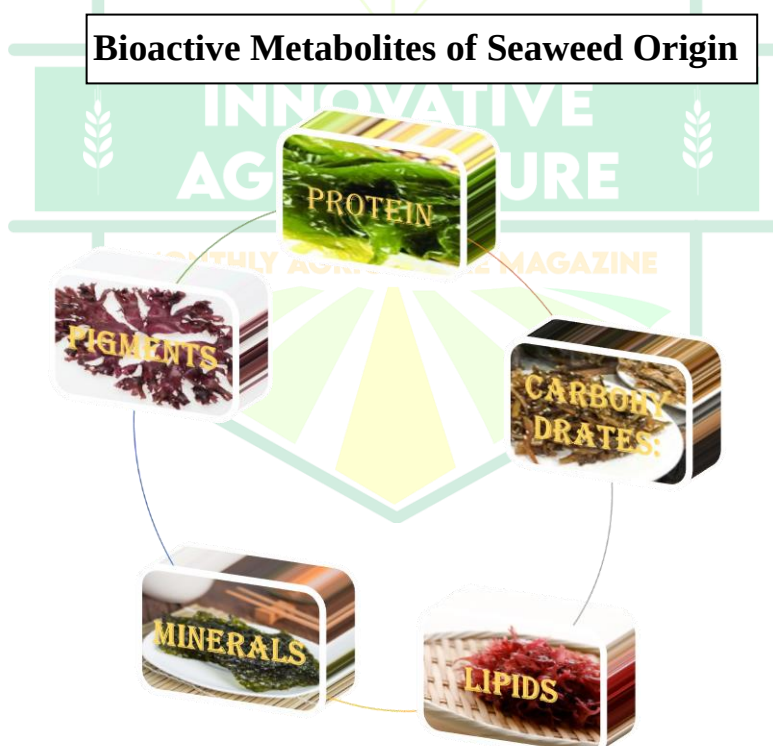
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Introduction

Seaweeds, also known as marine macroalgae, are multicellular, photosynthetic eukaryotic organisms with Chlorophyll a. They can be found in the intertidal zone up to 300 m deep (Levine 2016). Seaweeds are categorised into three phyla based on pigment composition: Chlorophyceae (green), Rhodophyceae (red), and Phaeophyceae (brown) (El-Beltagi et al. 2022). According to the FAO (2024), seaweed production reached 36.5 million metric tons in 2022, accounting for 28% of the global aquaculture total. The trend of eating seaweed-based food has increased as scientific reports have confirmed the antioxidant, antimicrobial and antiviral effects of seaweed metabolites (Lomartire and Goncalves, 2022). According to Ehrlich and Harte (2015), the global population is expected to reach over 10 billion by 2050, up from 7.3 billion currently. Food insecurity will become a critical issue due to this notable increase in food production demand.



Bioactive Metabolites of Seaweed Origin

Proteins:

Proteins are long chains of amino acids linked together by peptide bonds. The protein composition and content of marine algae vary by species, season, and environment (Pangestuti and Kim, 2015). The nutritional content of seaweed proteins varies with geographical location and environmental circumstances (Kadam et al. 2017). Brown seaweeds are frequently reported to contain the least protein, although green seaweeds have moderate protein

concentrations and red seaweeds have a highest protein (Ganesan et al. 2019). According to Murata and Nakazoe (2001), red seaweed has the highest protein content (30–40% of dry matter), comparable to legumes, while brown and green seaweeds have only 15% and 30%, respectively. The nutritional value of protein depends on two factors: protein digestibility and amino acid composition (Tabarsa et al. 2012). The majority of seaweeds are a great addition to the diet because of their high quantities of glycine, arginine, glutamic acid, and alanine, all of which are vital for human health (Aguilera-Morales et al. 2005).

Carbohydrates:

Seaweed comprises a significant quantity of carbohydrates in the form of structural, storage, and functional polysaccharides, with total carbohydrate content varying from 20% to 76% of dry weight, depending on the species (Holdt and Kraan, 2011). Seaweeds are considered a source of novel types of polysaccharides having numerous potential applications (Tanna and Mishra, 2019). Seaweeds are the most abundant source of polysaccharides, such as alginate, agar, fucoidan, agarose and carrageenan (Laurienzo 2010). Several significant commercial uses for polysaccharides include thickeners, stabilisers, food, drinks, feed and emulsifiers (Tseng, 2001).

Lipids:

Lipids are composed of fatty acids that include saturated, monounsaturated, and polyunsaturated fats (Misurcova et al. 2011). Seaweeds contain low concentrations of lipids, about 2–10% of their dry weight. Seaweed's lipid composition includes several types of polyunsaturated fatty acids (PUFAs) with established health advantages, including linoleic, lauric, linolenic, stearic, and docosahexaenoic (DHA) acids (Kendel et al. 2015). Essential fatty acids are being identified as functional foods and nutraceuticals with numerous health advantages, including lowering the risk of diabetes, cancer, cardiovascular disease, and osteoporosis (Tanna et al. 2018).

Vitamins:

All essential and non-essential vitamins are abundant in seaweeds (Ganesan et al., 2019). Some seaweeds contain vitamins with several health benefits and antioxidant activity, which lower a number of health conditions like high blood pressure, heart problems and cancer risk (Gupta et al. 2020). Various seaweeds, including *Crassiphycus changii* (formerly *Gracilaria changii*), *Porphyra umbilicalis* (Rhodophyta) and *Himanthalia elongata* (Ochrophyta, Phaeophyceae), have a higher vitamin content than terrestrial vegetables (Ganesan et al., 2019). Seaweeds rich in vitamins (A, B, C, D, and E) are extensively used for skincare (Jesumani et al. 2019).

Minerals:

Seaweeds have elevated levels of a diverse array of minerals due to their environment. Many of the essential minerals needed for human health, including potassium, sodium, phosphorus, calcium, iodine, magnesium, iron, and zinc, are available in adequate amounts in seaweeds, making them potentially valuable as health-promoting supplements (Rao et al. 2007). Seaweeds have been found to have a high mineral content, sometimes up to 40% of biomass (Kumar et al. 2011); this occurs because seaweeds take up metal ions from salt water and collect them as carbonate salts in their fronds (Chojnacka et al. 2012).

Pigments:

Natural pigments are lipid-soluble polyenes that are involved in many biological functions and also serve as colourants (Li and Kim, 2011). Seaweeds contain three classes of pigments: chlorophylls, phycobiliproteins and carotenoids (Pereira et al., 2014). Seaweed contains many carotenoids, including fucoxanthin, carotenes, zeaxanthin, lycopene, neoxanthin, lutein, and astaxanthin. Seaweed phycobiliproteins consist primarily of phycoerythrin (red pigment), phycocyanin (blue pigment), and allophycocyanin (light blue pigment) (Aryee et al. 2018). Seaweed chlorophylls are fat-soluble green pigments that serve an important role in photosynthesis (Aryee et al. 2018). These pigments used as food colouring agent, nutraceutical components, and biologically active substances with anti-inflammatory, immunomodulatory, antidiabetic, anticancer, and antioxidant properties (Aryee et al. 2018).

Conclusion:

This review focuses on the bioactive metabolites of seaweeds, which are commonly consumed by humans as condiments and vegetables. The integration of bioactive components from specific seaweeds has the ability to increase the nutritional value of food. According to numerous studies, eating seaweeds offers numerous

advantages, including anticancer, antioxidant, cardioprotective, antibacterial, and anti-inflammatory properties. To analyse their nutritional worth, more research is needed, particularly for biochemical examination utilising contemporary technology and assessment of their bioavailability.

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Heat Stress During Flowering as a Major Cause of Yield Reduction in Vegetable Crops



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Abstract

Heat stress has become a significant constraint to vegetable production under rising global temperatures and frequent heat waves. Among all growth stages, flowering is the most vulnerable because it directly determines pollination success, fruit set, and yield. High temperatures during this phase disrupt pollen development, stigma receptivity, and fertilisation, leading to flower drop, sterility, and poor fruit initiation. Unlike vegetative injury, which plants can often outgrow, reproductive damage at flowering is irreversible, making even short heat spells highly destructive. This article examines the physiological basis of heat-induced yield loss, highlights crop-specific sensitivity, and outlines agronomic and genetic strategies to protect reproductive success. Strengthening heat resilience through targeted breeding and adaptive management is essential for sustaining vegetable yields and food security under a warming climate.

Keywords: Heat stress, Flowering stage, Vegetable crops, Yield loss, Climate change

1. Introduction

In recent decades, rising temperatures and recurrent heat waves have become significant constraints to vegetable production, especially during critical growth phases. Among these, flowering is the most heat-sensitive stage because it determines pollination success, fruit set, and final yield. Even brief exposure to high temperature during flowering can impair pollen viability, stigmatic receptivity, and fertilisation, leading to poor fruit development and severe yield losses in crops such as tomato and chilli (Sato et al., 2006; Rajeswari et al., 2020). Unlike vegetative stages, where plants can partially recover through new growth, damage during flowering is mainly irreversible and directly reduces marketable yield. This vulnerability is exacerbated by changing climatic patterns, particularly in tropical and subtropical regions, where heat events increasingly coincide with reproductive phases (Utobo et al., 2022). As extreme heat episodes become more frequent, understanding how heat stress disrupts reproductive processes during flowering is essential for sustaining vegetable productivity. This article examines the physiological basis of heat stress during flowering and its implications for yield formation, to support the development of practical strategies for resilient vegetable production.

2. Heat Stress in Vegetable Crops: Concept and Thresholds

Heat stress in vegetable crops occurs when ambient temperatures exceed the optimum range required for normal physiological functioning, growth, and reproduction. Each vegetable species has a defined optimum temperature range, beyond which metabolic balance is disturbed, photosynthetic efficiency declines, and reproductive development is impaired. The temperature at which growth or yield begins to decline is called the threshold temperature, while the critical temperature is the point beyond which damage becomes irreversible. These limits vary widely among vegetable crops, reflecting their ecological origin and adaptation. Cool-season vegetables such as cabbage and peas are susceptible to elevated temperatures, whereas warm-season crops like tomato and okra tolerate relatively higher heat before stress symptoms appear.

The severity of heat injury depends not only on temperature intensity but also on its duration and timing. Short heat spells during sensitive stages, particularly flowering and fruit set, can disrupt pollination and sharply reduce yield. Heat stress also rarely occurs in isolation and often coincides with moisture stress or high humidity, further aggravating its impact. A clear understanding of these temperature concepts and their interactions is essential for predicting crop responses under climate warming and for designing management strategies that sustain productivity in vegetable-based systems.

3. Heat Stress Effects on Floral Biology and Reproductive Success

3.1 Heat Stress and Pollen Function

Heat stress during flowering strongly impairs reproductive success in vegetable crops, often leading to poor fruit set and substantial yield reductions. The male reproductive system is susceptible to elevated temperatures. Heat stress disrupts pollen development within the anthers by altering sugar transport, hormonal balance, and cellular differentiation required for normal microsporogenesis. As a result, pollen produced under high temperatures is frequently shrivelled, malformed, or non-viable. Even when viable pollen is formed, its germination on the stigma and subsequent pollen tube growth through the style are often inhibited. High temperatures accelerate pollen dehydration, reduce stigma receptivity, and weaken pollen–stigma interactions, collectively lowering fertilisation efficiency, as demonstrated in crops such as tomato (Sato et al., 2006). Among all developmental stages, flowering shows the highest sensitivity to elevated temperature (Figure 1).

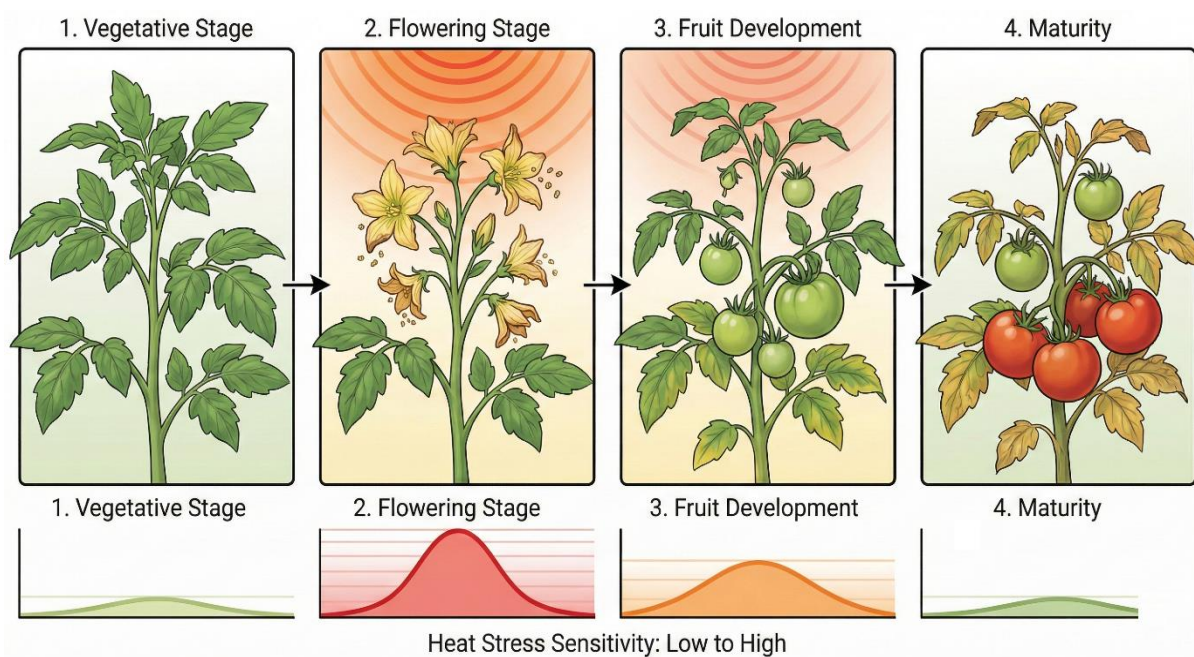


Figure 1. Sensitivity of Vegetable Crop Growth Stages to Heat Stress

3.2 Effects on Female Organs and Fertilisation

Female reproductive structures are also susceptible to temperature extremes. Heat stress shortens stigma receptivity, narrowing the window for successful pollen germination, while ovule viability declines due to disrupted cellular integrity and nutrient flow within the ovary. The combined failure of pollen performance and female reproductive function often results in partial or complete sterility. Heat-induced hormonal imbalance further accelerates flower abscission, a response commonly observed in crops such as tomato and pepper, even when flowers appear morphologically normal (Sato et al., 2006). In many cases, fertilisation fails silently, and embryo abortion follows, leading to a marked reduction in fruit number.

3.3 Irreversibility and Yield Implications

Unlike vegetative tissues, reproductive organs function within a narrow and non-repeatable developmental window. Once pollination or fertilisation is impaired, the resulting damage is irreversible. Yield recovery then depends on the initiation of new flowers, a process that delays harvest and reduces cumulative productivity. Notably, short heat episodes during flowering can cause yield losses comparable to, or greater than, prolonged stress during earlier growth stages, underscoring why flowering is regarded as the most critical phase for yield determination in vegetable crops.

3.4 From Floral Damage to Yield Loss

At harvest, the consequences of floral heat injury become clearly visible. Elevated temperatures reduce fruit set, limit fruit size, and impair seed development, ultimately lowering both yield and market quality. Fruits formed

under heat stress often show poor uniformity and reduced commercial value. Recognizing the cascading effects of reproductive failure on yield loss is essential for guiding breeding and management strategies. Protecting the flowering phase through heat-tolerant genotypes, microclimate modification, and appropriate cultural practices remains central to sustaining vegetable productivity under a warming climate.

4. Yield Reduction During Flowering: Why Losses Are Severe

4.1 Irreversible Nature of Reproductive Damage

Heat stress during flowering causes far greater yield losses than stress during vegetative growth because this stage determines final reproductive success. Flowering involves tightly regulated processes, such as pollination, fertilization, and early embryo development, which operate within a narrow temperature range. When high temperature disrupts these events, the damage is rapid and irreversible. Flowers that abort or fail to set fruit cannot be replaced, and ovules that lose viability do not recover even if temperatures later decline. Unlike vegetative tissues that can regenerate new leaves or branches, reproductive tissues function within a brief developmental window, making yield loss permanent once pollination fails. The sequence by which heat stress during flowering leads to reduced fruit set and yield loss is illustrated in Figure 2.

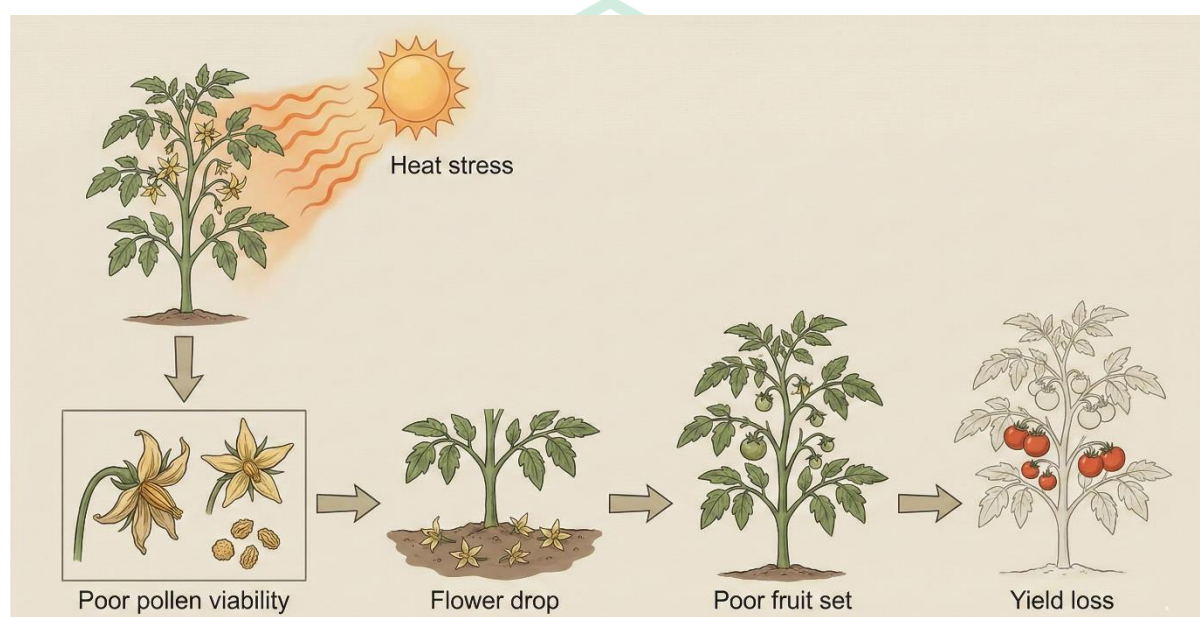


Figure 2. Heat Stress During Flowering and Its Consequences on Yield in Vegetable Crops

4.2 Fewer Fruits, Not Just Smaller Fruits

Heat stress reduces yield primarily by lowering fruit number rather than fruit size, because it directly disrupts flower retention, pollen performance, and fertilisation. Under high temperatures, many flowers either abort prematurely or remain unpollinated, sharply reducing fruit set per plant. Even when vegetative growth and assimilate supply are sufficient, unfertilized flowers cannot develop into fruits. In contrast, heat stress during later stages of fruit development mainly affects fruit size or weight, with relatively little impact on fruit number. Failure to establish fruits at flowering, therefore, causes the most severe and irreversible reduction in yield potential.

4.3 From Flower Drop to Yield and Quality Loss

Poor fruit set, partial fertilisation, and increased flower abortion together lead to substantial yield decline. Fruits that do develop often show poor seed set, uneven filling, deformities, or irregular shapes, all of which lower marketable quality. As a result, even short heat episodes during flowering can cause disproportionate economic losses by reducing both fruit quantity and quality. As summarised in Table 1, yield losses due to heat stress during flowering vary widely among vegetable crops, with fruit vegetables showing particularly high sensitivity. Protecting the reproductive phase from elevated temperature is therefore critical for sustaining productivity and fruit quality under warming climatic conditions.

Table 1. Crop-wise yield loss in vegetable crops due to heat stress during the flowering stage.

Crop	Sensitive Reproductive Stage	Critical Temperature Range (°C)	Reported Yield Loss (%)	Remarks	References
Tomato	Flowering & fruit set	32–38	50–90	Highly sensitive; pollen sterility	Sato et al. (2006)
Chilli	Flowering & pollination	34–40	40–80	Flower drop common	Rajeswari et al. (2020)
Brinjal	Anthesis & fruit set	32–37	30–70	Varietal tolerance varies	Liu et al. (2024)
Okra	Flowering	36–42	20–50	Moderately tolerant	Utobo et al. (2022)
Cowpea	Flowering & pod set	33–39	35–65	Pod abortion prominent	Bijarnia et al. (2024)
Cabbage	Flower initiation	25–32	60–95	Extreme sensitivity	Chen et al. (2022)
Cucumber	Female flower & fruit set	32–38	40–75	Poor fruit set under heat	Hongal et al. (2023)
Bitter gourd	Flowering	35–41	25–55	Heat-adapted but still affected	Agriculture Institute, (2025)

5. Management and Adaptation Strategies to Minimize Yield Loss

5.1 Agronomic and Crop Management Approaches

Minimising yield loss from heat stress during flowering relies largely on practical, field-based interventions that moderate crop microclimate and reduce thermal load. Adjusting sowing or transplanting dates so that flowering avoids the hottest weeks remains one of the simplest and most effective strategies. Soil mulching with crop residues or organic materials helps moderate soil temperature, conserve moisture, and protect the root zone from heat extremes. Protective structures such as shade nets, low tunnels, or polyhouses further reduce exposure to intense radiation and high air temperatures around flowers. Equally important is proper irrigation scheduling; maintaining adequate soil moisture enhances evaporative cooling, sustains plant turgor, and reduces flower drop under combined heat and moisture stress. Together, these agronomic practices reduce heat exposure during flowering and improve fruit set under warm growing conditions.

5.2 Genetic and Breeding-Based Approaches

Long-term resilience to heat stress ultimately depends on genetic improvement and informed varietal selection. Developing vegetable cultivars that maintain pollen viability, stigma receptivity, and stable fruit set under elevated temperatures is critical for sustaining yield under climate warming. Breeding efforts, therefore, need to prioritize screening genotypes for tolerance specifically at the reproductive stage, as this phase most directly determines yield stability. Recent studies across vegetable crops have shown that heat tolerance traits are genetically diverse and can be effectively targeted through focused breeding programs (Chen et al., 2022; Hongal et al., 2023).

An integrated strategy that combines sound agronomic management with genetic tolerance offers the most reliable pathway for stabilising vegetable yields. Continued research on climate-resilient traits, along with the deployment of heat-tolerant cultivars, will be essential to equip farmers to cope with rising temperatures and safeguard vegetable productivity in a warming climate.

6. Heat Stress and Climate Change: Implications for Vegetable Production

6.1 Changing Climate and Rising Heat Stress

Climate change is increasing the frequency, intensity, and unpredictability of high-temperature events across vegetable-growing regions. Heat waves are now more likely to coincide with sensitive developmental stages, particularly flowering, making this phase increasingly vulnerable. As global temperatures continue to rise, heat stress episodes during flowering are expected to become longer and more severe, posing a serious threat to

vegetable productivity. Because damage to reproductive processes is irreversible, even brief exposure to extreme temperatures can result in permanent yield loss.

6.2 Implications for Yield and Future Adaptation

This growing climatic instability undermines yield reliability, increases production risk, and threatens food and nutritional security. In tropical and subtropical regions, where vegetables play a central role in farm income and diets, repeated heat stress events can disrupt both livelihoods and market supply. Strengthening resilience will therefore depend more on adaptation than mitigation alone. Climate-resilient vegetable production systems must integrate improved crop management, protective cultivation practices, and precise irrigation to reduce heat injury during flowering. Equally critical are breeding programs that prioritise tolerance at the reproductive stage and stable yield under high-temperature conditions.

The next generation of vegetable scientists and postgraduate students will play a key role in advancing these adaptive strategies. Their research, innovation, and field-level application will shape the resilience and sustainability of vegetable production in an increasingly uncertain climate.

7. Conclusion

The flowering stage is the most vulnerable phase of vegetable crop growth, during which even brief exposure to high temperatures can severely disrupt reproductive processes and drastically reduce yield. Heat stress during this period impairs pollination, fertilisation, and fruit set, leading to largely irreversible losses once flowering has passed. Protecting this stage is therefore vital for ensuring yield stability and crop success. Integrated strategies combining sound agronomic management with the breeding of heat-tolerant varieties offer the most effective pathway forward. For postgraduate students, the key lies in research, innovation, and informed practices that sustain vegetable productivity in a rapidly warming climate.

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Impact of Water Stress in Vegetable Production and Their Management Strategies



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Water stress significantly reduces vegetable yield and quality by directly impacting overall plant growth processes viz. photosynthesis, cell expansions and nutrient uptake alongwith increased susceptibility to insect pests and diseases. Here more details are given below:

Water Stress may arise as a result of two Conditions, either due to excess of water or water deficit. The more common water stress is known as the drought stress.

Symptoms of water stress in plants:

Plants under water stress can have many symptoms including yellowing and wilting leaves that develop early fall color and burning or scorching on edges of leaves. Ultimately plants may drop some or fall of their leaves and appear dead.

Factors influence for water stress:

- **Plant species:** Different vegetables have varying levels of drought tolerance. Some of like cabbage can experience severe yield reduction (over 65.3%) while others like mustard may have more resilient.
- **Growth stage:** The impact of water stress varies depending on the plant's growth stage with some stages being more critical than others.
- **Water logging:** Conversely, excessive water (water logging) also cause stress by depleting oxygen in the soil, which inhibits root function and can lead to plant death.

Causes of Water stress:

- **Drought:** A primary cause is a lack of rainfall, leading to low soil moisture.
- **High soil Salinity:** High salt concentration in the soil prevent plant's growth from taking up water a condition known as "physiological drought."
- **Poor irrigation:** Inadequate or inconsistent watering can also lead to water stress.
- **Environmental Factors:** High temperature and low humidity can increase the rate of transpiration, exacerbating water stress even if soil moisture is adequate.

Factors responsible for water stress:

Water stress is one of the most adverse effect of the plant growth and productivity which considered to severe threat for sustainable vegetable crop production in the conditions on climate change as follows:

- Erratic rainfall.
- Poor soil water storage.
- Less capability of water in soil.
- Soil type.
- Irrigation channel facilities.
- Saline water irrigation / saline soil.
- Poor drainage systems.
- Water logging conditions.
- Plant architecture
- Global warming
- Deforestation
- Natural Calamities

Effect of water stress in vegetable crops

Water stress notably reduces vegetable production by causing reduced plant growth, lower yield and poor quality due to hampered photosynthesis, turgor loss and nutrient uptake. The effects are wide-ranging including wilting, leaf yellowing, smaller and deformed fruits and increased susceptibility of pest and diseases which discussed as following important points:

1. Physiological and growth impacts:

- **Reduced growth:** Water stress inhibits cell elongation, growth and the overall size and number of leaves and fruits.
- **Stomatal closure:** The plant's spores (stomata) close to reduce water loss, which also limits the intake of carbon dioxide need for photosynthesis.
- **Impaired photosynthesis:** Lack of water can halt photosynthesis affecting the production of sugars and the plants overall metabolism.
- **Tainted all growth:** The reduction in turgor pressure from a lack of water inhibits cell elongation and expansion, leading to permanent reduction in growth and yield.
- **Wilting:** Plants lose turgor pressure, causing them to appear limp and weak.
- **Nutrient deficiency:** Water stress interferes with the uptake of essential nutrients from the soil, leading to reduced nutrient content in the plant at harvest.
- **Oxidative damage:** The water stress can lead to the production of reactive oxygen species (ROS) which can cause oxidative damage to cellular components like carbohydrates, proteins and lipids.

2. Impact on yield and quality:

- **Lower yield:** Overall crop yield is significantly reduced due to hindered growth and development.
- **Poor quality:** Water stress can lead to issues like tough leaves, deformed roots, bitterness and increased nitrate accumulation in certain vegetables.
- **Smaller leaves and fruits:** Cell enlargement is one of the most sensitive processes to water deficiency, leading to smaller leaves and reduced fruit size.
- **Premature Senescence:** Water stress can lead to premature aging and the death of the plant.
- **Increased pests and diseases susceptibility:** Reduced plant defences make vegetables more vulnerable to pests and diseases.

3. Morphological and developmental changes:

- **Root system adjustments:** Plants may develop a deeper, more expensive root system to access water, but often fine root growth is inhibited and root hairs may elongate.
- **Altered leaf structure:** Leaves may become smaller, thicker and have a thicker cuticle to reduced water loss.
- **Shorter plant height:** Plant height and stem diameter are often significantly reduced under severe drought conditions.

4. Long-term consequences:

- **Lower quality:** The quality of the produces is negatively impacted which can include smaller fruit size and poor texture.
- **Food insecurity:** At a larger scale, water stress can contribute to food insecurity due to decreased crop yield.

Specific example of vegetable crops in water stress condition:

- **Tomatoes:** Flower and fruit shedding, smaller fruits and splitting disorders.
- **Potatoes:** Inadequate tuber development and lower yield.
- **Cucumbers:** Deformed pollen, bitterness and abnormal fruit shape.
- **Onions:** Splitting and doubling, which reduces shelf life.
- **Leafy vegetables:** Leaf toughness and tip burn.

Table-1: Effect of water stress on different vegetable crops.

Sl.No.	Vegetables	Critical stage	Impact of water deficient
1	Tomato	Flowering and fruiting enlargement	Flower shedding, BER reduced fruit rice
2	Brinjal	Flowering and fruit development	Less yield, poor colour development
3	Chilli and capsicum	Flowering and fruit setting	Shedding of flowers and fruits
4	Cabbage and cauliflower	Head / Curd formation and enlargement	Tip burning, splitting of head and riceyness in cauliflower
5	Root Crops	Root enlargement	Distorted, rough and poor roots, splitting firkling
6	Cucumber	Flowering and fruit development	Bitteremes and deformity of fruits
7	Okra	Flowering and fruit development	Loss of yield and fibre development
8	Melons	Flowering and fruit development	Poor fruit quality due to less T.S.S.
9	Lettuce	Throughout the development stage	Toughness in leaves, tip burnning
10	Pea	Flowering and pod filling	Less root nodulation, poor grain filling
11	Potato	Tuberization and enlargement	Poor tuber growth and yield, splitting
12	Leafy vegetables	Throughout development	Toughness in leaves, poor foliage.

Management strategies:

Management practices of water Stress in vegetable crops involves a combination of strategies as follows:

1. Agronomic and cultural practices:

- **Soil and moisture conservation:** Use, cover crops and conservation of tillage to reduce evaporation and retain soil moisture.
- **Melching:** Cover the soil with crop residues or plastic film to reduce evaporation and conserve moisture.
- **Improve soil health:** Increase organic matter content in soil to improve water retention capacity.
- **Improve seedling production:** Ensure healthy and robust seedlings are used, as they are better equipped to handle water stress.
- **Crop selection:** Choose vegetable varieties / cultivars that are naturally more tolerant to drought.
- **Wind breaks:** Plant wind breaks to reduce wind speed, which decreases soil evaporation rates and plant transpiration.

2. Irrigation techniques and water uses:

- **Water-saving methods:** Implement drip-irrigation or micro sprinkler systems, which can save water and deliver it directly to the root zone and are more efficient than conventional irrigation method.
- **Timely Imigation:** Water at critical plant growth stage to minimizes yield loss.
- **Protected Cultivation:** Use greenhouse or other protected structures, which can help to control the growing environment (micro-climate) and better water application.
- **Concentrate rain water:** Use physical structures to collect and concentrate rain water in areas where it can percolate to deeper soil layers.

3. Plant-based, chemical solutions strategies:

- **Hydrogels:** Apply hydrogels in the soil to increase water retention and moisture availability to the plants.
- **Plant Growth Regulators (PGR):** Apply plant growth regulators to help plants cope with water stress by regulating growth and stomatal closure which reducing water loss through transformation. Also PGRs that can increase a plant's tolerance to brought, such as solicylic acid, gibberellin or absciescid acid (ABA).
- **Grafting:** Using grafting techniques can enhance a plant tolerance to drought.
- **Foliar nutrition:** Applying nutrients directly to the leaves (Foliar application) can help the plant cope with stress.

Conclusion

Water stress severely limits vegetable crop production and with quality which the problem expected to worsen with climate change. Therefore, the successful management strategies requires a combination of modern techniques, genetic advancements and traditional agronomic practices to improve water-use efficiency and resilience which leads higher yield with better quality.

Digital Soil Mapping: Concepts, Techniques, and Applications in Modern Soil Science



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Abstract

Soil is a fundamental natural resource that supports agricultural productivity, ecosystem functioning, and environmental sustainability. Traditional soil mapping methods, although valuable, are often time-consuming, expensive, and limited in spatial resolution. Digital Soil Mapping (DSM) has emerged as a transformative approach that integrates soil science, geospatial technologies, statistical modeling, and machine learning to predict and map soil properties across landscapes. DSM utilizes environmental covariates such as topography, climate, vegetation, and remote sensing data to model spatial variability of soil attributes with higher accuracy and efficiency. The increasing availability of high-resolution satellite imagery, geographic information systems (GIS), and advanced computational techniques has significantly enhanced the capability of DSM to generate detailed soil information for large regions. This paper provides a comprehensive overview of the concepts, methodologies, and applications of digital soil mapping in modern soil science. The paper discusses the theoretical framework of DSM, commonly used techniques such as geostatistics, machine learning algorithms, and remote sensing-based approaches, as well as data sources and environmental predictors used in modeling soil properties. Furthermore, the study highlights major applications of DSM in precision agriculture, land-use planning, soil health monitoring, environmental management, and climate change studies. Challenges and limitations associated with DSM, including data scarcity, model uncertainty, and computational constraints, are also discussed. Finally, the paper explores future perspectives in DSM, emphasizing the role of artificial intelligence, big data, and cloud computing in improving soil prediction accuracy and supporting sustainable land management practices.

Keywords: Digital soil mapping, GIS, machine learning, soil variability, precision agriculture

1. Introduction

Soil is one of the most vital natural resources that sustain agricultural productivity, biodiversity, and ecosystem stability. Understanding soil properties and their spatial variability is essential for effective land management, crop production, environmental conservation, and sustainable development. Soil maps provide valuable information about soil distribution, texture, nutrient status, organic matter content, and other important properties that influence agricultural productivity and environmental processes.

Traditionally, soil mapping has been carried out through extensive field surveys combined with laboratory analysis and expert knowledge. Conventional soil mapping methods involve soil profile observations, classification, and manual delineation of soil boundaries on maps. While these methods have contributed significantly to soil science, they are often labor-intensive, time-consuming, and costly. Moreover, traditional soil maps are usually produced at coarse spatial scales and may not capture the fine-scale variability of soil properties that is critical for modern agricultural and environmental applications.

In recent decades, advances in geospatial technologies, remote sensing, geographic information systems (GIS), and statistical modeling have revolutionized soil mapping techniques. Digital Soil Mapping (DSM) has emerged as a modern approach that combines soil observations with environmental variables to predict soil properties across landscapes. DSM relies on quantitative relationships between soil characteristics and environmental factors such as terrain attributes, climate conditions, vegetation indices, and land use patterns.

The concept of DSM was formally introduced in the early 2000s and has since gained widespread attention in soil science and environmental research. It involves the use of spatial prediction models to generate continuous maps of soil properties using digital datasets. These models utilize environmental covariates derived from digital elevation models (DEMs), satellite imagery, climate databases, and other spatial datasets.

Digital soil mapping offers several advantages over traditional soil mapping methods. It enables rapid generation of soil information over large geographic areas, improves spatial resolution, and allows continuous updating of soil datasets as new information becomes available. Furthermore, DSM facilitates the integration of modern computational techniques such as machine learning and artificial intelligence, which significantly improve prediction accuracy.

In modern soil science, DSM plays a crucial role in supporting precision agriculture, sustainable land management, environmental monitoring, and climate change research. Accurate soil information is essential for optimizing fertilizer application, improving crop productivity, reducing environmental pollution, and assessing soil degradation processes.

This paper provides a comprehensive review of digital soil mapping by examining its fundamental concepts, techniques, and applications in contemporary soil science. The paper also discusses challenges associated with DSM implementation and highlights emerging technological advancements that are shaping the future of soil mapping.

2. Concept and Principles of Digital Soil Mapping

Digital Soil Mapping refers to the process of creating spatial predictions of soil properties using statistical models and environmental covariates. The concept is based on the assumption that soil formation processes are influenced by environmental factors such as climate, organisms, relief, parent material, and time, commonly known as the **CLORPT model** proposed by Hans Jenny.

The general framework of DSM can be expressed as:

Soil Property = f (Climate, Organisms, Relief, Parent Material, Time, Spatial Position)

This conceptual model highlights the relationship between soil characteristics and environmental factors that influence soil formation and distribution. By using digital datasets that represent these environmental variables, DSM models can predict soil attributes across landscapes.

DSM typically involves several key steps:

1. Collection of soil samples and field observations
2. Acquisition of environmental covariate data
3. Data preprocessing and spatial analysis
4. Model development and calibration
5. Spatial prediction of soil properties
6. Validation and uncertainty assessment

The output of DSM is usually in the form of continuous raster maps representing soil attributes such as soil organic carbon, pH, clay content, moisture content, or nutrient availability.

3. Data Sources for Digital Soil Mapping

The success of digital soil mapping largely depends on the availability and quality of spatial datasets used as environmental predictors. Several types of data sources are commonly used in DSM.

3.1 Soil Sample Data

Soil samples collected through field surveys provide the primary dataset for DSM modeling. These samples are analyzed in laboratories to determine soil properties such as texture, organic carbon, nitrogen content, pH, and nutrient concentrations.

Field sampling techniques include:

- Grid sampling
- Stratified sampling
- Random sampling
- Transect sampling

The spatial distribution and density of soil samples significantly influence the accuracy of DSM predictions.

3.2 Remote Sensing Data

Remote sensing technologies provide valuable information about land surface characteristics that influence soil properties. Satellite imagery from sensors such as Landsat, Sentinel, MODIS, and hyperspectral sensors is widely used in DSM.

Remote sensing data can provide information on:

- Vegetation indices (NDVI, EVI)
- Land use and land cover
- Surface reflectance characteristics
- Soil moisture conditions
- Surface temperature

These variables help identify spatial patterns related to soil variability.

3.3 Digital Elevation Models (DEM)

Terrain plays a crucial role in soil formation and distribution. Digital Elevation Models provide elevation data that can be used to derive various terrain attributes such as:

- Slope
- Aspect
- Curvature
- Topographic wetness index
- Elevation

These terrain variables are strong predictors of soil moisture, erosion, and sediment deposition processes.

3.4 Climate Data

Climate influences soil formation through temperature, precipitation, and evapotranspiration patterns. Climate datasets obtained from weather stations or global climate models are used to represent climatic variables in DSM models.

Common climatic variables include:

- Mean annual temperature
- Annual precipitation
- Evapotranspiration
- Humidity

3.5 Land Use and Vegetation Data

Vegetation and land management practices influence soil organic matter and nutrient cycling. Land use maps and vegetation indices derived from remote sensing provide important predictors for DSM.

4. Techniques Used in Digital Soil Mapping

Various statistical and computational techniques are used in digital soil mapping to establish relationships between soil properties and environmental predictors.

4.1 Geostatistical Methods

Geostatistics is widely used in DSM for analyzing spatial variability of soil properties. The most common geostatistical techniques include:

Kriging

Kriging is an interpolation method that predicts soil properties at unsampled locations based on spatial autocorrelation between observed data points.

Types of kriging include:

- Ordinary kriging
- Universal kriging
- Indicator kriging
- Co-kriging

Kriging provides both predicted values and associated uncertainty estimates.

4.2 Regression Models

Regression analysis is commonly used to model relationships between soil properties and environmental variables.

Common regression methods include:

- Multiple linear regression

- Generalized linear models
- Partial least squares regression

Regression models are simple to implement and provide interpretable relationships between predictors and soil variables.

4.3 Machine Learning Techniques

Machine learning algorithms have gained significant popularity in DSM due to their ability to handle complex nonlinear relationships.

Common machine learning techniques include:

Random Forest

Random Forest is one of the most widely used machine learning methods in DSM. It is an ensemble learning technique that builds multiple decision trees and combines their predictions.

Support Vector Machines (SVM)

SVM is used for classification and regression problems and is effective in handling high-dimensional datasets.

Artificial Neural Networks (ANN)

Neural networks simulate the functioning of the human brain and are capable of capturing complex relationships in soil data.

Gradient Boosting Machines

These algorithms sequentially build models that improve prediction accuracy by minimizing prediction errors. Machine learning techniques often outperform traditional statistical methods in DSM applications.

5. Integration of Remote Sensing and GIS in Digital Soil Mapping

Remote sensing and GIS play a critical role in modern DSM workflows. GIS provides a platform for managing spatial datasets, performing spatial analysis, and visualizing soil maps.

Remote sensing contributes to DSM by providing continuous spatial data that represent environmental conditions influencing soil properties.

Examples of remote sensing applications in DSM include:

- Mapping soil organic carbon using spectral reflectance
- Detecting soil moisture variability
- Identifying salinity and soil degradation
- Monitoring land cover changes affecting soil properties

The integration of GIS and remote sensing allows researchers to efficiently analyze large spatial datasets and generate high-resolution soil maps.

6. Applications of Digital Soil Mapping

Digital soil mapping has numerous applications in agriculture, environmental management, and land-use planning.

6.1 Precision Agriculture

Precision agriculture relies on detailed soil information to optimize crop management practices. DSM provides high-resolution maps of soil nutrients, organic matter, and moisture content, enabling farmers to apply fertilizers and irrigation more efficiently.

Benefits include:

- Improved crop yield
- Reduced fertilizer costs
- Efficient resource management
- Reduced environmental pollution

6.2 Soil Health Monitoring

DSM helps monitor soil health by mapping key indicators such as soil organic carbon, nutrient availability, and soil structure. These maps allow researchers and policymakers to identify areas experiencing soil degradation.

6.3 Land Use Planning

Digital soil maps provide essential information for land-use planning and sustainable development. Soil suitability analysis helps determine the best use of land for agriculture, forestry, urban development, or conservation.

6.4 Environmental Management

DSM is widely used in environmental studies to assess soil contamination, erosion risk, and land degradation. For example, digital soil maps can help identify areas affected by heavy metal contamination or industrial pollution.

This application aligns closely with modern research on **soil contamination mapping**, particularly studies focusing on spatial analysis of pollutants.

6.5 Climate Change Studies

Soils play a major role in the global carbon cycle. DSM helps estimate soil carbon stocks and monitor changes in soil carbon sequestration over time. This information is essential for climate change mitigation strategies and carbon accounting.

6.6 Water Resource Management

Soil properties influence water infiltration, runoff, and groundwater recharge. DSM helps map soil hydraulic properties that affect water movement and availability.

7. Challenges and Limitations of Digital Soil Mapping

Despite its advantages, DSM faces several challenges that limit its widespread implementation.

Data Availability

High-quality soil sample data are often limited in many regions, especially in developing countries.

Model Uncertainty

Prediction models may produce uncertainties due to limitations in input data or modeling techniques.

Scale Issues

DSM predictions may vary depending on spatial resolution and scale of analysis.

Computational Complexity

Large datasets and advanced machine learning algorithms require significant computational resources.

Addressing these challenges requires improved data sharing, advanced modeling techniques, and collaboration between soil scientists, data scientists, and geospatial experts.

8. Future Perspectives of Digital Soil Mapping

The future of digital soil mapping is closely linked to advancements in data science, remote sensing, and artificial intelligence.

Artificial Intelligence and Deep Learning

Deep learning models are capable of analyzing complex datasets and extracting patterns from large volumes of spatial data.

Hyperspectral Remote Sensing

Hyperspectral sensors provide detailed spectral information that can improve soil property estimation.

Big Data and Cloud Computing

Cloud platforms such as Google Earth Engine allow researchers to process massive geospatial datasets efficiently.

Integration with Internet of Things (IoT)

Soil sensors connected through IoT networks can provide real-time soil data, enhancing DSM accuracy and timeliness.

These technological advancements are expected to transform soil mapping practices and provide more accurate and dynamic soil information systems.

9. Conclusion

Digital Soil Mapping has emerged as a powerful tool in modern soil science, enabling efficient prediction and mapping of soil properties across landscapes. By integrating soil observations with environmental covariates and advanced statistical models, DSM provides high-resolution soil information that supports sustainable land management and agricultural productivity.

The integration of remote sensing, GIS, and machine learning techniques has significantly enhanced the ability of researchers to analyze soil variability and generate accurate soil maps. DSM applications extend across multiple domains, including precision agriculture, environmental monitoring, land-use planning, and climate change studies.

However, challenges such as data scarcity, model uncertainty, and computational limitations still need to be addressed to fully realize the potential of DSM. Future developments in artificial intelligence, hyperspectral remote sensing, and cloud computing are expected to further improve DSM methodologies and expand their applications.

As global demand for food production and sustainable resource management continues to grow, digital soil mapping will play an increasingly important role in supporting evidence-based decision-making and promoting sustainable soil management practices.



Fish Bone Calcium: Turning Waste into Wellness



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Introduction:

Food waste, improper waste disposal, and inadequate management of by-products have become significant concerns affecting both aquatic and terrestrial ecosystems. These issues not only lead to environmental degradation but also contribute to economic losses and challenges in maintaining food security. Effective strategies for waste utilization and management are therefore essential to ensure sustainability and resource efficiency. Fish processing industries generate substantial amounts of waste, with fish bones constituting a major portion that is often discarded or underutilized. Despite being treated as waste, these bones are rich in valuable nutrients, particularly calcium and other minerals essential for human health. Improper disposal of such by-products can also contribute to environmental pollution and economic loss. With increasing awareness about sustainable practices and resource optimization, there is a growing interest in converting fish bone waste into value-added products. These can be utilized in food fortification, animal feed, pharmaceuticals, and nutraceutical formulations. Efficient processing and recovery of nutrients from fish bones not only reduces waste but also provides an economical and eco-friendly solution, supporting both environmental sustainability and the development of functional food ingredients.

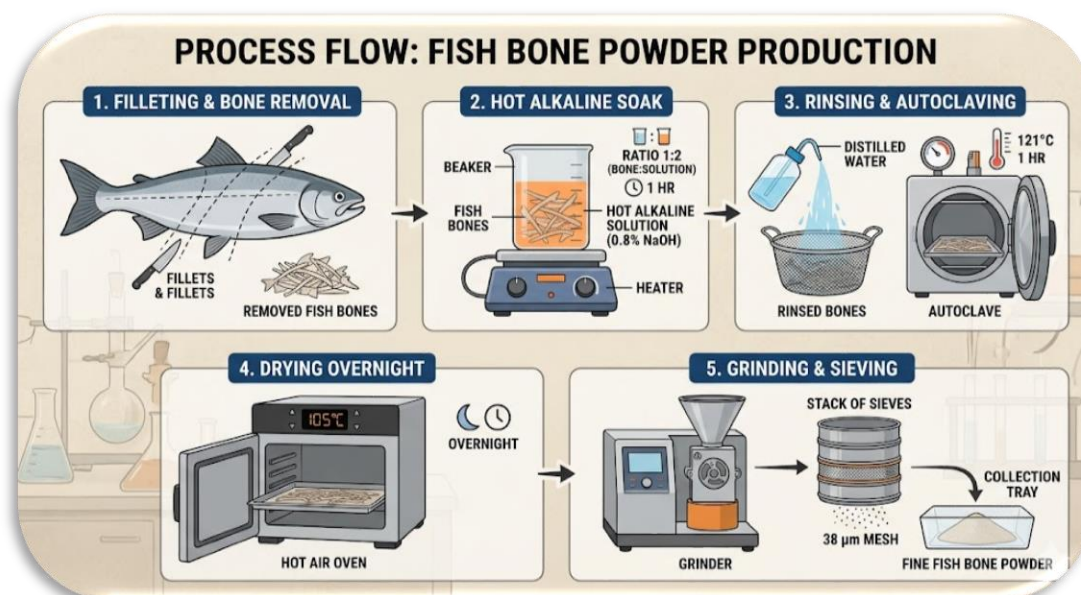
Dietary Reference Intakes (DRIs): Estimated Average Requirement of Calcium in different age groups -

Life Stage Group	Calcium (mg/d)
Children	
1-3 years	500
4-8 years	800
Males	
9-13 years	1,100
14-18 years	1,100
19-30 years	800
31-50 years	800
51-70 years	800
> 70 years	1000
Female	
9-13 years	1,100
14-18 years	1,100
19-30 years	800
31-50 years	800
51-70 years	1,000
> 70 years	1,000

Fish bones are rich in calcium and bioactive peptides and can be used as ingredients for the manufacture of functional foods or to improve the technological properties of food. Thus, fish bones may be an interesting alternative to traditional sources of calcium, such as dairy products. However, the consumption of milk and milk products has reduced steadily over the past few decades because of their reported association with high fat levels and their association with weight increase and obesity.

Fish Bone Powder Preparation:

To prepare the fish bone powder, the fish were filleted and the bones were removed from the fish body. The fresh tissue was removed from the bone (main frame) of fish by soaking in a hot alkaline solution (0.8% NaOH) at a ratio of bone to solution of 1:2 (weight by weight) for 1 hr. Subsequently, bone samples were rinsed with distilled water and autoclaved at 121°C for 1 hr. The obtained samples were dried out overnight in a hot air oven at 105°C. The dried samples were ground into powder and sieved through a 38 µm mesh.



Uses of fish bone calcium

Fish bone calcium, derived from marine waste, is a highly bioavailable source of calcium phosphate and collagen, primarily used to support bone health and treat osteoporosis. Its high biocompatibility makes it valuable for manufacturing hydroxyapatite bioceramics, serving as bone substitutes/fillers in medical applications, while also acting as a sustainable nutrient fortifier in food.

Key Uses of Fish Bone Calcium:

- **Nutraceuticals & Dietary Supplements:** Due to its high absorption rate, fish bone calcium is used in health supplements to strengthen bones and prevent osteoporosis, especially when processed into nanoparticles to boost bioavailability.
- **Biomedical & Bone Regeneration:** Extracted calcium phosphate, particularly hydroxyapatite, is used in bone tissue engineering to create scaffolds and fillers for bone defects, as it integrates effectively with the body, encouraging tissue repair.
- **Food Fortification:** Fish bone powder is added to functional foods to improve nutritional value and as a sustainable calcium source to replace dairy in certain diets.

Fish bones are an excellent source of calcium carbonate and phosphorus, which are often produced as a byproduct of the seafood industry, making them a sustainable and cost-effective alternative to traditional calcium sources.

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Advancing Regenerative Agriculture in India: A Pathway to Climate-Resilient and Restorative Farming Systems



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Abstract:

To feed a growing population on a warming world, the agricultural idea of "sustainability"-merely preserving the status quo-is no longer sufficient. Regenerative agriculture is now the main focus as we move through 2026. This all-encompassing approach to land management actively fixes and restores the environment rather than merely "sustain" it.

Regenerative agriculture is a systemic method that takes agriculture beyond sustainability by actively improving and rebuilding ecosystems rather than just minimizing harm. Its main goals are to improve water cycles, boost biodiversity, restore soil health, and sequester carbon, turning farms into resilient, living systems as opposed to extractive producing facilities. Regenerative agriculture creates ecological wealth that helps farmers, communities, and the climate, in contrast to conventional farming, which frequently depletes natural capital.

What is agricultural regeneration? (The Five Pillars): In contrast with industrial farming, which frequently depletes soil nutrients, regenerative agriculture seeks to create "living soil." The following five fundamental ideas characterize it:

1. **Reducing tillage:** In order to maintain soil structure and microbial networks for minimal soil disturbance.
2. **Soil Covering:** Applying mulch or cover crops to stop erosion and maintain a steady soil temperature.
3. **Biodiversity:** Cultivating a variety of crops and including trees (agroforestry) to disrupt pest and disease cycles.
4. **Livestock Integration:** Using animals in farming practices and for grazing to promote plant development and organically fertilize land.
5. **Living Roots Year-Round:** Making sure that plants continue to develop in order to nourish the soil micro biome.

Recent Research & Technological Breakthroughs (2025–2026):

1. **AI-Guided Cover Crop Cocktails:** Research from 2025 showed that soil organic matter (SOM) may be increased by 27% in just two seasons by employing AI to choose specific seed mixtures based on local soil sensors.
2. **Mycorrhizal Inoculation:** Farmers can restore fungal networks in "dead" soil by using new biological coats for seeds. According to a 2026 study published in Nature Food, wheat cultivated using these networks needed 50% less phosphate fertilizer.
3. **Nutritional Density Mapping:** Researchers have established a direct link between human health and soil health for the first time. In 2026, vegetables farmed regenerative is touted as having 20-40% more antioxidants than traditional produce.
4. **Integration of AI and Digital Agriculture:** Progress has accelerated due to the intersection of digital innovation and regenerative principles. Among the technologies are:
 - 1) Crop health monitoring with drones,
 - 2) AI-powered methods for managing nutrients,
 - 3) Software for estimating soil carbon,
 - 4) Tools for predicting the climate.Digital agriculture has been highlighted by the World Economic Forum as a driving force for the global expansion of regenerative systems.
5. **Growth of Agroforestry:** A key component of regenerative landscapes is agroforestry, which integrates trees with crops and cattle. Agroforestry systems, according to research from the International Crops

Research Institute for the Semi-Arid Tropics (ICRISAT): Boost biodiversity Enhance the organic matter in the soil, Improve the stability of the microclimate, Increase farmer income diversity, Agroforestry is becoming more widely acknowledged as a solution for both climate adaptation and mitigation in 2025–2026.

The Indian Scenario: Government Policies & Schemes Supporting Regeneration:

1. NMNF (National Mission on Natural Farming) Scheme:

The aim of the mission, which was introduced as a stand-alone Centrally Sponsored Scheme in late 2024, is to change Indian agriculture by switching from chemical-intensive farming to an environmentally friendly, nature-based approach. To advance an agricultural system based on traditional Indian knowledge, such as the *Bharatiya Prakritik Krishi Paddhati* (BPKP), that is chemical-free, sustainable, and climate-resilient.

- Budget: The mission now spends ₹2,481 crore after receiving a significant hike in the Union Budget for 2025–2026.
- Scope: Through 15,000 clusters, the government hopes to reach 1 crore (10 million) farmers.
- Progress: As of February 2026, more than 8.57 lakh hectares had received formal certification as "Natural Farming" land.

2. PM-PRANAM (PM Programme for Restoration, Awareness Generation, Nourishment, and Amelioration of Mother Earth) Scheme:

It was started by the Indian government with the fundamental goal of encouraging states to use sustainable, organic, and alternative fertilizers in order to improve agricultural sustainability and restore soil health. To encourage organic and natural farming while reducing the use of artificial fertilizers (such as Urea, DAP, and NPK).

- In 2023–2024, 14 states reported consuming 1.51 million tons less chemical fertilizer than they had on average over the previous three years. This allowed the savings from subsidies to be distributed as grants.

3. 10,000 Bio-Input Resource Centers:

Farmers visit these BRCs to obtain natural formulations such as *Beejamrut* (seed treatment) and *Jeevamrut* (microbial culture) rather than purchasing chemicals.

4. PKVY (Paramparagat Krishi Vikas Yojana):

Introduced in 2015 as a part of the National Mission on Sustainable Agriculture's (NMSA) Soil Health Management (SHM) program, it seeks to improve soil health, encourage organic farming, and lessen reliance on chemical fertilizers. It emphasizes a cluster-based method for certification that makes use of the Participatory Guarantee System (PGS). Financial support for production, harvesting, and selling should be given at a rate of ₹31,500/ha for three years, totaling ₹50,000/ha.

- More than 14.99 lakh hectares have been planted to organic farming since 2015–16, creating 52,289 clusters and helping 25.30 lakh farmers.
- Financial Investment: More than ₹2,265 crore had been made available to support the plan by the beginning of 2025.

5. NICRA (National Initiative on Climate Resilient Agriculture):

Launched by ICAR in 2011, aims to improve Indian agriculture's climate resilience through capacity building, technology demonstration, and strategic research. In order to maintain food security in the face of growing climate unpredictability, it focuses on creating climate-resilient livestock, crop varieties, and natural resource management strategies throughout sensitive districts.

- High-Yield Varieties: To combat drought and heat stress, more than 1,900 climate-resilient crop varieties (such as millets, pulses, and vegetables) have been developed; 109 of these were released in August 2024.
- Operational Scope: The Technology Demonstration Component (TDC) is still in operation. For instance, eight Krishi Vigyan Kendras (KVKs) in Zone X will be carrying out projects in 2024–2025.

6. **Bharat-VISTAAR (Virtually Integrated System to Access Agricultural Resources):**

In February 2026, the Indian government unveiled a comprehensive digital public infrastructure (DPI) driven by artificial intelligence (AI) with the goal of transforming the agricultural industry. It provides farmers with individualized, real-time, science-based information in local languages, serving as a digital partner around-the-clock. Bharat-VISTAAR's main objective is to use technology to empower farmers and increase the productivity, sustainability, and self-sufficiency of agriculture. Among the main objectives are: **Unified Digital Platform, AI-Powered Advisory, Direct Access to Services, Bridging the Digital Divide and Increasing Farmer Income.**

7. **Namo Drone Didi Scheme:**

In November 2023, a central sector project was started to equip 15,000 women-led Self-Help Groups (SHGs) with drones for agricultural tasks such as spraying pesticides and fertilizer. The main objective is to empower rural women, provide new revenue streams, and improve agriculture through accurate, safe, and effective spraying. With 3% interest loans and an 80% subsidy (up to ₹8 lakh) for drone purchases, it aims to generate ₹1 lakh+ in revenue annually.

- Under the Deendayal Antyodaya Yojana-National Rural Livelihoods Mission (DAY-NRLM), 15,000 Women Self-Help Groups (SHGs) will get ₹1,261 crores between 2023–2024 and 2025–2026.

8. **AgriStack and Digital Agriculture Mission:**

By 2026-2027, we want to transform Indian agriculture by building a centralized, technologically advanced digital public infrastructure (DPI) that would increase production, loan availability, and service delivery for more than 11 crore farmers. With integrated AI-driven solutions, digital crop surveys, and distinctive Farmer IDs (Kisan Pehchan Patra), today's scenario demonstrates quick deployment.

- Millions of Farmer IDs have been generated, nine states have signed Memorandums of Understanding, and pilot projects (such as those in Maharashtra, MP, and Chhattisgarh) have used them for MSP procurement and KCC loans.
- A budget of ₹2,817 crore was authorized by the federal cabinet specifically for the Digital Agriculture Mission.

Future challenges

- **Absence of Standardized Definitions:** The term "regenerative agriculture" lacks a widely accepted definition, which raises questions about "greenwashing" and creates uncertainty. It is challenging to discern between really restorative and conventional treatments in the absence of a unified concept.
- **Inconsistent Measurement Frameworks:** It is difficult to measure the practical effects of regenerative activities, such as carbon sequestration and biodiversity enhancements, in the absence of defined metrics and strong Monitoring, Reporting, and Verification (MRV) frameworks.
- **Limited Extension Services:** Farmers are unable to obtain the advice required to switch to regenerative methods, especially when it comes to region-specific, site-specific, and context-dependent solutions, due to a lack of experienced advisers and technical assistance.
- **Policy Fragmentation:** Present agricultural policies frequently support traditional, industrial methods, including incentives and subsidies that discourage the transition to regenerative techniques.
- **Financial Risks During Transition:** As the soil ecosystem adjusts, farmers frequently experience a "dip in profits" during the first few years. This makes it challenging for them to absorb the financial risks related to the high upfront expenses of new equipment and possible, albeit temporary, output decreases.

Conclusion

By 2030 the "Brown Revolution" of soil will take the place of the "Green Revolution" of chemicals. The only approach that concurrently tackles these issues is regenerative agriculture.

1. **Climate Change:** By making soil an enormous carbon sink.
2. **Water Scarcity:** The capacity of healthy soil is ten times more than that of deteriorated soil.
3. **Farmer Profitability:** By introducing carbon credit revenue and doing away with costly chemical inputs.

By moving from damage control to ecological restoration, regenerative agriculture is rethinking contemporary farming. Adoption is being accelerated by developments in soil micro biome research, perennial crops, AI-based digital agriculture, agroforestry growth, and carbon accounting technology. Corporate pledges further mainstream these practices, while government initiatives in India and around the world are increasingly in line with regenerative concepts. Regenerative agriculture offers a potent route toward climate resilience, biodiversity restoration, food security, and rural prosperity—moving decisively beyond sustainability toward regeneration by fusing ecological research with digital innovation and supportive policy frameworks.

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Cacti and Succulents - Beautifying Indoors



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Introduction

Indoor gardening has become a popular trend in recent years as people look for simple ways to bring nature into their homes. Plants not only improve the appearance of indoor spaces but also create a calm and refreshing environment. Among the many plants used for indoor decoration, cacti and succulents are particularly admired for their unique beauty and easy care.

Cacti and succulents are drought-tolerant plants that store water in their stems, leaves, or roots. This special ability helps them survive in dry and harsh environments. Because they require very little water and attention, they are perfect plants for indoor gardening. Their unusual shapes, attractive colors, and compact size make them ideal decorative plants for homes, offices, and apartments.

The Unique Structure of Cacti and Succulents

Cacti and succulents are well adapted to survive in dry climates. Their thick stems and fleshy leaves act as water storage organs, allowing them to store moisture for long periods. This adaptation helps them survive even when watering is irregular.

Cacti usually have spines instead of leaves. These spines protect the plant from animals and also reduce water loss. Succulents, on the other hand, have thick leaves that may appear waxy or glossy. Some species have rosette-shaped leaves, while others grow in clusters or trailing forms.

The unusual structures of these plants make them visually appealing. Their geometric shapes, symmetrical patterns, and interesting textures give them a sculptural quality that looks beautiful in indoor settings.

A Wide Variety of Shapes and Colors

One of the reasons cacti and succulents are loved by plant enthusiasts is their incredible diversity. These plants come in many shapes such as spherical, columnar, star-shaped, and rosette-forming types.

Succulents often display a variety of colors including green, bluish-green, purple, red, pink, and even silver. Some varieties change color depending on the amount of sunlight they receive. During certain seasons, many succulents produce bright flowers that add extra charm to indoor gardens.

This wide range of forms and colors allows gardeners and interior designers to create visually attractive plant arrangements. Even a small collection of different succulents can create a beautiful indoor display.

Perfect Plants for Small Spaces

Cacti and succulents are ideal plants for homes with limited space. Because they grow slowly and remain compact, they can be placed in small containers and decorative pots.

They are commonly displayed on window sills, bookshelves, office desks, and study tables. Even tiny corners of a room can be decorated



with these plants. Their small size makes them suitable for apartments and urban homes where space for gardening may be limited.

Another advantage is that they can be grouped together to form miniature indoor gardens. A collection of different succulents in a single container can create an attractive display that adds beauty to any room.

Creative Ways to Display Cacti and Succulents

There are many creative ways to use cacti and succulents for indoor decoration. One popular method is creating a **succulent terrarium** using glass containers. Decorative stones, sand, and small figurines can be added to enhance the design.

Hanging planters are also widely used for trailing succulents. These arrangements add a vertical element to home decoration and look especially attractive near windows or balconies.

Another modern trend is **succulent wall frames**, where plants are arranged in a vertical structure and mounted on walls. This creates a living wall art that combines nature with interior design.

Miniature succulent gardens are also becoming popular. These gardens often include different plant varieties arranged together to create a small landscape effect.

Easy Propagation: Growing New Plants

One of the most interesting features of succulents is their ability to reproduce easily. Many succulents can be propagated from leaves or stem cuttings. When a healthy leaf is placed on soil, it can gradually develop roots and grow into a new plant.

This simple method allows gardeners to expand their plant collection without purchasing new plants. It also makes succulents popular among hobby gardeners and plant collectors.

Cacti can also be propagated from offsets or small shoots that grow from the main plant. These offsets can be carefully removed and planted in new pots to grow independently.

Propagation not only helps increase plant numbers but also makes indoor gardening an enjoyable and educational activity.

Health and Psychological Benefits

Indoor plants are known to have positive effects on human well-being. Cacti and succulents contribute to a calm and pleasant environment inside homes and workplaces.

Their presence adds greenery that can reduce stress and improve mood. Many people feel relaxed and happy when surrounded by plants. Caring for indoor plants can also provide a sense of responsibility and satisfaction.

These plants are especially helpful in modern urban lifestyles where access to outdoor gardens may be limited. Even a small indoor plant collection can create a peaceful and refreshing atmosphere.

Common Mistakes to Avoid

Although cacti and succulents are easy to grow, some common mistakes can harm them. The most frequent problem is **overwatering**. Because these plants store water, they do not require frequent watering. Excess water can cause root rot and damage the plant.

Another mistake is placing them in areas with insufficient light. Most cacti and succulents need bright light to grow well. Keeping them near windows or bright indoor locations is usually the best option.

Using heavy soil without proper drainage can also affect plant health. Well-drained soil mixtures specially designed for cacti and succulents are recommended.

By avoiding these simple mistakes, these plants can remain healthy and beautiful for many years.

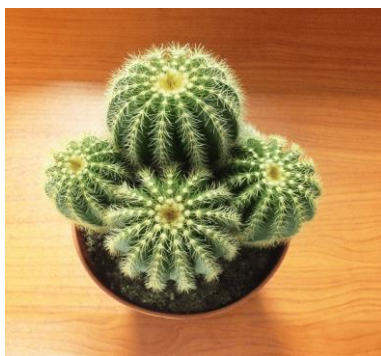
Popular Indoor Cactus and Succulent Types

Some cactus and succulent species are particularly popular for indoor decoration.

The Barrel cactus is known for its round shape and attractive spines. The Bunny Ear cactus has flat pads that resemble rabbit ears. These unusual forms make cactus plants interesting decorative pieces.

Among succulents, Echeveria is widely admired for its rosette-shaped leaves. Jade plant is another popular succulent that symbolizes good luck and prosperity in many cultures. Aloe species are also commonly grown indoors because of their ornamental value and medicinal uses.

These plants are not only beautiful but also easy to grow, making them ideal for beginners.



Barrel cactus



Bunny Ear cactus



Echeveria



Jade plant



Aloe species

Conclusion

Cacti and succulents are among the most fascinating indoor plants available today. Their remarkable ability to survive in dry conditions, combined with their striking shapes and colors, makes them excellent choices for indoor decoration.

These plants require minimal care yet offer maximum beauty. From miniature gardens and terrariums to stylish pots and wall displays, they can transform ordinary indoor spaces into lively green environments.

As more people embrace indoor gardening, cacti and succulents continue to gain popularity for their elegance, simplicity, and adaptability. By growing these resilient plants, anyone can enjoy the beauty of nature inside their home while adding a touch of creativity and freshness to their living spaces.

Precision Farming in Potato Cultivation for Yield Maximization



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1. Introduction

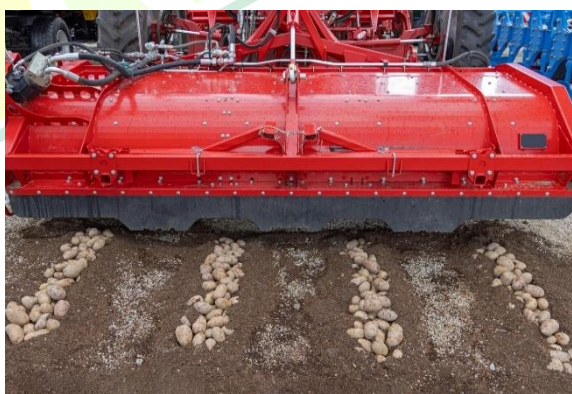
Potato (*Solanum tuberosum* L.) is one of the most important food crops globally, ranking after rice, wheat and maize in terms of production and consumption. It serves as a staple food and a vital source of carbohydrates, vitamins and minerals for millions of people. In India, potato plays a crucial role in food security and farmer livelihoods; however, productivity is often constrained by inefficient resource use, soil variability, climate change and pest and disease pressures. Conventional farming practices rely on uniform input application, which often leads to overuse or underuse of inputs, reduced efficiency and environmental degradation. Precision farming has emerged as an advanced approach that utilizes modern technologies such as sensors, Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing and data analytics to optimize crop management. By applying inputs at the right time, place and quantity, precision farming enhances resource use efficiency, increases yield and reduces environmental impact.

2. Concept and Principles of Precision Farming

Precision farming, also known as site-specific crop management, involves the use of advanced technologies to monitor and manage spatial and temporal variability within agricultural fields. The core principles include variability assessment, data-driven decision-making and targeted input application. In potato cultivation, precision farming focuses on optimizing soil fertility, irrigation, pest control and crop monitoring to achieve maximum yield and quality.

Key components include:

- Soil and crop sensing technologies
- GPS and GIS-based field mapping
- Variable rate technology (VRT)
- Remote sensing and drone-based monitoring
- Decision support systems



3. Agro-Climatic Requirements and Soil Variability

Potato thrives in cool climates with an optimal temperature range of 15–20°C for tuber formation. High temperatures above 30°C reduce tuber development, while frost can damage the crop. Soil variability plays a significant role in potato productivity, as differences in soil texture, organic matter and nutrient availability affect plant growth. Precision farming enables site-specific soil management through detailed soil mapping and analysis.

4. Soil Mapping and Site-Specific Nutrient Management

Soil mapping is a fundamental component of precision farming. It involves analyzing spatial variability in soil properties such as pH, nutrient content and moisture levels.

Table 1: Soil Parameters for Precision Potato Farming

Parameter	Optimal Range	Importance
pH	5.0–6.5	Nutrient availability
Organic Carbon	>0.5%	Soil fertility
Nitrogen	Medium	Vegetative growth
Phosphorus	Medium to high	Root development
Potassium	High	Tuber quality

Site-specific nutrient management ensures that fertilizers are applied according to crop needs, improving nutrient use efficiency and reducing losses.

5. Use of GPS, GIS and Remote Sensing

GPS and GIS technologies are used to create detailed maps of fields, enabling precise application of inputs. Remote sensing, including satellite imagery and drone-based monitoring, provides real-time information on crop health, soil moisture and nutrient status. Vegetation indices such as NDVI (Normalized Difference Vegetation Index) help assess crop vigor and detect stress conditions early.

6. Precision Irrigation Management

Efficient water management is crucial for potato cultivation, as both water stress and waterlogging can reduce yield. Precision irrigation systems such as drip and sprinkler irrigation enable uniform water distribution and minimize losses.

Table 2: Irrigation Scheduling in Potato

Growth Stage	Water Requirement
Germination	Moderate
Vegetative	High
Tuber initiation	Critical
Tuber bulking	Very high

Soil moisture sensors and automated irrigation systems ensure timely water application, improving water use efficiency and crop performance.



7. Variable Rate Technology (VRT)

Variable Rate Technology allows the application of inputs such as fertilizers, water and pesticides at variable rates across the field based on site-specific requirements. This technology reduces input costs, minimizes environmental impact and enhances crop productivity.

8. Precision Planting and Mechanization

Precision planting ensures uniform seed placement, spacing and depth, which are critical for optimal plant growth and yield. Advanced planting machinery equipped with GPS systems improves accuracy and efficiency.

Mechanization in potato farming, including automated planting, harvesting and grading, reduces labor costs and improves productivity.

9. Integrated Pest and Disease Management

Precision farming enhances pest and disease management through early detection and targeted interventions. Sensors and imaging technologies help identify pest infestations and disease symptoms at early stages. Site-specific pesticide application reduces chemical usage and environmental impact.

Table 3: Major Pests and Diseases in Potato

Problem	Symptoms	Management
Late blight	Leaf lesions	Fungicides, resistant varieties
Aphids	Sap sucking	Biological control
Cutworms	Tuber damage	Soil treatment

10. Data Analytics and Decision Support Systems

Data analytics plays a crucial role in precision farming by analyzing data collected from sensors, drones and satellites. Decision support systems provide recommendations for irrigation, fertilization and pest management based on real-time data. These tools help farmers make informed decisions and improve crop management efficiency.

11. Harvesting, Yield and Quality Improvement

Precision farming techniques result in uniform crop growth, improved tuber size and higher yield. Yield under precision farming can increase by 20–40% compared to conventional methods. Quality parameters such as tuber size, shape and dry matter content are also improved.

12. Economic Benefits of Precision Farming

Precision farming reduces input costs, improves resource use efficiency and increases yield, resulting in higher profitability. Although initial investment in technology may be high, long-term benefits outweigh the costs.

13. Constraints and Challenges

Major challenges include high initial investment, lack of technical knowledge, limited access to advanced technologies and data management issues. Small and marginal farmers may face difficulties in adopting precision farming practices.

14. Future Prospects

The future of precision farming in potato cultivation is promising, with advancements in artificial intelligence, machine learning and IoT-based systems. Integration of these technologies will further enhance productivity, sustainability and profitability.

15. Conclusion

Precision farming represents a revolutionary approach to potato cultivation by optimizing resource use and improving productivity. Through the integration of advanced technologies such as GPS, GIS, remote sensing and data analytics, farmers can achieve higher yields, better quality produce and increased profitability. Despite challenges, the adoption of precision farming practices will play a crucial role in ensuring sustainable potato production and meeting the growing demand for food.

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Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu under the dynamic leadership of Prof. B. N. Tripathi, Hon'ble Vice Chancellor is witnessing a huge metamorphosis in the form of distinct and transformative initiatives focusing on profitability and sustainability, inclusivity and outreach, innovation and entrepreneurship and mobilization & empowerment. The target group comprises of the farmers, including farm women, innovators, entrepreneurs and aspiring youths. Ensuring that the vision and mission of Hon'ble Vice Chancellor percolates deeper down to the grassroots level, Directorate of Extension headed by Prof. Amrish Vaid has been leading from the front through its nine Krishi Vigyan Kendras working in different districts of the division in different agro-climatic zones. The KVKs are entrusted with the responsibility of extension and dissemination of sustainable technologies, refinement of technologies, awareness of different government schemes, mobilization of farming communities through various collectives, facilitating marketing support, partnerships and convergence with line departments and all other works as allotted to these front line extension institutes from time to time. One of important platform for dissemination of technologies and sensitization and awareness of the farmers is the Farmers' Fair or *Kisan Mela*. Every agriculture university uses this opportunity and organizes such type of melas at different periodicity for the farming community of their region. Carrying forward its tradition of pro-farming endeavors, SKUAST-Jammu also being the leading university of north India is also organizing a three days long Agriculture Summit and Farmers' Fair w.e.f Feb. 11-13 at its main campus Chatha, Jammu.

AI-enabled Advanced Agriculture: The visionary Vice Chancellor of the University has decided to organize the mela with the theme '*AI-enabled Advanced Agriculture*.' The theme of the mela thus specifies that special focus will be on technologies which are based on Artificial Intelligence and that come with the added advantage of precision, timeliness, resource use efficiency and real time solutions for the issues confronting the farming community in agriculture and allied sectors in the country. Digital technologies like Artificial Intelligence have given the world a new developmental paradigm. With more than 9 billion people predicted to populate the planet by 2050, finding better and smarter ways to grow food is essential. We thus need new ways to grow more food more sustainably and profitably by applying digital technologies such as data science, advanced sensors in the field and from space, digital communication channels, and automation on the field. Today agriculture is also witnessing what is called 'Digital Farming or Digitalisation'. Digital Farming encompasses 'ICT and data ecosystems to support the development and delivery of timely, targeted information and services to make farming profitable and sustainable while delivering safe nutritious and affordable food for all'. Use of various AI tools in agriculture has also emerged as another revolution, more so for the large numbers of the world's smallholder farmers. Nearly a third of the global population relies on agriculture for a living, and growth in this sector has been shown to be at least twice as effective at reducing poverty as growth coming from other sectors. Thus use of AI in agriculture has to be promoted for advancement of agriculture. Among various AI tools are Internet of Things (IoT), precision Farming, Drones and Robots. The use of sensors, cameras, and other devices to turn every element and action involved in farming into data. Weather, moisture, plant health, mineral status, chemical applications, pest presence and much more can all be turned into large data sets that allow big data engineers to draw out insights about the farm at varying levels of granularity via software algorithms. The AI technologies also ensure that information collected about that unit is measured, collected, analyzed, and actioned for the same location and is differentiated from all of the other surrounding assets. AI technologies have the potential to improve agricultural productivity even in areas with limited resources.

The three days long event of the University besides focusing on AI enabled agriculture will also provide a platform to all the relevant stakeholders including farmers, farm women, students, youths, entrepreneurs, private

players, and input dealers, officers/officials from line departments and financial institutions and of different agencies from all across the country where they can witness, exchange sell, purchase and showcase their products ideas and sustainable technologies. With the SKUAST-Jammu having important MoUs with leading foreign universities, international participation is also expected in the summit. Organized with the active collaboration of all its faculties, Krishi Vigyan Kendras, research institutes and all the constituent units of the University, it is expected that the mela will witness a footfall of many thousands.

The event will specially focus on sustainable agricultural practices and approaches like Organic and Natural Farming. The present government is also focusing a lot on Natural farming. In the next 2 years, one crore farmers will be initiated into natural farming supported by certification and branding. A flower show, a vegetable & fruit show at the mela will also be a point of attraction where the growers will display their products. Dog show will also be a great fun and learning experience for the pet lovers. The participants can win exciting prizes also. Sports are also an important part of our day to day lives. The Mela will also host sports events and chaff cutting competitions especially for rural youths where they will get engaged in various sports to prove how much physically fit they are.

The mela will also provide an opportunity to visitors to purchase all kinds of inputs/planting material and farm implements being displayed by many input dealers and private agencies. The summit will focus on technologies demonstrating the organic inputs like Bio fertilizers, Bio-control agents, bio organic nutrient management, organic waste treatment and microbial preparations like Bijamrita, and Jeevamrita. Farmers of the region including farm women and youths who have earned a name through development of various products/technologies/practices will also be a part of this mela depicting and showcasing their innovations/products. Different collective organizations i. e Self Help groups/Farmer Producer Companies and Farmer Producer Organizations will also participate in this event with various kinds of prototypes/products they have developed. Students from different educational institutes of the region will also be attending the mela to learn more about agriculture. Shri Anna i. e Millets called as '*Super Foods*' and '*Food of Future*' will also be an important feature of this summit. Various types of ethnic value added food products made from different traditional crops including millets will be at display. The country has become the Startup capital of world with so many startups coming up in agriculture and allied sectors. The startups have an important role in employment and income generation. This mela will also give an opportunity to the young entrepreneurs to depict their business models and prototypes.

Lack of awareness about different government schemes is an important constraint for the farming community to avail the benefits of these schemes. SKUAST-Jammu has taken special care of this. To ensure that the farming community becomes aware of all schemes related to them, different allied departments as well as financial institutions like NABARD, J&K Bank, SBI, JKEDA; IFFCO, Department of Rural Development and Panchayati Raj, Jammu Kashmir Academy of Arts Culture and Languages (JKAACL) and many other organizations will be there to guide and aware all. The farming community will be able to avail the benefits by on spot registration.

There will be expert sessions between farmers and scientists and live demonstrations including use of Drones in Agriculture, Farmer Scientist interactions, Field visits. Special sessions on empowerment of women in Agriculture, Industry-Academia Linkages, Post-harvest processing and value addition and on many other aspects related to farm sector will also be a key feature of the mela.

To conclude, the mega event is going to be a one stop solution for the farming community. All of must save the date and be a part of this grand occasion to learn, update and explore new ideas, skills and opportunities.

Digital Soil Twins: Virtual Modelling for Precision Land Management and Climate-Adaptive Farming



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Abstract

Digital Soil Twins (DSTs) represent an emerging paradigm in digital agriculture, where a dynamic virtual replica of soil systems is created to simulate and predict soil processes under varying management and environmental conditions. With increasing climate variability, land degradation, and resource limitations, conventional soil monitoring approaches often fail to provide timely and location-specific information for effective decision-making. Digital soil twins address this limitation by integrating diverse data streams such as soil sensor measurements, satellite observations, weather information, field management records, and laboratory soil analyses into advanced computational platforms. Using artificial intelligence, machine learning algorithms, and process-based simulation models, DSTs enable real-time monitoring and predictive analysis of soil moisture dynamics, nutrient availability, soil carbon changes, and crop responses. These capabilities support precision nutrient management, optimized irrigation scheduling, and improved assessment of climate risks. In developing countries where agriculture is largely dependent on smallholder and rainfed systems, digital soil twins can significantly enhance resource-use efficiency and farm resilience. Despite their promising potential, challenges related to data availability, infrastructure, model accuracy, and technology adoption remain. Future research should focus on scalable sensor networks, integration of biological soil indicators, and development of cost-effective digital platforms to enable widespread implementation of DST-based decision support systems.

Keywords: Digital Soil Twins; Precision Agriculture; Soil Modelling; Artificial Intelligence; Climate-Smart Agriculture; Soil Health Monitoring; Digital Agriculture.

Introduction

Soil is a fundamental natural resource that supports agricultural productivity, environmental sustainability, and global food security. It acts as the primary medium for plant growth by supplying essential nutrients, water, and physical support to crops. Beyond crop production, soil provides multiple ecosystem services such as nutrient cycling, water filtration, biodiversity conservation, and carbon sequestration. Healthy soils play a vital role in regulating the global carbon cycle by storing large amounts of organic carbon, thereby contributing to climate change mitigation. However, soils across the world are increasingly under pressure due to unsustainable land management practices, excessive use of chemical fertilizers, soil erosion, nutrient depletion, and declining organic matter. Climate change further intensifies these challenges through irregular rainfall patterns, temperature extremes, and a higher frequency of droughts and floods, making sustainable soil management more complex and urgent.

Conventional soil monitoring methods are largely based on periodic soil sampling and laboratory analysis. Although these approaches provide valuable information about soil properties, they are generally static and represent soil conditions only at a specific time and location. Such methods often lack adequate spatial and temporal resolution and may fail to capture the dynamic nature of soil processes influenced by climate, cropping systems, and management practices. Moreover, delays between soil sampling, laboratory analysis, and advisory recommendations can limit timely decision-making for farmers and land managers.

Recent advances in digital agriculture offer new opportunities to overcome these limitations. Technologies such as remote sensing, geographic information systems (GIS), Internet of Things (IoT) sensors, artificial intelligence (AI), and big data analytics are increasingly integrated into agricultural management systems. The concept of digital twins, originally developed in engineering and manufacturing to create virtual replicas of physical systems, is now being applied to soil and environmental sciences. A Digital Soil Twin (DST) represents

a dynamic virtual model of a soil system that continuously updates using real-time data, enabling simulation of soil processes and supporting improved land management decisions.

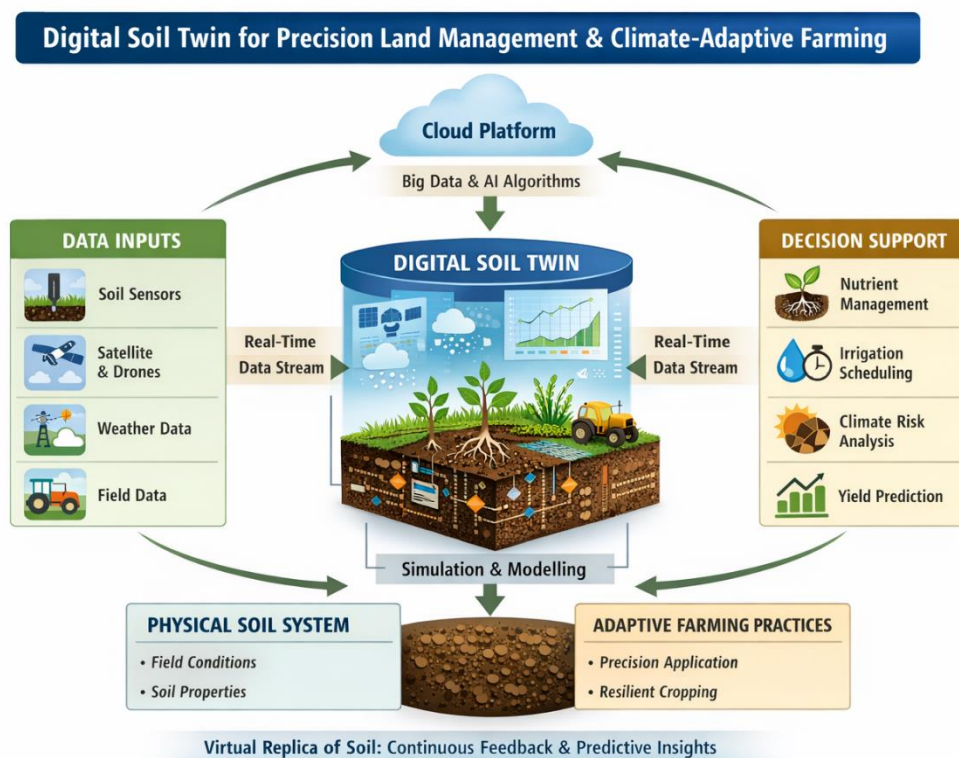


Figure 1. Conceptual representation of a Digital Soil Twin illustrating the interaction between the physical soil system, data sources, modelling platforms, and decision-support outputs.

Components of a Digital Soil Twin System

A Digital Soil Twin (DST) system is composed of several interconnected components that work together to create and maintain a dynamic virtual representation of real-world soil systems. These components enable continuous data collection, analysis, and simulation to support improved soil management and agricultural decision-making. **Physical Soil System:** The physical soil system forms the foundation of a digital soil twin. It represents the actual soil environment in agricultural fields, including its physical, chemical, and biological properties such as texture, structure, soil moisture, nutrient availability, soil organic carbon, and microbial activity. These factors influence crop growth, water movement, nutrient cycling, and overall soil health. The physical soil environment acts as the real-world system whose behaviour is replicated and monitored through the digital model.

Data Acquisition Layer: The data acquisition layer collects real-time and periodic information from multiple sources. Soil sensors installed in the field measure parameters such as soil moisture, temperature, and electrical conductivity. Satellite and drone imagery provide spatial data related to vegetation health, soil moisture, and land surface temperature. Weather stations supply meteorological information including rainfall, temperature, humidity, and evapotranspiration. In addition, farm management records such as fertilizer application, irrigation practices, and cropping patterns provide important contextual information.

Data Integration and Modelling: The collected data are integrated and stored using cloud computing and big data platforms. These systems enable efficient management of large datasets from multiple sources. At the core of the digital soil twin is the modelling layer, which combines process-based soil models with artificial intelligence and machine learning algorithms. These models simulate soil processes such as nutrient cycling, moisture dynamics, and carbon changes, allowing prediction of soil behaviour under different management and environmental conditions.

Decision Support and Feedback: The outputs are delivered through visualization dashboards and mobile-based advisory tools that help farmers and land managers make informed decisions regarding fertilizer use, irrigation scheduling, and crop planning. A continuous feedback loop updates the digital model using new field observations, improving prediction accuracy over time.

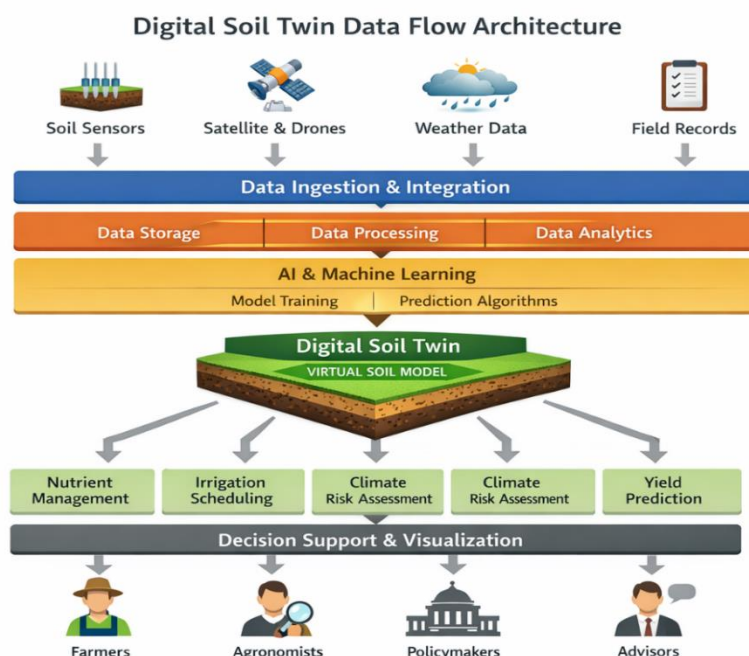


Figure 2. Architecture of data flow in a Digital Soil Twin system showing data acquisition, integration, modelling, and decision-support layers.

Technologies Enabling Digital Soil Twins

The successful implementation of Digital Soil Twins (DSTs) relies on the integration of several advanced technologies that enable continuous data collection, analysis, and simulation of soil processes. These technologies form the backbone of digital agriculture by providing real-time insights into soil conditions and supporting predictive decision-making.

Internet of Things (IoT) Soil Sensors

Internet of Things (IoT)-based soil sensors play a crucial role in the development of digital soil twins by enabling real-time monitoring of soil parameters directly from the field. These sensors are capable of measuring key variables such as soil moisture, temperature, electrical conductivity (EC), and in some advanced systems, nutrient concentrations like nitrate or potassium. Data collected from these sensors are transmitted through wireless communication networks to central data platforms where they are analyzed and integrated into digital soil models. Continuous monitoring helps capture the temporal variability of soil conditions, which is often missed in traditional soil sampling methods. Such real-time measurements improve irrigation scheduling, nutrient management, and early detection of soil stress conditions.

Remote Sensing and GIS

Remote sensing technologies, including satellite imagery and drone-based observations, provide large-scale spatial information about soil and crop conditions. Satellite sensors can estimate parameters such as soil moisture, vegetation health through vegetation indices (e.g., NDVI), land surface temperature, and crop growth patterns. Geographic Information Systems (GIS) facilitate the integration and visualization of spatial data layers, enabling better interpretation of soil variability across landscapes. Remote sensing data also supports monitoring of land degradation, soil erosion risk, and changes in vegetation cover, which are important for sustainable land management.

Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) algorithms are central to the analytical capabilities of digital soil twins. These technologies analyze large datasets generated from sensors, satellite imagery, and historical records to identify patterns and relationships among soil properties, weather conditions, and crop responses. AI-driven predictive models can estimate nutrient availability, soil moisture dynamics, crop growth trends, and potential yield outcomes. Such predictive analytics allow farmers and agronomists to make proactive management decisions rather than relying on reactive approaches.

Digital Soil Mapping

Digital Soil Mapping (DSM) uses statistical models and machine learning techniques to predict the spatial distribution of soil properties using environmental covariates such as climate, topography, vegetation, and remote sensing data. High-resolution digital soil maps provide detailed information about soil texture, organic carbon, nutrient status, and other soil characteristics across large areas. These maps serve as a critical foundation for building digital soil twins by providing baseline soil information at fine spatial scales.

Cloud Computing and Big Data

Digital soil twin systems generate and process enormous volumes of data from multiple sources. Cloud computing platforms enable efficient storage, processing, and real-time accessibility of these datasets. Big data technologies allow integration of heterogeneous datasets such as sensor streams, satellite images, weather records, and farm management data. Cloud-based infrastructure also facilitates collaboration among researchers, farmers, and policymakers by providing centralized access to soil information and decision-support tools.

Applications in Precision Land Management

Digital Soil Twins (DSTs) have the potential to significantly enhance precision land management by enabling real-time monitoring, predictive analysis, and site-specific decision-making. By integrating soil data from sensors, remote sensing platforms, and laboratory analyses with advanced modelling tools, DSTs help farmers and land managers optimize resource use while maintaining soil health and long-term productivity.

One of the most important applications of DSTs is **site-specific nutrient management (SSNM)**. Soil nutrient availability often varies within a single field due to differences in soil properties, cropping history, and management practices. Digital soil twins can analyze these variations using soil sensor data, geospatial information, and crop models to predict nutrient deficiencies and fertilizer requirements at fine spatial scales. Based on these insights, DSTs can recommend precise fertilizer types, doses, and application timings for different field zones. This targeted approach improves nutrient use efficiency, reduces environmental pollution caused by excessive fertilizer use, and lowers production costs.

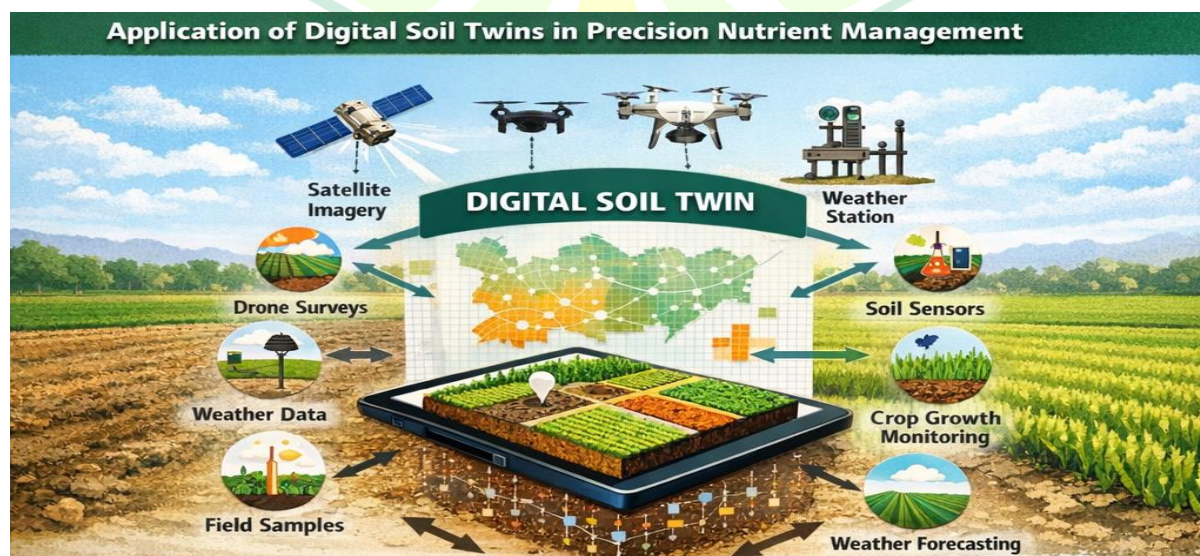


Figure 3. Application of Digital Soil Twin technology in precision nutrient management for site-specific fertilizer recommendations.

Another critical application is **soil moisture monitoring and irrigation scheduling**. By integrating soil moisture sensor data, weather forecasts, and crop evapotranspiration models, digital soil twins can simulate soil water dynamics and predict moisture availability. These insights enable farmers to schedule irrigation more accurately, ensuring that crops receive adequate water without over-irrigation. Such precision irrigation strategies improve water use efficiency and help prevent issues like waterlogging, drought stress, and nutrient leaching.

DSTs also support **soil carbon monitoring and management**. Soil organic carbon (SOC) plays a crucial role in maintaining soil fertility, structure, and resilience against climate stress. By integrating long-term soil data, crop residue management records, and environmental variables, digital soil twins can model SOC dynamics and track changes in carbon stocks over time. This capability is valuable for evaluating soil health improvement practices and assessing carbon sequestration potential.

In addition, DSTs help in **soil degradation monitoring** by identifying early signs of problems such as erosion, salinity, compaction, or nutrient depletion. Through the integration of remote sensing data, terrain information, and soil process models, DSTs can generate early warnings and guide conservation measures. Finally, digital soil twins assist in crop suitability assessment, enabling farmers to select appropriate crops and cropping systems based on soil characteristics and climatic conditions, thereby improving productivity and resilience.

Role in Climate-Adaptive Farming

Climate change poses serious challenges to agricultural sustainability by increasing the frequency of droughts, heat waves, irregular rainfall, and extreme weather events. These factors directly affect soil processes, water availability, and crop productivity. In this context, Digital Soil Twins (DSTs) provide an advanced decision-support system that enables simulation, prediction, and proactive management of soil-crop systems under changing climatic conditions.

One of the key contributions of DSTs is **climate risk prediction**. By integrating real-time weather data, historical climate records, and soil process models, digital soil twins can simulate the effects of drought, heat stress, and heavy rainfall on soil moisture, evapotranspiration, and erosion risk. These predictions help farmers anticipate climate-related threats and adopt suitable mitigation measures such as adjusting sowing dates, selecting drought-tolerant crop varieties, and implementing soil conservation practices.

DSTs also play a vital role in **soil carbon sequestration modelling**. By analyzing crop residue management, organic amendments, and land-use practices, digital soil twins can simulate carbon inputs and decomposition processes to estimate long-term changes in soil organic carbon stocks. This helps identify management practices that enhance carbon storage and contribute to climate change mitigation.

In addition, DSTs promote **sustainable input management** by optimizing fertilizer and irrigation use based on real-time soil conditions and climate forecasts. This reduces nutrient losses, greenhouse gas emissions, and water wastage. Furthermore, DSTs support **adaptive crop planning** by evaluating crop performance under different climate scenarios, enabling farmers to select resilient cropping systems and maintain stable productivity in a changing climate.

Potential Applications in Developing Countries and Rainfed Systems

Digital Soil Twins (DSTs) offer significant potential for improving agricultural productivity and sustainability in developing countries, where agriculture is largely dominated by smallholder farmers and rainfed cropping systems. In these regions, limited access to inputs, climate variability, and dependence on monsoon rainfall make efficient soil and water management essential for ensuring food security and farm resilience. By integrating real-time soil data, weather information, and crop management records into predictive models, DSTs can generate location-specific recommendations that help farmers optimize resource use and reduce production risks.

One of the major advantages of DST technology is its compatibility with **mobile-based advisory systems**. As smartphone use increases among farmers, digital soil twin platforms can deliver timely advisories on fertilizer application, irrigation scheduling, soil moisture status, and crop management directly to mobile devices. This strengthens the link between scientific research and farm-level decision-making.

DSTs are particularly valuable in **rainfed and semi-arid farming systems**, where rainfall variability significantly affects crop performance. By simulating soil moisture dynamics and crop responses to changing

weather conditions, DSTs can guide farmers in selecting suitable crops, adjusting sowing dates, and adopting soil moisture conservation practices. Additionally, they can support **watershed management and soil conservation planning** by identifying erosion-prone areas and evaluating appropriate land management interventions.

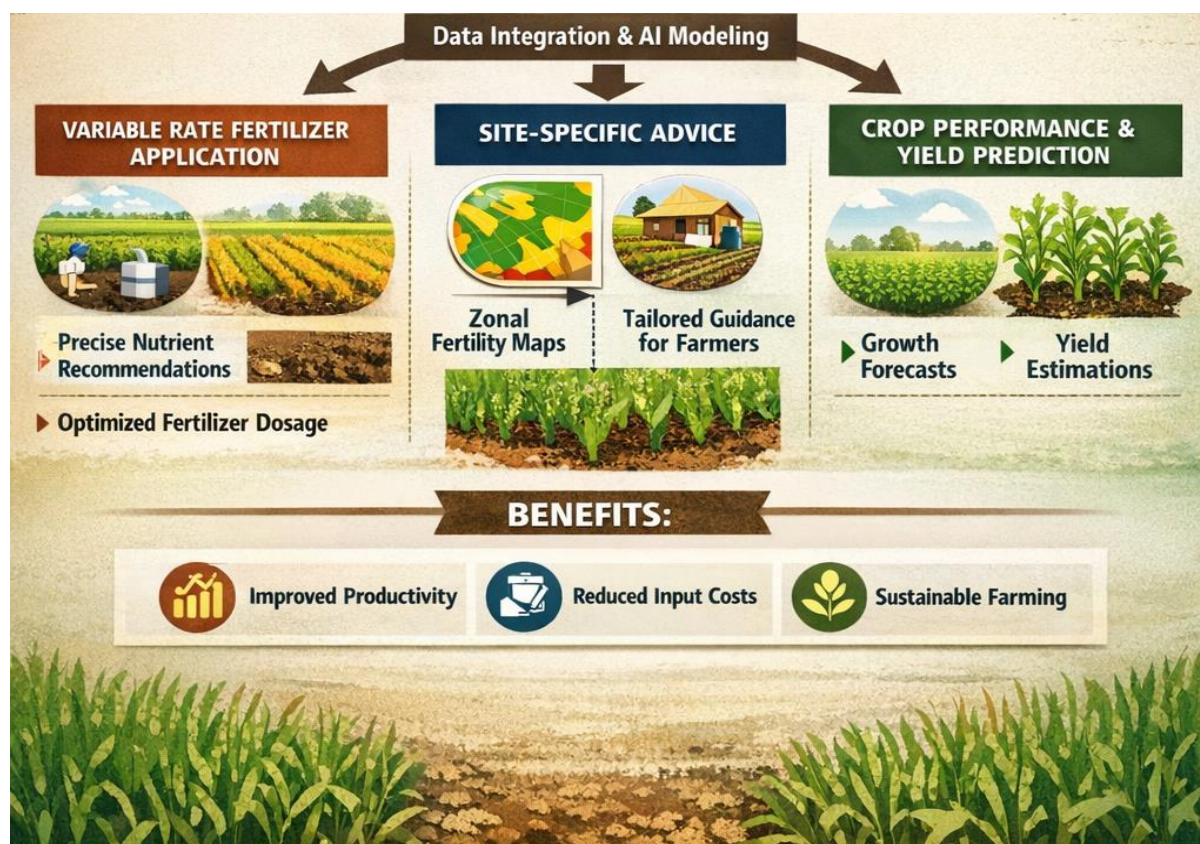


Figure 4. Proposed Digital Soil Twin framework for rainfed agricultural systems integrating soil, climate, and management data.

Challenges and Limitations

Despite the significant potential of Digital Soil Twins (DSTs) in improving soil management and precision agriculture, several challenges limit their widespread adoption. One major constraint is the limited availability of high-resolution and continuous soil data, as many regions still rely on conventional soil surveys and sporadic laboratory analyses. The lack of technological infrastructure, including sensor networks, reliable electricity, and internet connectivity in rural areas, further restricts real-time data collection and system updates. Additionally, establishing and maintaining digital soil twin systems requires substantial financial investment and skilled expertise in soil science, data analytics, and geospatial technologies, which may not be readily available in many developing regions. Another challenge is model uncertainty, as soil processes are complex and influenced by multiple interacting physical, chemical, and biological factors. Finally, data privacy and ownership concerns have emerged due to the large volumes of agricultural data generated, highlighting the need for clear data governance policies to protect farmer interests and ensure responsible use of digital technologies.

Conclusion

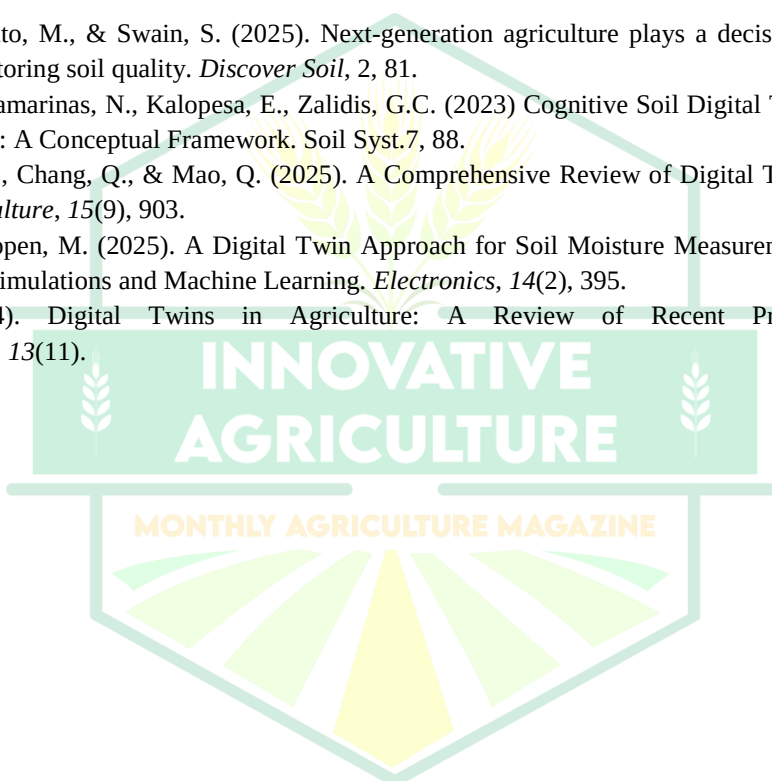
Digital Soil Twins (DSTs) represent a transformative advancement in soil science and agricultural management by enabling the creation of dynamic virtual models that mirror real-world soil systems. By integrating real-time data from sensors, remote sensing platforms, weather stations, and farm management records with advanced modelling and artificial intelligence, DSTs provide a comprehensive framework for monitoring, analysing, and predicting soil processes. This capability significantly enhances the precision and efficiency of land management practices.

The adoption of digital soil twins has the potential to revolutionize **precision agriculture and climate-smart farming** by supporting site-specific nutrient management, optimized irrigation scheduling, and early detection of soil degradation. Through predictive modelling and real-time monitoring, DSTs enable farmers and land managers to make proactive and informed decisions that improve resource use efficiency while maintaining soil health.

However, the successful implementation of digital soil twins requires strong multidisciplinary collaboration among **soil scientists, agronomists, data scientists, engineers, and policymakers**. Investments in digital infrastructure, sensor technologies, and capacity building are also essential. With supportive policies and technological innovation, digital soil twins can play a vital role in enhancing sustainable agricultural productivity and resilience in the face of growing climate and resource challenges.

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Waterlogging stress: an emerging threat for global food security



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Introduction

Waterlogging stress occurs when excess water saturates the soil for prolonged period, leading to poor soil aeration and reduced oxygen availability in the root zone. Under such conditions, normal root respiration is disrupted, impairing nutrient uptake, metabolic activities and overall plant growth. Although water is essential for crop production, its excess can be as damaging as drought, making waterlogging a serious yet often unrecognized abiotic stress in agriculture (Akchaya et al., 2024; Reddy et al., 2025). In recent years, the incidence of waterlogging has increased markedly due to climate change, induced extreme rainfall events, rising groundwater tables, sea-level rise in coastal regions and inadequate drainage affecting 16% of global cultivate area.

Waterlogging stress adversely affects crop productivity by reducing germination, stunting growth, lowering yields and increasing susceptibility to pests and diseases. Major food crops such as rice, wheat, maize, pulses and oilseeds exhibit varying degrees of sensitivity, with yield losses becoming more severe when waterlogging coincides with critical growth stages (Ashraf, 2012; Gangana Gowdra et al., 2025). Given the escalating frequency of waterlogging events and their profound impact on soil health, crop performance and farming livelihoods, waterlogging stress has emerged as a critical constraint to sustainable agriculture. Understanding its causes, plant responses and management strategies is therefore essential to ensure global food security under changing climatic scenarios (Manibharathi et al., 2025).



Fig 1. Waterlogging in a maize field

Effects of waterlogging on soil environment

Waterlogging severely alters the soil environment by creating oxygen-deficient (anaerobic) conditions due to the filling of soil pores with water. This condition restricts gaseous exchange, leading to accumulation of carbon dioxide and other harmful gases in the root zone. The reduction in oxygen supply lowers soil redox potential and promotes the formation of toxic reduced compounds such as ferrous iron, manganese, hydrogen sulphide, and methane, which adversely affect root growth (Sandeep et al., 2025). Waterlogging also causes nutrient imbalance, particularly loss of nitrogen through denitrification and reduced availability of nitrate-nitrogen (Luo et al., 2024). Soil pH tends to change under prolonged saturation, where acid soils show a rise in pH, while alkaline soils may

exhibit a slight decrease. The biological environment of soil is also disturbed (Senthamil et al., 2024a), with aerobic microorganisms being suppressed and anaerobic microbes becoming dominant, resulting in reduced microbial diversity and slower decomposition of organic matter. Structurally, waterlogging weakens soil aggregates, reduces soil strength and restricts root penetration (Senthamil et al., 2025a). Overall, prolonged waterlogging deteriorates soil health, lowers soil fertility and creates an unfavourable environment for normal crop growth.

Impact of waterlogging on crop physiology

Waterlogging adversely affects shoot physiology by impairing root function, which leads to reduced water and nutrient supply to aerial parts and triggers stomatal closure, thereby limiting CO₂ diffusion and reducing photosynthetic rate (Senthamil et al., 2024b). Chlorophyll degradation and nitrogen deficiency cause leaf chlorosis and diminished light-harvesting efficiency, while restricted gas diffusion results in ethylene accumulation that induces leaf epinasty, premature senescence, and reduced leaf expansion (Zhang et al., 2025). Waterlogging also promotes oxidative stress in shoots through excessive production of reactive oxygen species, causing membrane damage and disruption of chloroplast structure (Salakinkop et al., 2025). In addition, reduced photosynthate production and impaired assimilate transport limit shoot growth, leaf area development, and biomass accumulation, ultimately leading to poor reproductive performance and yield reduction.

Impact of waterlogging on crop growth and yield

Waterlogging generally exerts a negative influence on crop growth and yield by suppressing key morphological, physiological and yield-related traits, while inducing a few adaptive responses. Across cereals, legumes, oilseeds and fibre crops, waterlogging commonly leads to a reduction in root length, root dry weight, shoot biomass, leaf area, plant height, branching, and yield components such as number of pods, bolls, or grains. These reductions are primarily associated with oxygen deficiency in the root zone, impaired nutrient uptake and disruption of carbon assimilation (Zhang et al., 2025). Yield penalties are frequently observed due to poor reproductive development, including fewer pods or bolls, reduced seed setting and abnormal grain or ear development. At the same time, several crops exhibit adaptive morphological responses under waterlogged conditions, such as increased formation of adventitious roots and root aerenchyma, which facilitate internal oxygen transport and improve survival under hypoxic stress (Senthamil et al., 2025b). However, these adaptations are often insufficient to fully compensate for growth inhibition, resulting in overall yield decline. Thus, waterlogging stress generally shifts crop performance toward survival-oriented traits at the expense of productivity, with the magnitude of impact varying among species, genotypes and duration of stress.

Implications for global food security

Waterlogging stress has serious implications for global food security as it directly threatens crop productivity, stability of food supply and farmer livelihoods. With climate change increasing the frequency of intense rainfall events, floods and poor drainage situations, waterlogging is emerging as a major constraint in both rainfed and irrigated agricultural systems (Akchaya et al., 2024; Senthamil et al., 2024b). Prolonged soil saturation reduces crop growth and yields of major food, feed, oilseed and fibre crops, leading to lower overall food production. Yield losses are often unpredictable and location-specific, increasing production risks and price volatility in global food markets. Waterlogging also degrades soil health by promoting nutrient losses and greenhouse gas emissions, thereby reducing the long-term productive capacity of agricultural lands (Sandeep et al., 2025). Smallholder farmers in low-lying and poorly drained regions are particularly vulnerable, as repeated crop failures can undermine income security and access to food. Furthermore, expansion of waterlogged areas limits effective land use and necessitates costly investments in drainage and crop adaptation strategies (Manik et al., 2019). Collectively, these impacts weaken agricultural resilience and pose a significant challenge to achieving sustainable food security under changing climatic conditions.

Management and mitigation strategies

Management and mitigation of waterlogging stress require an integrated approach combining engineering, agronomic, soil and genetic strategies to reduce excess water accumulation and improve crop tolerance.

1. Agronomic strategies

Improving drainage is the most effective measure, including surface drainage through field channels, bund opening, land levelling and broad-bed and furrow systems, as well as subsurface drainage using tile or pipe drains in chronically affected areas (Manik et al., 2019). Irrigation management plays a key role by avoiding over-irrigation, adopting need-based scheduling and improving conveyance efficiency to minimize seepage losses from canals and field ditches.

Soil management practices such as deep tillage or sub-soiling help break hard pans and improve infiltration, while the application of organic amendments enhances soil structure and permeability. In sodic or saline-waterlogged soils, chemical amendments like gypsum facilitate flocculation and improve drainage. From a crop management perspective, selecting waterlogging-tolerant crops and varieties, adjusting sowing time, adopting suitable cropping systems and rotations and using raised beds reduce crop exposure to saturated conditions. Incorporation of deep-rooted crops in rotations helps lower the water table (Asraf, 2012).

2. Breeding approaches

At the genetic and physiological level, breeding and development of varieties with adaptive traits such as adventitious root formation, aerenchyma development and efficient anaerobic metabolism improve crop survival under waterlogged conditions.

3. Foliar application of phytochemicals

Studies have shown that exogenous application of hormones helps in restoring endogenous hormonal balance, regulating carbohydrate metabolism and improving source-sink relationships, thereby strengthening plant defense mechanisms under waterlogging conditions (Manik et al., 2019). For example, foliar application urea at 2% significantly mitigated the waterlogging stress in maize (Senthamil et al., 2025c) and cowpea (Senthamil et al., 2025d). Similarly, foliar spray of kinetin and gibberellic acid has been reported to increase yield by 17–20% in mungbean subjected to five days of waterlogging, primarily through enhanced stress defense responses (Islam et al., 2022). Likewise, 6-benzyladenine (6-BA), a synthetic cytokinin, has been shown to scavenge reactive oxygen species, delay leaf senescence, extend the photosynthetic period, and improve photosynthetic efficiency under stress conditions (Senthamil et al., 2025c).

Conclusion

Waterlogging stress has emerged as a major abiotic constraint to agricultural productivity, profoundly affecting the soil environment, crop growth and yield, with far-reaching implications for global food security. The adverse soil changes create reduction in plant growth, poor reproductive development and significant yield losses across a wide range of crop species, despite the expression of limited adaptive responses such as aerenchyma and adventitious root formation. In the face of climate change, effective management of waterlogging requires an integrated approach involving improved drainage, real time adoption of mitigation strategies, soil management and the cultivation of waterlogging tolerant crops and varieties. Addressing waterlogging stress is essential not only for sustaining crop productivity and soil health but also for enhancing agricultural resilience and ensuring long-term global food security.

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“Supply chain management in the Digital Age”

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In today's evolving business landscape, technology is reshaping the way supply chains operate making processes more efficient, transparent, and responsive. The integration of digital tools and systems is no longer a luxury but rather a necessity for companies striving to stay competitive. From inventory management and logistics to demand forecasting and supplier coordination, technology's role in supply chain management is pivotal.

Below, we dive into the transformative impact of digital technology on supply chain management. In addition, we discuss career opportunities in the digital supply chain field, highlighting the skills and expertise needed to thrive in this innovative sector.

Exploring the Digital Supply Chain Revolution

The digital supply chain revolution marks a significant shift from traditional, linear supply chains to interconnected, intelligent networks. This transformation leverages cutting-edge technologies to enhance visibility, streamline operations, and foster real-time decision-making. By adopting digital tools such as artificial intelligence (AI)-driven analytics, blockchain for secure transactions, and Internet of Things (IoT) devices for real-time tracking, businesses can achieve unprecedented levels of efficiency and resilience.

The Shift from Traditional to Digital Supply Chains

The transition from traditional to digital supply chains represents a fundamental transformation in how businesses operate and manage their logistics. Traditional supply chains are typically linear and reactive, relying on historical data and standalone systems, which often results in limited visibility and slow response times.

In contrast, digital supply chains leverage advanced technologies like artificial intelligence, IoT, blockchain, and cloud computing to create interconnected and intelligent networks. These digital systems enable real-time data sharing, predictive analytics, and enhanced transparency, allowing companies to respond more quickly to market changes and disruptions.

Key Technologies Driving the Digital Supply Chain

The digital transformation of supply chains is powered by several key technologies that collectively enhance efficiency, visibility, and responsiveness. As previously mentioned, AI and machine learning enable predictive analytics and intelligent decision-making, helping businesses anticipate demand and optimize inventory levels. The IoT provides real-time tracking and monitoring of assets, ensuring better visibility and control throughout the supply chain. To add, blockchain technology enhances transparency and security by creating immutable records of transactions, which is crucial for traceability and reducing fraud. Cloud computing then offers scalable solutions for data storage and processing, facilitating seamless integration and collaboration among supply chain

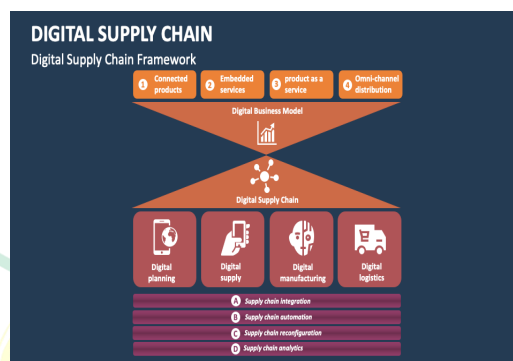


Figure 1: Digital Supply Chain Framework

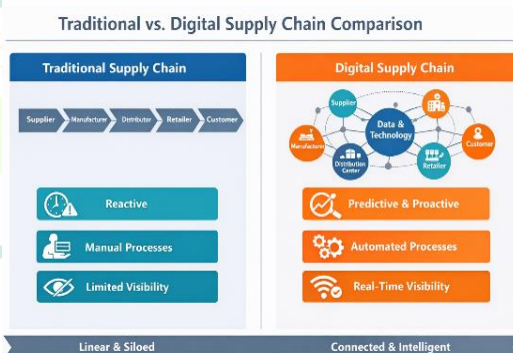


Figure 2: Traditional vs Digital Supply Chain Comparison

partners. Lastly, advanced robotics and automation streamline warehouse operations, improving accuracy and reducing labor costs.

Altogether, these technologies create a robust digital infrastructure that allows companies to adapt quickly to changing market conditions and drive continuous improvement across their supply chain operations.

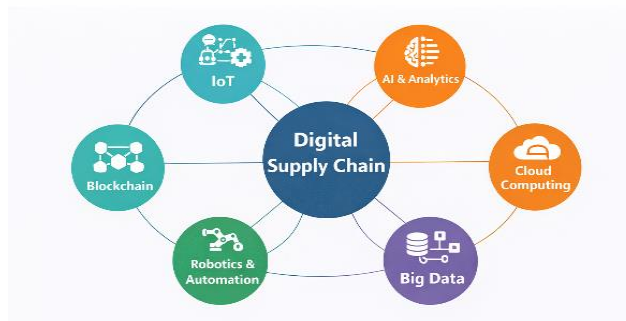


Figure 3: Digital Supply Chain Technologies Integration

Benefits of Digital Supply Chain Management

Implementing digital supply chain management offers numerous advantages that can significantly influence a business's efficiency and customer satisfaction.

Enhanced Efficiency and Reduced Costs

One of the primary benefits is enhanced efficiency and reduced costs. By leveraging automation and real-time data analytics, businesses can streamline their supply chain operations, minimize human errors, and optimize inventory management. This leads to cost savings through reduced operational expenses and improved resource allocation.

Improved Customer Satisfaction and Service Levels

Digital supply chains contribute to improved customer satisfaction and service levels. With advanced technologies like AI and predictive analytics, companies can better anticipate customer demands and ensure timely deliveries. This further enhances the overall customer experience, fosters customer loyalty, and provides a competitive edge in today's fast-paced market.

Challenges and Risks in Digital Supply Chain Management

Digital supply chain management presents a range of benefits, but it also comes with challenges and risks worth noting.

Cybersecurity Threats and Data Privacy Concerns

Cybersecurity threats and data privacy concerns are paramount as digital supply chains expand, increasing the vulnerability to cyberattacks. Nearly all companies have experienced a cybersecurity breach within their supply chain, highlighting the need for robust security measures to protect against unauthorized access and data theft.

Managing Supply Chain Disruptions in the Digital Age

Managing supply chain disruptions in the digital age requires real-time monitoring and adaptive strategies to maintain operational continuity and mitigate risks associated with technological advancements.

The Role of AI and Machine Learning in Supply Chains

AI and machine learning are revolutionizing supply chain management by optimizing processes, enhancing decision-making, and providing real-time visibility. AI-based solutions can predict potential problems and prescribe solutions proactively, helping companies manage disruptions more effectively. AI and machine learning improve forecasting accuracy, optimize inventory levels, and enhance overall operational efficiency by automating routine tasks and analyzing large datasets.

Predictive Analytics for Demand Forecasting

Predictive analytics plays a crucial role in demand forecasting by using historical data, statistical algorithms, and machine learning techniques to predict future demand. This approach enables businesses to anticipate customer needs more accurately, reduce inventory costs, and improve service levels. By analyzing patterns and trends in

past sales data, predictive models can identify factors influencing demand—such as seasonality, market trends, and promotional activities.

Automation of Supply Chain Operations

Automation in supply chain operations leverages advanced technologies like robotics, AI, and machine learning to streamline and optimize various processes. This transformation reduces the need for manual intervention, minimizes errors, and increases efficiency. Automated systems can handle tasks ranging from inventory management and order processing to transportation and logistics, enabling faster and more accurate operations. For instance, AI-powered robots in warehouses can pick and pack items with precision, while automated tracking systems provide real-time visibility into shipment status. By integrating these technologies, businesses can achieve substantial cost savings, improve delivery times, and enhance overall supply chain performance.

Blockchain Technology: A Game Changer for Supply Chains

Blockchain technology has emerged as a transformative force in supply chain management, providing unparalleled transparency, security, and efficiency. By creating an immutable ledger of transactions, blockchain ensures that all participants in the supply chain can trust the data's accuracy and integrity.

Ensuring Transparency and Traceability

Transparency and traceability are critical benefits of integrating blockchain technology into supply chains. By recording every transaction on a secure, immutable ledger, blockchain provides a comprehensive, tamper-proof record of a product's journey from origin to consumer. This capability allows companies to verify the authenticity of products, prevent fraud, and ensure compliance with regulatory standards. Enhanced traceability helps quickly identify and address issues such as recalls, thereby ensuring swift action to protect consumers. Additionally, providing stakeholders with real-time access to supply chain data builds trust and fosters accountability across the entire supply network.

Reducing Frauds and Errors

Integrating blockchain technology into supply chains considerably reduces fraud and errors by creating a secure, transparent, and immutable ledger of all transactions. Blockchain's decentralized nature ensures that once a transaction is recorded, it cannot be altered or deleted, making it nearly impossible to manipulate data or introduce counterfeit products into the supply chain. This level of security prevents common fraudulent activities and ensures the integrity of the entire supply chain. Furthermore, the automation of processes through smart contracts minimizes human errors by executing predefined actions automatically when certain conditions are met, thereby enhancing overall accuracy and reliability.

Career Opportunities in Digital Supply Chain Management

The digital transformation of supply chains has created a wide array of career opportunities for professionals and digital supply chain managers with the right skill sets.

Emerging Roles and Skill Sets

The digital supply chain landscape is rapidly evolving, bringing forth new roles and skill sets essential for navigating this transformation. Emerging roles include positions such as data analysts, digital supply chain managers, and AI specialists who focus on optimizing supply chain operations through advanced technologies. These roles require a blend of traditional supply chain knowledge and expertise in data analytics, AI, and blockchain technologies.

How to Prepare for a Career in Digital Supply Chain

To thrive in these emerging roles, individuals need to focus on continuous learning and staying updated with the latest technological advancements. This includes gaining proficiency in tools like predictive analytics software, AI-driven supply chain management systems, and blockchain platforms. Also, developing soft skills including problem-solving, critical thinking, and effective communication is crucial. These roles often require cross-functional collaboration and the ability to translate complex data insights into actionable strategies.

Pursue Your Career in Supply Chain Management

Are you looking to advance your career in the dynamic field of supply chain management? University of the Cumberlands offers a comprehensive Supply Chain and Project Management Bachelor's degree program designed to equip students with the skills and knowledge needed to excel in the modern digital supply chain

landscape. With a curriculum that covers the latest technologies and best practices, you'll be better prepared to take on emerging roles and drive innovation within your organization.

Don't miss this opportunity to enhance your expertise and open doors to exciting career opportunities; request more information today or apply now and start leveling up your skills in the industry!



“The Role of Artificial Intelligence in Decision Making”



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INTRODUCTION

Artificial intelligence (AI) is defined as the ability of an artificial entity to solve complicated problems using its own intelligence. Computer science and physiology are combined in Artificial Intelligence. In layman's terms, intelligence is the computational component of one's capacity to attain goals in the real world. Intelligence is defined as the capacity to think, envision, memorize, and comprehend, see patterns, make decisions, adapt to change, and learn from experience. Artificial intelligence is focused with making computers behave more human-like and in a fraction of the time it takes a person to do it. As a result, it is known as Artificial Intelligence. Artificial intelligence is also concerned with pushing the boundaries of practical computer science in the direction of systems that are adaptable, flexible, and capable of forming their own analyses and solution techniques by applying general knowledge to specific situations.

THE ROLE OF AI IN DECISION MAKING PROCESSES

AI is crucial in enhancing the decision-making process by augmenting various stages of the decision-making framework. Here's a breakdown of how AI aids in each step of the decision-making process:

Identifying the problem: AI algorithms assist in identifying and defining problems more accurately by analyzing vast datasets to uncover underlying patterns, anomalies, or emerging trends that might not be readily apparent to humans. These insights help in framing the decision and setting precise, measurable objectives.

Gathering relevant information: AI's capacity to process and analyze extensive data sources rapidly and accurately is valuable. Machine learning model's NLP and data mining enable businesses to extract actionable insights from large volumes of data, ensuring a comprehensive understanding of the situation.

Identifying alternatives: AI systems can generate and assess numerous potential solutions by simulating scenarios based on historical data, market trends, and even external factors like social media sentiment, AI can propose alternative strategies or solutions that might not be immediately obvious to human decision-makers.

Evaluating alternatives: AI aids in evaluating and comparing different options by providing data-driven insights. Machine learning models can assess the historical success of similar strategies or decisions in various scenarios. They can identify potential risks and predict the likely outcomes of each alternative, enabling more informed decision-making.

Selecting the best alternatives: While the final decision remains a human prerogative, AI systems can offer recommendations or predictions based on the analyzed data, helping decision-makers make more informed and evidence-based choices.

Taking action: AI aids in the implementation phase by providing strategic insights, facilitating the creation of detailed action plans, optimizing resource allocation, and assigning tasks for execution based on data-driven recommendations, thereby enhancing the efficacy of the decision-making process.

Reviewing decisions: AI supports the post-decision evaluation process by continuously monitoring the impact of decisions through real-time data analysis. They can track key performance indicators and provide feedback on whether the decision yields the expected outcomes. If not, AI can suggest adjustments or even automatically adapt strategies in real time.

AI and human decision-making provide data-driven insights, enhancing the quality and efficiency of the decision-making process across various business domains. Its ability to process, analyze, and derive insights from vast datasets significantly influences the accuracy and effectiveness of the decisions made.

APPLICATIONS OF AI

1. AI in Astronomy

Artificial Intelligence can be very useful to solve complex universe problems. AI technology can be helpful for understanding the universe such as how it works, origin, etc.

2. AI in Healthcare

In the last, five to ten years, AI becoming more advantageous for the healthcare industry and going to have a significant impact on this industry. o Healthcare Industries are applying AI to make a better and faster diagnosis than humans. AI can help doctors with diagnoses and can inform when patients are worsening so that medical help can reach to the patient before hospitalization.

3. AI in Gaming

AI can be used for gaming purpose. The AI machines can play strategic games like chess, where the machine needs to think of a large number of possible places.

4. AI in Finance

AI and finance industries are the best matches for each other. The finance industry is implementing automation, Chabot, adaptive intelligence, algorithm trading, and machine learning into financial processes.

5. AI in Data Security

The security of data is crucial for every company and cyber-attacks are growing very rapidly in the digital world. AI can be used to make your data more safe and secure. Some examples such as AEG bot, AI2 Platform, are used to determine software bug and cyber-attacks in a better way.

6. AI in Social Media

Social Media sites such as Facebook, Twitter, and Snap chat contain billions of user profiles, which need to be stored and managed in a very efficient way. AI can organize and manage massive amounts of data. AI can analyse lots of data to identify the latest trends, hashtag, and requirement of different users.

7. AI in Travel & Transport

AI is becoming highly demanding for travel industries. AI is capable of doing various travel related works such as from making travel arrangement to suggesting the hotels, flights, and best routes to the customers. Travel industries are using AI-powered chatbots which can make human-like interaction with customers for better and fast response.

8. AI in Automotive Industry

Some Automotive industries are using AI to provide virtual assistant to their user for better performance. Such as Tesla has introduced TeslaBot, an intelligent virtual assistant. o Various Industries are currently working for developing self-driven cars which can make your journey more safe and secure.

9. AI in Robotics

Artificial Intelligence has a remarkable role in Robotics. Usually, general robots are programmed such that they can perform some repetitive task, but with the help of AI, we can create intelligent robots which can perform tasks with their own experiences without pre-programmed. o Humanoid Robots are best examples for AI in robotics, recently the intelligent Humanoid robot named as Erica and Sophia has been developed which can talk and behave like humans.

10. AI in Agriculture

Agriculture is an area which requires various resources, labor, money, and time for best result. Now a day's agriculture is becoming digital, and AI is emerging in this field. Agriculture is applying AI as agriculture robotics, solid and crop monitoring, predictive analysis. AI in agriculture can be very helpful for farmers.



11. AI in E-commerce

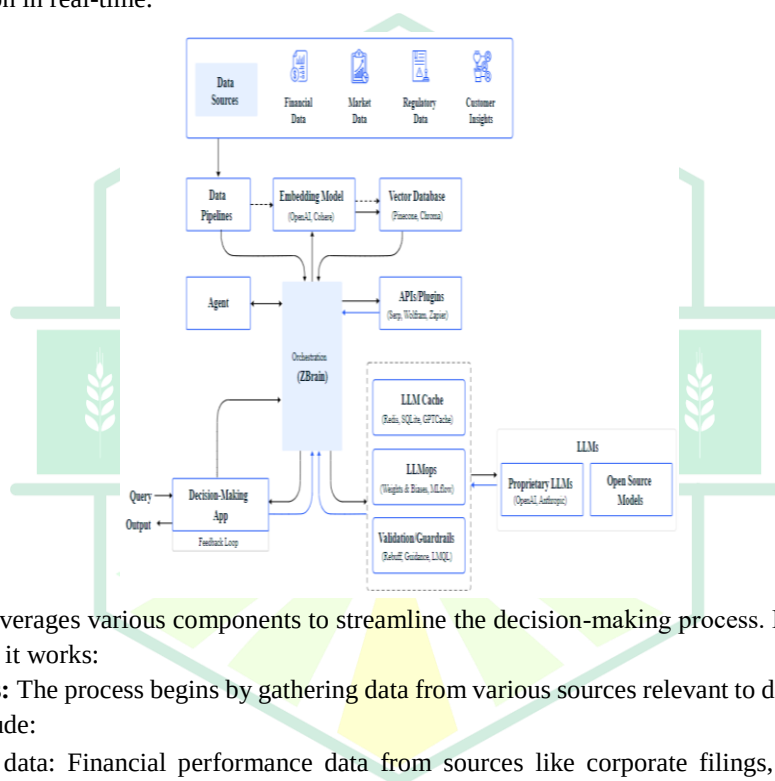
AI is providing a competitive edge to the e-commerce industry, and it is becoming more demanding in the ecommerce business. AI is helping shoppers to discover associated products with recommended size, color, or even brand.

12. AI in education

AI can automate grading so that the tutor can have more time to teach. AI chatbot can communicate with students as a teaching assistant. o AI in the future can be work as a personal virtual tutor for students, which will be accessible easily at any time and any place.

HOW DOES AI FOR DECISION-MAKING WORK?

Incorporating AI into decision-making processes involves various components to streamline data analysis, generate insights, and support strategic planning. It goes beyond traditional decision-making processes by incorporating powerful Large Language Models (LLMs) and connecting them with an organization's unique knowledge base. This architecture unlocks a new level of insight generation and empowers businesses to make data-driven decision in real-time.



The architecture leverages various components to streamline the decision-making process. Here's a step-by-step breakdown of how it works:

- 1. Data sources:** The process begins by gathering data from various sources relevant to decision-making. This data can include:
 - Financial data: Financial performance data from sources like corporate filings, public records, and financial databases.
 - Market data: Market trends, competitor analysis, and industry reports from sources like Gartner, Forrester, and Statista.
 - Operational data: Internal data related to production, sales, customer feedback, and employee performance.
 - Regulatory data: Legal documents, compliance records, and regulatory filings.
 - Customer insights: Customer surveys, social media analytics, and purchase behaviour data.
- 2. Data pipelines:** Data from the sources listed above are then routed through data pipelines. These pipelines are responsible for the ingestion, cleaning, and structuring of data, making it ready for further analysis.
- 3. Embedding model:** The prepared data is then processed by an embedding model. This model transforms the textual data into numerical representations called vectors that AI models can understand. Popular models include those from OpenAI, Google, and Cohere.

4. **Vector database:** The generated vectors are stored in a vector database, which allows for efficient querying and retrieval. Examples of prominent vector databases include Pinecone, Weaviate, and PGvector.
5. **APIs and plugins:** APIs and plugins like Serp, Zapier, and Wolfram play a key role by connecting different components and enabling additional functionalities, such as accessing extra data or performing specific tasks with ease.
6. **Orchestration layer:** The orchestrating layer is critical in managing the workflow. ZBrain is an example of this layer that simplifies prompt chaining, manages interactions with external APIs by determining when API calls are required, retrieves contextual data from vector databases, and maintains memory across multiple LLM calls. Ultimately, this layer generates a prompt or series of prompts that are submitted to a language model for processing. The role of this layer is to orchestrate the flow of data and tasks, ensuring seamless coordination across all components in the decision-making architecture.
7. **Query execution:** The data retrieval and generation process begins when the user submits a query to the decision-making app. This query can be about anything relevant to strategic planning, operational improvements, or market positioning.
8. **LLM processing:** Once received, the app transmits the query to the orchestration layer. This layer retrieves relevant data from the vector database and LLM cache and sends it to the appropriate LLM for processing. The choice of LLM depends on the nature of the query.
9. **Output:** The LLM generates an output based on the query and the data it receives. This output can take various forms, such as strategic recommendations, risk assessments, or market analysis reports.
10. **Decision-making app:** The validated output is then presented to the user through the decision-making app. This is the core application where all the data, analysis, and insights converge. It presents the findings in a user-friendly format for decision-makers.
11. **Feedback loop:** User feedback on the LLM's output is another important aspect of this architecture. The feedback is used to improve the accuracy and relevance of the LLM output over time.
12. **Agent:** AI agents step into this process to address complex problems, interact with the external environment, and enhance learning through post-deployment experiences. They achieve this by employing advanced reasoning/planning, strategic tool utilization, and leveraging memory, recursion, and self-reflection.
13. **LLM cache:** Tools like Redis, SQLite, or GPTCache are used to cache frequently accessed information, speeding up the response time of the AI system.
14. **Logging/LLMOps:** Throughout this process, LLM operations (LLMOps) tools like Weights & Biases, MLflow, Helicone, and Prompt Layer help log actions and monitor performance. This ensures the LLMs are functioning optimally and continuously improve through feedback loops.
15. **Validation:** A validation layer is employed to validate the LLM's output. This is done through tools like Guardrails, Rebuff, Guidance, and LMQL to ensure the accuracy and reliability of the information provided.
16. **LLM APIs and hosting:** LLM APIs and hosting platforms are essential for executing decision-making tasks and hosting the application. Depending on the requirements, developers can select from LLM APIs provided by companies like OpenAI and Anthropic or opt for open-source models. Similarly, they can choose hosting platforms from cloud providers like AWS, GCP, Azure, and Coreweave or opt for opinionated clouds like Databricks, Mosaic, and Anyscale. The choice of LLM APIs and cloud hosting platforms depends on the project's needs and preferences.

This structured flow provides a detailed overview of how AI facilitates decision-making, leveraging various data sources and technological tools to generate accurate and actionable insights. Overall, AI automates various tasks involved in decision-making, improves efficiency, and enables a more comprehensive and timely analysis of business scenarios

AI TECHNOLOGIES USED IN DECISION-MAKING

AI technologies play a significant role in decision-making by offering various tools and techniques to process data, generate insights, and support informed choices. Some of the key AI technologies used in decision-making include:

Machine Learning (ML): Machine learning is employed to analyze vast datasets, extract patterns, and make predictions. It aids in identifying trends and potential outcomes based on historical data, assisting decision-makers in forecasting and optimizing strategies.

Natural Language Processing (NLP): NLP technology plays a crucial role in decision-making by enabling systems to understand and derive insights from human language. It supports sentiment analysis, aids in customer interactions through chatbots, and helps glean valuable information from textual data, influencing informed decision-making.

Computer vision: In decision-making, computer vision technology interprets visual data from images and videos, providing insights through image recognition, object detection, and analysis. This aids in quality control, identifying anomalies, and visual data-driven decision processes.

Expert systems: AI-driven decision-making expert systems mimic human expertise in specific domains. In decision-making scenarios, these systems use knowledge bases and inference engines to provide recommendations and make decisions. They contribute by offering insights or suggestions within specialized areas like healthcare, law, and finance.



Insects as Indicators of Environmental Stress and Climate Extremes



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1. Introduction

Environmental stress and climate extremes are increasingly defining features of the Anthropocene. Rising global temperatures, altered precipitation regimes, more frequent heatwaves, prolonged droughts, intense flooding, and rapid land-use change are reshaping ecosystems at unprecedented rates. Detecting, interpreting, and forecasting the biological consequences of these changes are central challenges in ecology, conservation biology, and applied environmental science. Among the most informative biological tools for this purpose are insects. Insects comprise more than half of all described living species and occupy virtually every terrestrial and freshwater ecosystem. Their short generation times, high reproductive rates, physiological sensitivity to environmental conditions, and close coupling with plants, soils, and aquatic systems make them especially responsive to environmental change. These characteristics position insects as powerful bioindicators—organisms whose presence, abundance, behaviour, or physiological condition reflects the state of the environment. Insects as indicators of environmental stress and climate extremes, focusing on their ecological sensitivity, mechanistic responses to stressors, and practical applications in monitoring global change. Designed for undergraduate students, the chapter integrates ecological theory with empirical case studies to illustrate how insect responses provide early-warning signals of ecosystem disruption. Within the broader context of Entomology Beyond Insects, this discussion highlights insects not merely as study organisms, but as interpreters of ecological intelligence operating at the interface of climate dynamics, agriculture, and ecosystem resilience.

2. Environmental Stress and Climate Extremes

Environmental stress refers to external factors that reduce organismal performance, fitness, or survival beyond optimal ranges. In the context of climate change, stressors include both gradual trends (e.g., rising mean temperatures) and acute extremes (e.g., heatwaves, floods, cold snaps). Climate extremes are particularly significant because they often exceed physiological thresholds, triggering nonlinear ecological responses.

From an ecological perspective, stress can be categorized into:

- Thermal stress (heat and cold extremes)
- Hydrological stress (droughts, floods, altered moisture regimes)
- Chemical stress (pollution, pesticides, salinization)
- Habitat stress (fragmentation, land-use change)
- Biotic stress (altered species interactions)

Insects experience these stressors directly through their physiology and indirectly through changes in food availability, habitat structure, and interactions with predators, parasites, and mutualists. Because insects often occupy lower trophic levels and have limited capacity for behavioural buffering against environmental change, their responses can precede visible impacts on larger, longer-lived organisms such as vertebrates and trees.

3. Why Insects Are Effective Bioindicators

Several biological and ecological traits make insects particularly effective indicators of environmental stress and climate extremes:

3.1 Physiological Sensitivity

Insects are ectotherms, meaning their body temperature and metabolic rates are largely determined by ambient environmental conditions. Even small changes in temperature or moisture can significantly affect development rates, survival, fecundity, and behavior. Thermal performance curves in insects are often steep, with narrow

optimal ranges and sharp declines beyond critical thresholds. This sensitivity allows insects to respond rapidly and measurably to climate anomalies.

3.2 Short Generation Times and Rapid Evolution

Many insects' complete multiple generations per year, enabling populations to respond quickly to environmental change. These responses may include shifts in phenology, altered life-history strategies, or rapid evolutionary adaptation. From a monitoring perspective, such changes provide near-real-time signals of environmental stress.

3.3 Trophic and Functional Diversity

Insects occupy a wide range of ecological roles, including herbivores, predators, decomposers, pollinators, and parasites. This functional diversity means that insect responses can reflect changes across multiple ecosystem processes, such as primary productivity, nutrient cycling, and food-web stability.

3.4 High Abundance and Sampling Feasibility

Insects are abundant and relatively easy to sample using standardized methods (e.g., pitfall traps, sweep nets, light traps). Long-term datasets based on insect monitoring are therefore more feasible to establish and maintain than those for many vertebrate groups.

4. Mechanisms of Insect Responses to Environmental Stress

Understanding insects as indicators requires examining the mechanisms through which stress and climate extremes influence their biology.

4.1 Thermal Stress and Heatwaves

Temperature strongly influences insect metabolism, development, and survival. Heatwaves can cause direct mortality, disrupt reproductive processes, and alter sex ratios in temperature-sensitive species. Sublethal effects, such as reduced fecundity or impaired immune function, may persist long after temperatures return to normal. For example, exposure to extreme heat can denature proteins, disrupt membrane integrity, and increase oxidative stress. In response, insects may produce heat shock proteins, but this physiological buffering is energetically costly and often insufficient under repeated or prolonged extremes.

4.2 Drought and Moisture Stress

Water availability directly affects insects through desiccation and indirectly through host plant quality and habitat structure. There is a drought-stressed nutrient content in plant tissues and defensive chemistry that cascades in herbivorous insect populations. Changes in species composition are informative socio-biological indicators of decreased moisture in soil and leaf-litter communities, favoring the dominance of desiccation-tolerant taxa at the expense of less tolerant species leading to diminished diversity.

4.3 Flooding and Aquatic Stress

In freshwater systems, insects such as mayflies, stoneflies, and caddisflies are sensitive to changes in water temperature, oxygen availability, and flow regimes; flood events can scour substrates, displace larvae, and alter community structure. On the other hand, lack of the periodic flooding can also reduce habitat heterogeneity leading to decline in specialist species.

4.4 Phenological Shifts

Many insects have also advanced their voltinism or number of generations per year in response to global warming. Phenological mismatches between insects and their food resources or mutualistic partners constitute a strong indicator of climate-driven disruption.

5. Case Studies: Insects as Indicators of Climate Extremes

5.1 Heatwaves and Insect Population Collapse in Temperate Ecosystems

This long-term monitoring in temperate regions has revealed a sharp decline in the abundance of insects after extreme heat.

In some grassland and forest ecosystems, heatwaves have led to sudden population crashes of thermally sensitive species, with incomplete recovery taking place thereafter.

These declines often precede any observable changes in the higher trophic levels, such as insectivorous birds and other higher-level consumers, thus highlighting insects as a key early-warning indicator. Importantly, such collapses never occur in association with long-duration warming trends but rather short-duration extremes that entirely transcend physiologic limitations.

5.2 Drought and Insect Community Shifts in Agricultural Landscapes

In agricultural systems drought conditions have been linked to changes in insect community composition, increasing stress-tolerant pest species and natural enemy declines. These shifts might destabilize biological control services and chemical inputs. Monitoring the insect assemblages subjected to drought conditions has given an ecosystem resilience and the degree of vulnerability of the agroecosystem to climatic variability. In this context, insects are indicative not only of environmental stress but also of agricultural sustainability.

5.3 Aquatic Insects and Flood Regime Alteration

In a river system, aquatic insect communities are widely used for ecological integrity. Altered flood regimes—causes of which include climate change and river regulation—can result in the decline of taxa adapted to specific flow condition. Loss of seasonal flooding has also been associated with reduced diversity of floodplain insects, which points towards broader changes in nutrient cycling and connectivity of habitats. On the other hand, increases in extreme flood events may lead to the elimination of sensitive species, with resultant homogenized communities dominated by disturbance-tolerant taxa.

6. Insects, Climate Extremes, and Ecological Intelligence

Insects can be regarded as sensors that are actively integrated into ecosystem intelligence bodies in the ecological intelligence context. Their responses combine multiple dimensions of environmental change, so that the climatic signals become biological patterns which can then be observed, measured and interpreted. In contrast to abiotic monitoring tools, insects respond to the interactions between temperature, moisture, availability of resources, and the presence of competing species. This integrative quality augments their significance as indicators, especially in a landscape of heterogeneity, where indicators based on one or a few factors may prove inadequate. Insects also prove exemplary in regard to thresholds and tipping points. Insect community structural shifts often lead to ecosystem boundaries with only a minimum recovery chance on the original boundaries. Recognition of these signals is essential for adaptive management and conservation planning under global change.

7. Limitations and Challenges

There are a number of challenges faced in using insects as indicators, despite their usefulness.

Taxonomic expertise: Some identifications may be accurate, but not always, especially in complex groups with many species.

Natural variability: Insect populations are not constant and they fluctuate naturally making it difficult to separate the natural population dynamics from a change in dynamics caused by stress.

Context dependence: Responses to stress may differ from one region/ecosystem to another, which limits the generality of some of the indicators. Multiple stressors: Climate extremes work in tandem with land-use change, pollution, and invasive species that makes attributing causes a complex matter. Programmed monitoring protocols, long-term datasets, and vectors and climatic and environmental data need to be integrated to address these challenges.

8. Implications for Monitoring, Conservation, and Policy

Environmental monitoring schemes at local, regional, and international levels have also progressively integrated the use of insects.

Their response to climate extremes can be used to inform;

- Early signs of ecosystem degradation
- Climate vulnerability and resilience assessment
- Assessment of conservation and restoration results
- Climate adaptive agricultural practices

Insect indicators give policymakers cost-effective and ecologically meaningful tools to track environmental change.

For scientists and students, they offer a biological perspective on the impacts of climate changes.

9. Conclusion

Insects are very important in the context of climate, ecology and environmental assessment.

Their sensitivity to environmental stress and climate extremes, their ecological diversity, and their short-term responses make them invaluable indicators of global change.

In a regime of climate variability, the insect-biology signals will be influential in interpretation on ecosystem and responses.

In the greater context of the Entomology Beyond Insects storyline, this chapter highlights the notion that insects are not just passive elements in an ecosystem, but have the capacity to convey ecological intelligence. In essence, ecology and insect physiology have provided important information about environmental stress.

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From crosses to crops: Understanding wide hybridisation and its barriers



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Abstract:

Hybridisation is the crossing of genetically distinct parents, enabling the transfer of desirable traits such as disease resistance, stress tolerance, and yield improvement. Hybridisation can be divided into sexual or somatic, and further as intraspecific, interspecific, or intergeneric, depending on the genetic relationship of the parents. Interspecific and intergeneric hybridizations are called wide or distant hybridisation. Historical milestones, from Fairchild's mule to triticale, highlight its significance in crop improvement. Wide hybridisation serves multiple objectives, including trait transfer, exploitation of heterosis, and creation of novel genotypes. However, its success is often constrained by crossability barriers, which are broadly categorised into pre-fertilisation (e.g., pollen germination failure, unilateral incompatibility, poor pollen tube growth) and post-fertilisation barriers (e.g., hybrid inviability, sterility, and breakdown). Techniques such as controlled pollination, chromosome doubling, and mentor pollination have been developed to overcome these challenges. Despite the complexities, hybridisation remains a powerful tool for generating improved crop varieties and ensuring sustainable agricultural advancement.

Keywords: Hybridisation, Intraspecific, interspecific, fertilisation, species

Introduction:

Hybridisation refers to the crossing between two genetically different parents of different varieties, species, or even genera, to produce progeny with desirable traits. This process may occur naturally or artificially. In case of natural occurrence, nature itself will play a key role and contribute to the evolution and speciation. In artificial breeding, plant breeders deliberately use hybridisation to improve crops by introducing beneficial traits such as yield, quality, biotic and abiotic stress tolerance (Stebbins, 1958; Singh, 2015). However, hybridisation is not always straightforward. The success of producing fertile offspring depends on overcoming several biological barriers that prevent effective reproduction.

Types of hybridisation

Hybridisation can be broadly classified in two ways:

1. Based on the type of cells involved

- **Sexual hybridisation** – involves fusion of male and female gametes
- **Somatic hybridisation** – involves fusion of somatic (non-reproductive) cells

2. Based on the genetic relationship of the parents

- **Intraspecific (within species)** – between varieties of the same species
- **Interspecific** - between species of the same genus
- **Intergeneric** - between different genera of the same family

Interspecific and intergeneric hybridisation is known as distant or wide hybridisation, which is often more challenging.

History

Hybridisation has a long and fascinating history in plant science. One of the earliest recorded attempts dates back to 1717, when Thomas Fairchild successfully created a hybrid between carnation and sweet william, famously known as the "Fairchild mule" (Hancock, 2004). This pioneering work laid the foundation for deliberate plant hybridisation. In the years that followed, scientists explored several experimental hybrids to better understand the

potential and challenges of crossing distinct species. A notable example is *Raphanobrassica* (radish × cabbage), which, although scientifically interesting, did not have much practical agricultural value. A major success in intergeneric hybridisation is *triticale*, developed by crossing wheat (*Triticum*) and rye (*Secale*). This hybrid effectively combines the high yield and grain quality of wheat with the hardiness and stress tolerance of rye. Triticale stands as an excellent example of how hybridisation can be used to merge beneficial traits from different species, contributing significantly to crop improvement and agricultural sustainability (Orellana et al., 1994).

Objectives of wide hybridisation

Wide hybridisation serves multiple purposes:

1. **Trait transfer:** Resistance to diseases and insects, tolerance to drought and cold, and quality traits such as fibre strength in cotton or sugar content in sugarcane (Khush, 1973).
2. **Exploitation of heterosis:** Particularly in ornamentals and vegetatively propagated crops, prolonging vegetative growth and blooming (Jauhar, 2006).
3. **Creation of novel genotypes:** Amphidiploids and unique F₁ hybrids with new trait combinations (Soltis & Soltis, 2009).

Interspecific Hybridisation:

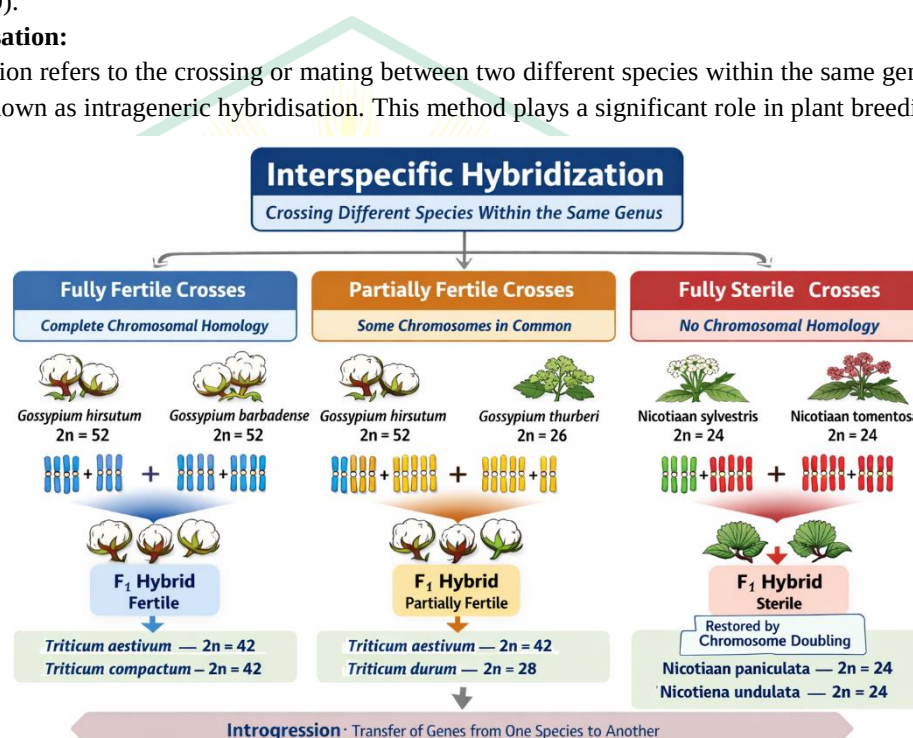
Interspecific hybridisation refers to the crossing or mating between two different species within the same genus, and is therefore also known as intragenic hybridisation. This method plays a significant role in plant breeding,

particularly when desirable traits are absent within a single species. By enabling gene transfer from related cultivated or wild species into crop plants, interspecific hybridisation broadens the genetic base and enhances crop improvement. It is especially effective in vegetatively propagated crops such as sugarcane

and potato, compared to seed-propagated species. An important outcome of this process is introgression, which involves the transfer of specific genes from one species into the genome of another, thereby incorporating beneficial traits into cultivated varieties. The success of interspecific hybridisation largely depends on the degree of chromosomal homology between the parent species, which influences chromosome pairing during meiosis and ultimately determines fertility in the hybrid offspring. Based on this, interspecific crosses can be classified into three categories: fully fertile, partially fertile, and fully sterile (de Nettancourt, 2001).

Fully fertile crosses occur when the parental species have complete chromosomal homology. In such cases, chromosomes pairing occurs normally during meiosis, leading to proper gamete formation and fully fertile F₁ hybrids. Examples include crosses between *Gossypium hirsutum* (2n = 52) and *Gossypium barbadense* (2n = 52), as well as *Triticum aestivum* (2n = 42) and *Triticum compactum* (2n = 42).

Partially fertile crosses are observed when the parental species differ in chromosome number but still share some homologous chromosomes. This partial homology allows limited chromosome pairing, resulting in hybrids that are partly fertile and partly sterile. Examples include *Gossypium hirsutum* (2n = 52) × *Gossypium thurberi* (2n = 26), and *Triticum aestivum* (2n = 42) × *Triticum durum* (2n = 28).

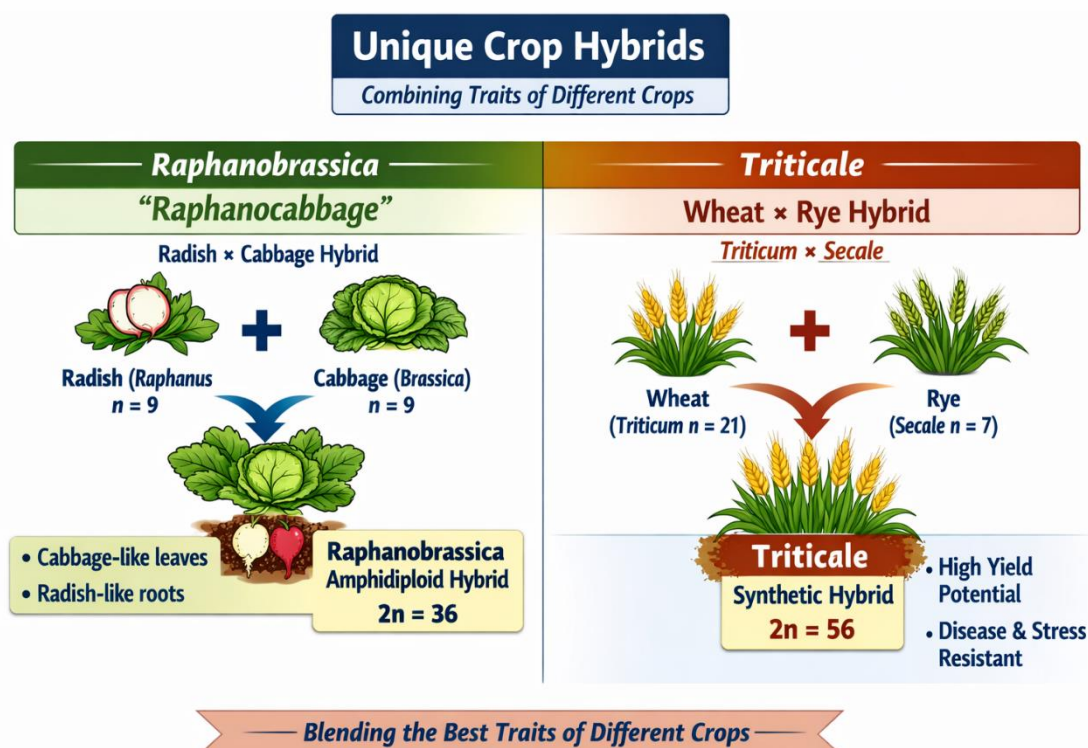


Fully sterile crosses occur when there is little or no chromosomal homology between the parental species. In such hybrids, chromosomes fail to pair during meiosis, leading to complete sterility in the F_1 generation. This sterility can often be overcome by chromosome doubling using chemicals such as Colchicine, which restores homologous pairing and fertility. Examples of such crosses include *Nicotiana sylvestris* ($2n = 24$) $\times$ *Nicotiana tomentosa* ($2n = 24$), and *Nicotiana paniculata* ($2n = 24$) $\times$ *Nicotiana undulata* ($2n = 24$). In many cases, sterility can be overcome by chromosome doubling, which restores fertility.

Intergeneric hybridisation:

Intergeneric hybridisation refers to the crossing between two different genera within the same family. Since it involves genetically distant parents, it is considered a more complex and less commonly used approach in plant breeding. The success of such crosses is often limited due to strong reproductive barriers, both at the pre- and post-fertilisation stages (Ramsey & Schemske, 1998). This method is generally employed only when desirable traits are not available within the species of the same genus. In such cases, breeders attempt to transfer specific genes from related (allied) genera into cultivated crops. However, due to the genetic distance between parents, intergeneric hybridisation is rarely used in crop improvement programs and is typically restricted to targeted trait transfer.

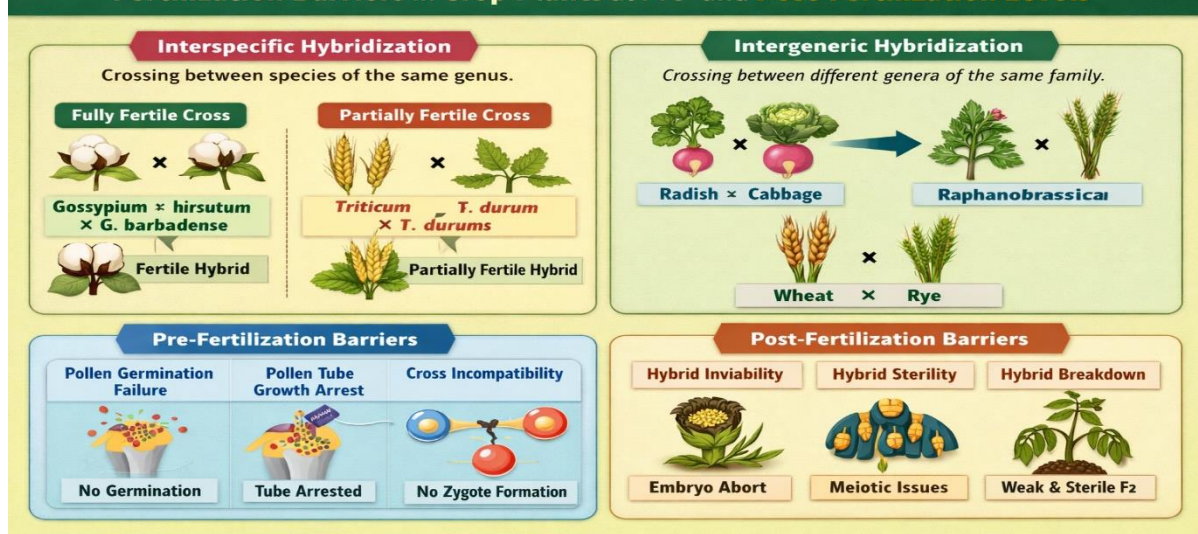
Intergeneric hybridisation has been more successful in asexually or vegetatively propagated crops, where fertility issues can be managed more easily. A major limitation of this approach is that the F_1 hybrids produced are almost always sterile. This sterility arises due to the lack of chromosomal homology, which prevents proper pairing during meiosis. To overcome this barrier, fertility can be restored through chromosome doubling using agents such as Colchicine. Chromosome doubling creates homologous pairs, allowing normal meiosis and enabling the development of stable hybrid lines.



Crossability barriers

Crossability barriers are biological constraints that hinder successful fertilisation or the formation of viable seeds during hybridisation. These barriers limit the effective use of hybrids in crop improvement and are broadly classified as pre-fertilisation and post-fertilisation barriers (Rieseberg & Willis, 2007).

Fertilization Barriers in Crop Plants at Pre- and Post-Fertilization Levels



Pre-fertilisation barriers

Pre-fertilisation barriers occur before zygote formation and prevent successful fertilisation. One common issue is pollen germination failure, in which pollen grains are unable to adhere to, hydrate, or germinate on the stigma due to incompatibility (de Nettancourt, 2001). In some cases, unilateral incompatibility is observed, where a cross is successful only in one direction but not the other (Wang & Filatov, 2023). Even when pollen germinates, poor pollen tube growth may prevent it from reaching the ovule due to nutritional imbalances, structural differences in the style, or abnormal growth patterns (Singh, 2015). Additionally, failure of gamete fusion can occur, resulting in unsuccessful fertilisation. These barriers can be overcome through techniques such as synchronising flowering time, performing controlled pollination, maintaining optimal humidity, and using mentor pollen to facilitate pollen tube growth.

Post-fertilisation barriers

Post-fertilisation barriers occur after fertilisation and affect embryo development and hybrid viability.

Hybrid inviability

Hybrid inviability arises when the zygote fails to develop properly due to lethal genes, chromosomal incompatibility, or poor coordination between embryo and endosperm (Khush, 1973).

Hybrid sterility

Hybrid sterility is another major limitation, where hybrids grow normally but fail to produce viable seeds due to meiotic irregularities or chromosomal mismatches (Chen, 2010).

Hybrid breakdown

Hybrid breakdown occurs, where the F₁ generation appears normal, but subsequent generations (F₂) exhibit weakness or sterility due to unfavourable gene interactions (Soltis & Soltis, 2009).

To overcome post-fertilisation barriers, breeders employ strategies such as embryo rescue, chromosome doubling using Colchicine, and backcrossing to stabilise desirable traits. Together, these approaches help in successfully exploiting wide hybridisation for crop improvement.

Conclusion

Hybridisation remains a powerful tool in plant breeding, enabling the development of improved crop varieties with superior traits. However, its success is often limited by complex pre- and post-fertilisation barriers. Understanding these barriers and developing techniques to overcome them is essential for advancing crop improvement and ensuring sustainable agriculture in the future.

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Production and Characterization of Biodegradable Packaging Film from Fish Processing By-Products



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Abstract

The growing environmental impact of petroleum-based plastics and the accumulation of waste from seafood processing have encouraged the development of sustainable packaging materials. Fish processing by-products such as skins, bones, scales, and viscera are rich sources of biopolymers including fish protein concentrates, myofibrillar proteins, gelatin and chitosan, which possess excellent film-forming properties. This review explores the production and characterization of biodegradable packaging films derived from these fish processing wastes. The article discusses extraction methods for obtaining key biopolymers and the preparation of film-forming solutions using solvent casting techniques. The resulting films are evaluated based on mechanical properties, tensile strength, barrier performance, optical characteristics, and surface wettability to determine their suitability for food packaging applications. Strategies to enhance film performance, including polymer blending with polyvinyl alcohol and incorporation of plant-based polysaccharides and natural extracts, are also highlighted. Overall, fish by-product-based biodegradable films present a promising approach for waste valorization and sustainable packaging development, although further research is required to improve scalability, consistency of raw materials, and industrial application.

Key words: Biodegradable packaging film, Fish processing by-product, Fish gelatin, Chitosan, Sustainable food packaging, Waste valorization.

1. Introduction

The management of enormous amounts of organic waste and the pressing need to replace traditional petroleum-based plastics with sustainable alternatives provide two challenges for the global food industry. Skins, bones, scales, and viscera are examples of fish processing by-products that make up a sizable amount of this waste and frequently account for almost one-third of the annual fish production (Athanasopoulou et al., 2023). In the past, these materials were either thrown away or turned into inexpensive goods like fertilizer or fishmeal. The potential of these by-products as rich sources of proteins and polysaccharides, such as gelatin, myofibrillar proteins, and chitosan, which have superior film-forming properties, has been brought to light by recent developments in biopolymer science (Gautam et al., 2016, Smaoui et al., 2025).

These waste products must be upcycled into valuable biodegradable packaging materials in order to make the shift to a circular economy paradigm. By giving seafood sector "waste" a useful purpose, these materials not only lessen the negative effects of plastic pollution on the environment but also improve the blue economy's economic viability (Zainal Arifin et al., 2023). Fish-derived polymers' distinctive structural characteristics and biocompatibility are what propel the creation of biodegradable films. Fish-based biopolymers are naturally biodegradable and can be designed to have particular functional characteristics, like antioxidant and antibacterial properties, in contrast to synthetic plastics, which linger in the environment for centuries (Zainal Arifin et al.,

2023, Getachew et al., 2021). Myofibrillar proteins and fish protein concentrates (FPC) can be isolated and processed into homogenous, flexible, and robust films, according to research (de Silva Pereira et al., 2019). Additionally, the mechanical and barrier performance of these bio-based composites can be further improved by adding other natural elements like pectin or plant extracts (Florentino et al., 2022).

This study of the literature examines the entire process of creating and describing these films, including sophisticated functionalization techniques, physicochemical analysis, and extraction techniques. This article attempts to give a thorough overview of how fish processing by-products might be converted into the next generation of environmentally friendly food packaging by combining recent results (Smaoui et al., 2025).

It is impossible to exaggerate how important the environment is to this research. Marine debris and microplastic contamination are largely caused by conventional packing materials, which are mostly made from non-renewable fossil fuels. Seafood-derived coatings and films, on the other hand, provide a "green" substitute that satisfies customer desires for "clean label" goods and ethical corporate methods. For example, the use of fish skin gelatin has become popular because of its high transparency and capacity to create a stable matrix when combined with other polymers such as polyvinyl alcohol (PVA) or chitosan (Ghaderi et al., 2019).

Fish by-products are a flexible substrate that can hold bioactive substances to prolong the shelf life of perishable items as the industry advances toward more complex "active" and "intelligent" packaging methods (Zainal Arifin et al., 2023). The optimization of these procedures, the resulting material qualities, and the necessary future steps to translate these lab achievements into commercial applications will all be covered in length in this review.

2. Extraction and Processing of Biopolymers from Fish Waste

2.1. Isolation of Fish Protein Concentrates and Myofibrillar Proteins

A crucial initial stage in the valuation of fish processing waste is the isolation of myofibrillar proteins and fish protein concentrates (FPC). FPC is usually made by washing, defatting, and drying a mixture of meat and skin by-catch, as that from gilthead seabream.

Isolating a stable, concentrated protein fraction with the functional groups required for film formation is the aim. The main contractile proteins in fish muscle, known as myofibrillar proteins, are especially prized for their capacity to create cohesive networks. According to studies, the extraction process needs to be carefully regulated to preserve the structural integrity of these proteins because denaturation, which has a detrimental effect on the mechanical strength of the final films, can be caused by excessive heat or harsh chemical treatments (Getachew et al., 2021). Before these proteins are cast onto thin membranes, they are frequently solubilized using pH-shift techniques or salt-assisted extractions.

To guarantee that the biopolymers maintain their ability to form films, the isolation procedure must be optimized. To find the optimal protein concentration, pH levels, and plasticizer ratios needed to create a stable film-forming solution for myofibrillar proteins, experimental designs are frequently used (da Silva Pereira et al., 2019). The resulting film's look and smell, which are crucial elements for customer acceptance in food packaging applications, are also greatly influenced by the purity of the extracted FPC. According to research, FPC can be effectively combined with other polymers, such as Gelatin, to produce composite materials that take advantage of both materials' advantages (Athanasopoulou et al., 2023). Researchers can increase the yield of high-quality biopolymers from low-value fish waste by improving these extraction methods. This will promote the production of biodegradable packaging and lessen the environmental impact of the seafood processing industry.

The type of fish and the particular portion of the waste that is used have an impact on the effectiveness of protein recovery. For instance, the amino acid profiles of proteins separated from muscle tissue and skin may differ, which could have an impact on the cross-linking density during film production. To avoid rancidity and guarantee a clear, odorless end product, sarcoplasmic proteins and lipids are frequently removed during the extraction of myofibrillar proteins (de Silva Pereira et al., 2019). Furthermore, the development of protein-based films from fish waste is not only a matter of waste reduction but also a medical and nutritional advancement, as these materials are non-toxic and biocompatible. As the demand for sustainable materials grows, the standardization of these extraction protocols becomes paramount to ensure consistent film performance across different batches of raw materials.

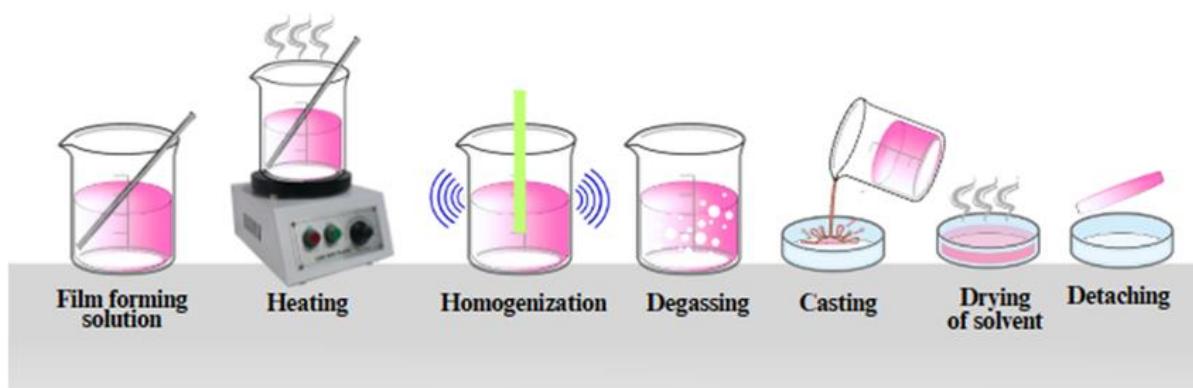


Fig. 1. Preparation of Biodegradable Film (Casting Method)

2.2. Recovery of Gelatin and Chitosan from Skin and Bone Discards

Two of the most common biopolymers recovered from fish processing by-products, particularly from skins, scales, and bones, are Gelatin and chitosan. Thermal denaturation of collagen, which entails acidic or alkaline pre-treatments and hot water extraction, yields fish skin gelatin. Because of its superior film-forming capacity, clarity, and oxygen barrier qualities, this gelatin is highly valued in the packaging industry (Zainal Arifin et al., 2023). Fish gelatin frequently has a lower melting point than mammalian gelatin, which might be advantageous under some processing circumstances but would need cross-linking to increase thermal stability. Another essential polymer is chitosan, which is produced by deacetylating chitin, which is present in the exoskeletons of crustaceans and occasionally in fish scales. It is well known for both its natural antibacterial qualities and its capacity to combine with other biopolymers, such as gelatin, or synthetic agents, such as PVA, to create robust, flexible films.

A key component of the circular economy in the seafood sector is the recovery of these materials. For example, natural extracts, such as those from wasted coffee grounds, can be functionalized with fish skin gelatin to generate active packaging that prevents oxidative deterioration of food. Chitosan and gelatin work particularly well together; ternary blends of chitosan, fish gelatin, and PVA have been demonstrated to improve UV barrier qualities and decrease film solubility, making them more appropriate for moist food settings. The process of extracting chitosan entails the chemical or enzymatic removal of proteins (deproteinization) and minerals (demineralization) from the raw waste. transformation of chitin into chitosan. This method solves the disposal problems related to large shell and bone waste in addition to producing a high-value material (Smaoui et al., 2025).

The extraction parameters, including temperature, time, and reagent concentration, have a significant impact on the structural properties of recovered gelatin and chitosan. The mechanical integrity of the films made from high-quality fish gelatin is correlated with its Bloom strength. In a similar vein, chitosan's solubility and antibacterial effectiveness are determined by the degree of deacetylation. The incorporation of these seafood-derived polymers into "green" coatings and films is a potent tool for the food industry, providing a biodegradable substitute that can rival the functional performance of conventional plastics. When these two polymers are combined, they frequently form a polyelectrolyte complex that enhances the overall water resistance and mechanical toughness of the packaging material.

2.3. Optimization of Film-Forming Solutions and Solvent Casting Techniques

The solvent casting method, which necessitates the meticulous optimization of film-forming solutions (FFS), is the main technique used to produce biodegradable films from fish by-products. Using this technique, the biopolymers are dissolved in an appropriate solvent, often water or a diluted acid-adding plasticizer, and the mixture is then poured onto a level surface to dry. One important factor that determines the viscosity of the FFS and the final film thickness is the concentration of the biopolymers, such as a 3% FPC and 3% Gelatin mixture. In order to overcome the intrinsic brittleness of protein-based films, plasticizers such as sorbitol or glycerol must be inserted between polymer chains. This increases the free volume and permits more flexibility and elongation (Gautam et al., 2016).

In order to identify the "sweet spot" where the film is both flexible enough to wrap around food items and robust enough to handle, optimization frequently entails experimental designs. To guarantee full protein solubilization and subsequent gelation during the drying process, this may include modifying the pH for myofibrillar proteins. Because they affect the rate of solvent evaporation and the configuration of the polymer network, the drying conditions themselves temperature, humidity, and airflow are equally significant. While overly slow drying may cause phase separation or microbiological growth within the FFS, rapid drying can cause internal strains and cracking. Research has demonstrated that when these characteristics are carefully managed, homogenous, robust, and flexible films may be produced, resulting in bioplastics that successfully lower industrial by-product waste.

Additionally, the rheological characteristics of the solution and the ultimate structure of the film can be considerably changed by the interaction of other components in the FFS, such as the inclusion of pectin or other polysaccharides. For instance, it has been demonstrated that the combination of passion fruit pectin with fish by-product proteins results in a stable, biodegradable substance with strong interfacial bonding. The optimization procedure can be made more difficult but also improved by functionalizing the FFS with bioactive substances using sophisticated methods like subcritical water extraction. The ultimate objective of FFS and casting procedure optimization is to create a reliable, high-performing material that can be scaled up for industrial application, offering a competitive substitute for petroleum-based films (Ghaderi et al., 2019).

3.1. Mechanical Properties and Tensile Strength Analysis

One of the main factors determining whether biodegradable films are appropriate for food packaging applications is their mechanical performance. Tensile strength (TS), which gauges the highest stress a film can bear, elongation at break (EAB), which shows flexibility, and Young's modulus, which indicates the stiffness of the material, are important metrics. Fish protein concentrate (FPC) can affect these characteristics, according to research on films made from gelatin and FPC. In particular, films supplemented with FPC frequently have poorer tensile strength than pure gelatin films. This is probably because the more complex protein structures in the concentrate disturb the highly ordered gelatin network. These films, however, often exhibit higher elongation values, indicating a more flexible matrix that is better able to withstand physical deformation without breaking. The ratio of polymers in the mix has a significant impact on the mechanical integrity of these films.

For example, the mechanical characteristics of ternary films made of chitosan, polyvinyl alcohol (PVA), and fish gelatin are tuned at certain ratios, as a 40/40/20 mix (Zainal Arifin et al., 2023). If the components are evenly distributed and interact favorably at the molecular level, adding fish gelatin to a chitosan/PVA matrix can increase the film's overall toughness. Hydrogen bonds between the amino groups of proteins and the hydroxyl groups of plasticizers or other polymers are frequently revealed by structural investigations like Fourier-transform infrared (FTIR) spectroscopy. These bonds are crucial for preserving a cohesive structure. The films would be too fragile to be used in the harsh setting of food logistics without these interactions.

Furthermore, the mechanical results are greatly influenced by the extraction process and the source of the fish waste. Myofibrillar proteins extracted under optimized conditions can produce films with high tensile strength, making them comparable to some synthetic films¹³¹. In these formulations, the use of plasticizers is essential; without them, protein-based films are vulnerable to breaking while being stored. Researchers must strike a compromise between the necessity for flexibility (to make sure the packaging doesn't break) and strength (to safeguard the food). Scientists may customize the film's composition for certain food products by closely examining these mechanical characteristics. For example, stronger films can be used for heavier objects, while more elastic films can be used for seafood or meat products with irregular shapes.

3.2. Barrier Properties and Water Vapor Permeability

Achieving sufficient barrier qualities, especially against water vapor, is one of the biggest challenges in the development of bio-based packaging. Fish proteins and gelatin have a high-water vapor permeability (WVP) due to their intrinsic hydrophilicity, which can shorten the shelf life of foods that are sensitive to moisture. Standardized techniques like ASTM E96/E96M, which gauge the rate at which moisture moves through the film under particular temperature and humidity gradients, are commonly used to assess the WVP. Fish-based films are

a great barrier against oxygen and UV radiation, but their resistance to water vapor has to be strengthened by mixing or adding hydrophobic agents, according to studies (Smaoui et al., 2025).

Researchers have looked into using polymer mixing or adding hydrophobic components to overcome this. For instance, it has been demonstrated that adding fish gelatin to chitosan/PVA films improves the water barrier qualities by making it more difficult for water molecules to get through (Ghaderi et al., 2019). Furthermore, adding hydrophobic areas to the protein matrix through the use of natural extracts or essential oils might lessen the film's attraction for water. Another important parameter is the film's wettability, which is determined by the contact angle. A more hydrophobic surface is indicated by a greater contact angle. Interestingly, the incorporation of FPC into gelatin membranes has been observed to reduce the contact angle (e.g., from 108.5° to 90.6°), although the materials often remain classified as hydrophobic.

The microstructure of the film is also related to the barrier performance. Low permeability requires a homogenous, thick network with few holes or fissures. The films' surface and cross-section are examined using methods like scanning electron microscopy (SEM) to make sure the polymers and additives are properly incorporated. The food will not be protected from external moisture or dehydration if the coating is overly permeable. Thus, the creation of a functional barrier that can sustain the quality and safety of the packed product over time is just as important to the optimization of the film-forming process as mechanical strength.

3.3. Optical Characteristics and Surface Wettability

For both food safety and consumer appeal, packaging materials' optical qualities—such as transparency, color, and UV light barrier—are essential. The majority of customers like clear packaging that enables them to check the food's freshness. Fish gelatin and FPC-based films have shown exceptional optical properties; they frequently seem colorless and extremely transparent, with "L" values (lightness) in the CIE Lab color system surpassing 90 (Athanasopoulou et al., 2023). Compared to other bio-based materials that could be opaque or highly colored, this remarkable transparency is a big benefit. Additionally, these films have inherent UV-blocking properties, which are crucial for stopping the photo-oxidation of vitamins and lipids in meat and fish products.

The contact angle, which measures surface wettability, gives information on how the film will interact with the food surface and the surrounding environment. Fish-based films can be designed to be moderately hydrophobic, even though they are typically more hydrophilic than synthetic polymers. The roughness and chemical makeup of the film surface affect the contact angle. For example, adding wasted coffee ground extracts to fish skin gelatin films can change the surface energy and increase the film's moisture resistance. When high-moisture foods come into touch with a film that is too hydrophilic, it may bloat or disintegrate, while a more hydrophobic surface guarantees that the packaging's structural integrity is preserved.



Fig. 2. Production and characterization of biodegradable packaging film from fish processing by-products

In addition to transparency, the colour parameters (a and b values) are tracked to make sure the films don't eventually take on an unsightly yellowish tinge, which can happen during high-temperature processing or as a result of the Maillard reaction between proteins and leftover sugars. The objective is to create a film that offers a strong functional barrier while being "invisible" to the viewer (Florentino et al., 2022). Fish-derived biopolymers are a very appealing choice for the creation of "green" packaging solutions that do not compromise on the aesthetic or protective needs of the food sector because of their high transparency, efficient UV shielding, and regulated wettability.

4. Functionalization and Blending Strategies for Enhanced Performance

4.1. Incorporation of Plant-Based Polysaccharides and Natural Extracts

Researchers often use plant-based polysaccharides and natural extracts to offset the intrinsic drawbacks of pure fish-protein films, such as their high water sensitivity and modest mechanical strength. Improved structural stability can result from the formation of interpenetrating networks between fish proteins and polysaccharides such as pectin, starch, or cellulose derivatives. For instance, it has been demonstrated that the combination of fish by-product proteins with passion fruit pectin results in a robust and uniform bioplastic. The pectin offers a stiff framework that balances the flexibility of the fish proteins, and these mixes profit from the synergistic effects of the various polymer chains.

This approach not only improves the physical properties of the film but also utilizes another stream of industrial by-products, further contributing to the circular economy.

Additionally, natural extracts are used to offer functional advantages including antibacterial and antioxidant properties. For example, fish skin gelatin films have been functionalized using extracts from spent coffee grounds, giving them bioactive qualities that can prolong the shelf life of packaged foods (Zainal Arifin et al., 2023). These extracts contain phenolic compounds that can scavenge free radicals and prevent the growth of microorganisms that cause spoiling. Such extracts frequently alter the microstructure of the film, as seen by atomic force microscopy (AFM) or scanning electron microscopy (SEM), where the additives may fill in gaps in the polymer matrix or produce a more complicated surface topography. A straightforward barrier film is functionalized into a "active" packaging element.

Maintaining the mechanical integrity and transparency of the film is a difficulty when adding these chemicals. Inadequate dispersion of the extracts may result in aggregates that serve as stress concentrators and cause early film breakdown. Additionally, high plant extract concentrations might occasionally give the film a strong color or smell that isn't ideal for all culinary applications. In order to accomplish the intended functional impact without sacrificing the film's primary purpose as a protective and aesthetically pleasing packaging material, the choice of extract and its concentration must be carefully calibrated.

4.2. Development of Active and Intelligent Packaging Systems

Food packaging has evolved from passive protection to "active" and "intelligent" technologies. While intelligent packaging gives information about the product's condition, active packaging works with the food or the interior environment to increase shelf life. By-products from fish processing are great substrates for these technologies. Antimicrobial agents like chitosan or antioxidant-rich extracts that stop lipid oxidation in meat and seafood can be used to make active films (Smaoui et al., 2025). By releasing advantageous substances or absorbing unwanted ones, including oxygen or ethylene, these films actively contribute to the preservation of food quality.

Sensors or indicators that react to changes in the food's surroundings, such as pH shifts or the formation of volatile amines during spoiling, are frequently used in intelligent packaging. Fruit waste anthocyanins, for instance, can be added to fish-based films to serve as natural pH sensors, changing color when the meal starts to deteriorate. This gives the customer a visual indication of the product's freshness, which is significantly more accurate than a straightforward "best before" date. Strict safety testing, such as in vitro cytotoxicity studies, is also a part of the development of these systems to make sure that the materials and their constituent parts do not endanger consumer health.

A thorough grasp of the active chemicals' release kinetics is necessary to include these sophisticated features into fish-based films. The antibacterial or antioxidant chemicals must be released by the polymer matrix at a regulated pace that corresponds to the food's rotting characteristic. This is frequently accomplished by employing

multi-layered structures or modifying the film's cross-linking density. These active and intelligent packaging solutions made from seafood by-products provide a high-tech, sustainable solution that significantly increases the value of the original waste material as the industry works to decrease food waste.

4.3. Polymer Blending with Polyvinyl Alcohol and Synthetic Biodegradable Agents

A popular method for improving the physicochemical and structural characteristics of fish-based films is polymer mixing. Researchers can create materials that combine the best of both worlds—the superior mechanical strength and water resistance of synthetic agents and the excellent film-forming and barrier properties of biopolymers—by combining fish gelatin or chitosan with synthetic biodegradable polymers like polyvinyl alcohol (PVA). Fish gelatin can improve UV barrier qualities and decrease the film's solubility, according to research on ternary films made of chitosan, PVA, and fish gelatin. Compared to pure protein films, these mixtures are frequently more durable and simpler to handle with industrial machinery.

The performance of the film depends on how well the polymers in the mix work together. To verify that the polymers are interacting at the molecular level rather than just existing as a physical mixture, structural investigations like FTIR and X-ray diffraction (XRD) are employed. The interactions between the various polymer chains in CH/PVA/FG (chitosan/polyvinyl alcohol/fish gelatin) films result in a less soluble and more stable matrix, which is crucial for packaging foods with high moisture content (Ghaderi et al., 2019). By varying the ratio of the constituents, the surface roughness (R_a and R_q values) of these films may also be adjusted, hence influencing the optical and tactile characteristics of the film.

PVA is a water-soluble and biodegradable polymer that is commonly used in food-contact applications, despite the fact that its use may seem to go against the "all-natural" objective. Because it can endure the rigors of the supply chain better than pure biopolymer films, it enables the manufacturing of more economically viable films. Developing "eco-friendly" packaging materials that offer a high degree of protection and are completely biodegradable at the end of their life cycle is the ultimate objective. This blending approach serves as a workable link between the packaging that is heavily plastic-based today and the 100% bio-based solutions of the future.

5. Conclusion and Future Work

An important development in the search for sustainable food packaging is the creation of biodegradable packaging films from fish processing byproducts. The process of extracting valuable biopolymers from seafood waste, such as fish protein concentrates, myofibrillar proteins, gelatin, and chitosan, and turning them into useful, high-performance films has been covered in length in this study. The study shows that these materials have special benefits including intrinsic antibacterial qualities, superior UV radiation barriers, and the possibility for active and intelligent functioning, in addition to being able to replace petroleum-based plastics in numerous applications. The seafood business may support a circular economy that lowers environmental degradation and generates new economic possibilities by upcycling what was previously thought of as waste (Gautam et al., 2016).

These films' characterisation has revealed that although they are very transparent and flexible, there are still issues with their mechanical strength and susceptibility to water vapor. However, these restrictions can be successfully overcome by carefully combining with synthetic biodegradable substances like PVA or other biopolymers like pectin. By offering antioxidant and antibacterial protection, the use of natural extracts—such as those from wasted coffee grounds or fruit waste—further improves the usefulness of these films and prolongs the shelf life of perishable food items. In line with worldwide trends toward sustainability and consumer health, the creation of these "green" active films and coatings is a potent instrument for the food sector.

Despite the promising results observed at the laboratory scale, several hurdles must be overcome before these fish-based films can see widespread industrial adoption. Future work should focus on the scalability of the extraction and film-forming processes. Current methods, such as solvent casting, are effective for research but may be too slow and energy-intensive for mass production. Exploring more industrial-friendly techniques like extrusion or blow-molding for fish-protein-based materials is a critical next step. Additionally, the long-term stability and performance of these films under various environmental conditions such as high humidity or fluctuating temperatures need further investigation to ensure they can protect food throughout the entire supply chain.

Another important area for future research is the standardization of raw materials. Fish waste is inherently variable, depending on the species, season, and processing method. Developing robust protocols that can handle this variability and still produce films with consistent properties is essential for commercial success. Furthermore, while the biodegradability of these films is a key selling point, more comprehensive life-cycle assessments (LCA) are needed to quantify their environmental impact compared to traditional plastics and other bio-based alternatives. This includes evaluating the energy and water used during the extraction and manufacturing phases. Finally, consumer perception and regulatory approval will play a vital role in the market's acceptance of fish-based packaging. While these materials are non-toxic and often edible, issues such as potential allergens (for those with fish allergies) and residual odour must be addressed through refined processing and clear labelling. Continued interdisciplinary research involving food scientists, polymer chemists, and environmental engineers will be necessary to refine these materials. By addressing these challenges, the transition from fish processing by-products to high-value, biodegradable packaging can become a reality, offering a truly sustainable solution for the future of food packaging.

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Nature's Shield: Harnessing Natural Extracts for Safer Fish Preservation



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Abstract

Natural extracts from plants and animals, such as essential oils, chitosan and different phytochemicals, have received widespread attention as efficient alternatives to synthetic preservatives in fish preservation. These organic substances have potent antibacterial and antioxidant qualities that prolong the shelf life of fish and shellfish items, prevent spoiling and preserve freshness. To maintain product quality and safety during storage, they are frequently applied via edible coatings, film wrapping or dipping solutions. Research has shown that extracts from sources such as guava leaves, mangosteen peels and red beetroot peels can improve sensory qualities and shelf stability by reducing microbial growth and lipid oxidation in fish fillets and processed foods. Furthermore, integrating natural extracts with cutting-edge packaging techniques improves their preservation benefits while satisfying customer desire for seafood with safer, cleaner labels. All things considered, natural extracts are potential bio-preservatives that support sustainable fish storage by lowering the need for chemical additions without sacrificing product quality.

Keywords: Natural extracts, Fish preservation, Bio-preservatives, Shelf-life extension, antimicrobial activity, Antioxidant properties.

1. Introduction

Fish and fisheries products are essential to human nutrition and global food security because they are nutritionally significant sources of high-quality protein, polyunsaturated fatty acids, vitamins and minerals (Ali *et al.*, 2022). However, fresh fish has a limited shelf life because of its high moisture content, neutral pH and presence of easily degradable nitrogenous chemicals, making it one of the most perishable food items. Enzymatic autolysis, microbial development and chemical processes such lipid oxidation cause quality to rapidly decline after harvest, resulting in the loss of sensory qualities, nutritional value and substantial economic waste. A significant amount of fish losses and seafood waste worldwide are caused by microbial oxidation and spoiling, which increases the need for more efficient preservation techniques (Tavares *et al.*, 2021).

Fish preservation has historically depended on packing, low temperatures (freezing, chilling) and artificial preservatives to prevent microbial development and delay oxidation (Olatunde *et al.*, 2018). Concerns have been raised by rising evidence and perception of possible health risks and toxicological dangers connected with particular synthetic compounds, despite the fact that such additions can successfully increase shelf life and enhance safety. At the same time, modern customers frequently reject meals that list chemical preservatives and seek fresh-like, minimally processed, "clean-label" items free of synthetic ingredients (Hussain *et al.*, 2021). A significant change toward natural and environmentally friendly preservation techniques has been sparked by these developments as well as tighter laws and sustainability objectives.

Natural extracts and bioactive substances derived from plants, microbes, animals, algae and mushrooms have developed as novel preservation methods with antibacterial and antioxidant capabilities. When combined with contemporary packaging and hurdle technologies, these natural preservatives such as essential oils, plant

extracts, bacteriocins, chitosan and other biopolymers can slow down microbial deterioration, prevent lipid oxidation and preserve sensory quality (Baptista *et al.*, 2020). As a result, natural extracts are being investigated extensively as viable, sustainable substitutes for artificial preservatives in order to increase the shelf life of fish while meeting customer demands and environmental concerns.

2. Why Fish Spoils Quickly

Fish degrades quickly due to its muscle composition and postmortem biochemistry, which provide perfect conditions for enzymatic, oxidative and microbiological degradation.

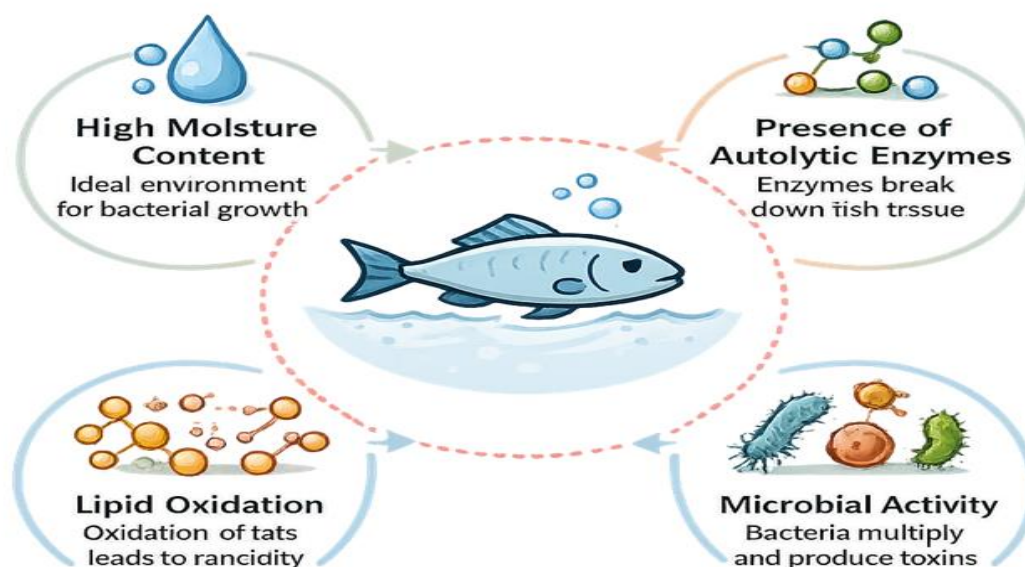


Fig. 1. Why Fish Spoils Quickly

2.1 High Moisture Content

Fish muscle is generally 70-80% water, making it an ideal substrate for microbial development and the transport of enzymes and nutrients. Even at refrigerator temperatures, high water activity enables psychotropic and mesophilic bacteria to proliferate rapidly, resulting in slime formation, off odours and texture degradation (Gandotra *et al.*, 2012).

2.2 Presence of Autolytic Enzymes

Endogenous proteolytic mechanisms (calpains, cathepsins, proteasome and others) activate immediately after death and begin the autolysis of muscle proteins and connective tissue. These enzymes cause fillets to soften and disintegrate structurally by breaking down myofibrillar proteins such as myosin heavy chain, actin-myosin complexes and structural proteins. The initial quality modifications are mostly enzymatic since autolytic responses begin prior to significant bacterial invasion (Gandotra *et al.*, 2012).

2.3 Lipid Oxidation

Fish lipids are abundant in polyunsaturated fatty acids (PUFAs), which are prone to oxidation. The production of hydroperoxides, aldehydes like malondialdehyde (MDA) and other reactive carbonyl species that result in rancid flavours, colour changes and nutritional loss is accelerated by reactive oxygen species and pro-oxidant substances such as haem pigments. Even in frozen or refrigerated storage, oxidation continues, particularly when handling damages membranes and exposes lipids to oxygen (Secci *et al.*, 2016).

2.4 Microbial Activity

After an initial phase dominated by autolysis, spoilage bacteria become the primary cause of degradation. On skin, gills and eventually muscle, both native and contaminant flora particularly *Pseudomonas* and *Shewanella* species proliferate and produce volatile bases, sulphides and biogenic amines that characterize rotting flavours and odours. During storage, microbial counts typically increase from $\sim 2-3$ to >6 log CFU/g, which corresponds with the end of the permissible shelf life (Roopma *et al.*, 2013).

3. What Are Natural Extracts?

Natural extracts are bioactive substances that are extracted physically or via a solvent from the secondary metabolites of plants, herbs, spices, algae, microbes and some animal tissues. These metabolites, which exhibit potent antibacterial, antioxidant and occasionally antifungal properties, include polyphenols, terpenes, carotenoids, alkaloids and polysaccharides.

Functional Properties

Natural extracts are being researched extensively as synthetic preservative substitutes because they -

- Provide wide antibacterial activity by disrupting membranes, inhibiting enzymes and interfering with metabolic pathways to prevent bacteria, yeasts and molds (Matin *et al.*, 2024).
- Provide potent antioxidant defense against lipid oxidation in food by donating electrons or hydrogen, chelating metals and neutralizing reactive oxygen species.
- Numerous essential oils and some plant extracts have antifungal and antimycotoxigenic properties, which inhibit the growth of mold and the generation of mycotoxins in food.

All things considered, natural extracts are adaptable, environmentally friendly and generally recognized as safe (GRAS) bioingredients with a variety of preservation-relevant bioactivities (Narayanankutty *et al.*, 2024).

4. Types of Natural Extracts Used in Fish Preservation

Natural extracts are frequently used in fish and shellfish to reduce synthetic additives, increase safety and prolong shelf life by slowing microbiological deterioration and lipid oxidation. Phenolics, flavonoids, terpenes and bioactive polysaccharides with potent antibacterial and antioxidant properties are the primary sources of their action (Martinez *et al.*, 2019).

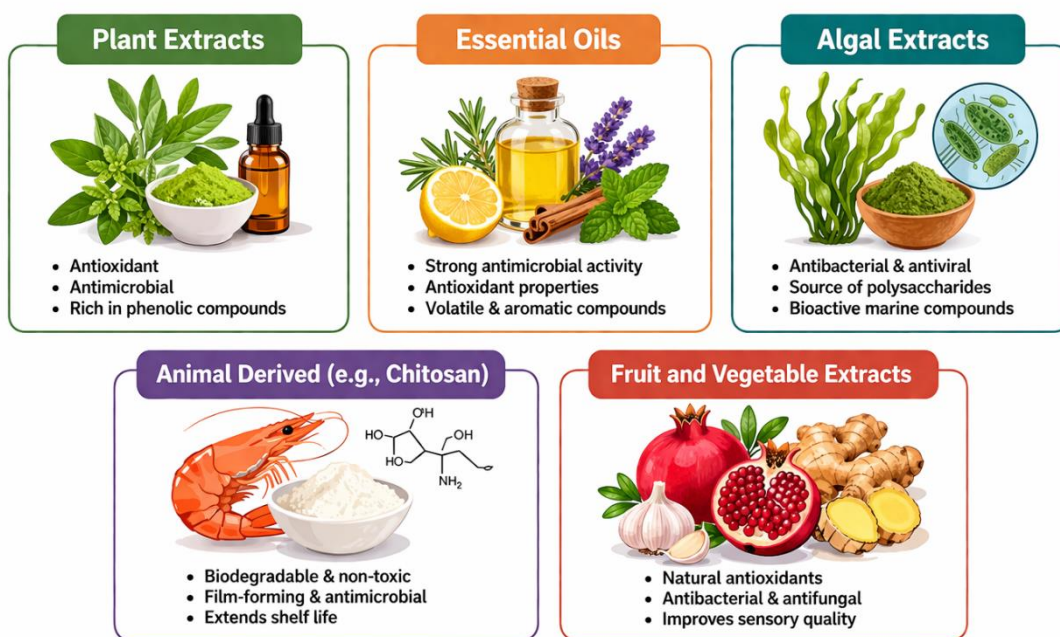


Fig. 2. Types of Natural Extracts

4.1 Plant-Based Extracts

The phenolics, flavonoids and alkaloids found in herbal extracts from garlic, ginger, turmeric, neem, tulsi, rosemary, green tea, pomegranate peel and other plants scavenge free radicals and prevent spoiling bacteria. In comparison to controls, they prolong the chilled or frozen shelf life of fish patties, shrimp and fillets by several days to weeks by lowering lipid oxidation and bacterial populations. For both oxidation and microbiological control, synergistic plant extract combos (such as clove + sage + fruit peels) frequently perform better than individual chemicals and even BHT (Parmar *et al.*, 2024). Alkaloids, flavonoids and phenolics are examples of active substances.

4.2 Essential Oils

Fish and shellfish have potent antibacterial and antioxidant activity when exposed to essential oils (EOs) from cloves (rich in eugenol), cinnamon, thyme, oregano, citrus and Zingiberaceae. Citrus, mentha, organum, thymus and zataria oils are particularly effective at lowering total viable counts and postponing sensory deterioration in cold fish, according to meta-analysis. EOs can reduce spoiling by 2.5–5 times when applied by dipping, spraying, or in edible films, with a little sensory influence of about 0.5–1% (Hassoun *et al.*, 2017).

4.3 Algal Extracts

Extracts from seaweed (brown, red and green algae) include antioxidant and antibacterial polyphenols and polysaccharides. Fish fillets' antioxidant status is enhanced by extracts from *Codium*, *Actinotrichia* and other macroalgae. These extracts can also prevent foodborne or spoilage bacteria, suggesting their potential as natural preservatives or functional fortifiers (Hafez *et al.*, 2022).

4.4 Chitosan (from crustacean shells)

An edible, biodegradable covering for fish is made of chitosan, a polymer obtained from animals. It limits oxygen, moisture loss and microbiological penetration by forming a semipermeable barrier surrounding the surface. The refrigerated shelf life of fillets, burgers and shrimp is significantly extended by chitosan coatings alone or in combination with EOs or plant extracts, which reliably prevent bacterial growth, lipid oxidation and texture loss (Hussain *et al.*, 2021).

4.5 Fruit and Vegetable Extracts

Natural antioxidants (phenolic acids, tannins and flavonoids) are especially abundant in extracts from lemon, grape seed, mangosteen peel, pomegranate peel and olive byproducts. When compared to untreated or artificially preserved controls, these extracts dramatically slow down lipid oxidation, reduce microbial counts and frequently enhance or maintain sensory ratings in fish patties, fingers and balls (Presenza *et al.*, 2023).

5. Mechanism of Action

Fish shelf life is increased by natural antimicrobials, antioxidants and edible coatings, which primarily prevent bacteria, oxidation and enzyme-driven spoiling.

5.1 Antimicrobial Activity

Activity Against Microbes Bacterial cell membranes are disrupted by a variety of plant extracts, essential oils and chitosan-based systems. Cell death results from their interactions with membrane lipids, hole development, ATP and protein leakage and obvious structural deformation. Alkyl gallates and essential oils penetrate the lipid bilayer, disrupt the fatty acid content of the membrane, collapse the membrane potential and obstruct respiratory chains and energy metabolism. Additionally, they reduce ATP generation and biosynthesis by inhibiting enzyme systems such as ATPases, TCA cycle enzymes and important metabolic dehydrogenases. They may also harm nucleic acids or prevent the formation of biofilms, which further reduces the amount of spoilage bacteria on fish surfaces (Zhang *et al.*, 2021).

5.2 Antioxidant Activity

Natural antioxidants in extracts and coatings scavenge free radicals (ROS) and peroxy/alkoxy radicals, disrupting the lipid auto-oxidation chain reaction. Additionally, phenolics can chelate pro-oxidant metals like Fe²⁺, which lessens the production of radicals and the breakdown of hydrogen peroxide. This reduces peroxide value, TBARS and secondary aldehydes/ketones that lead to rancid flavours and nutritional loss by delaying the lipid oxidation of polyunsaturated fatty acids in fish muscle and oil (Rathod *et al.*, 2021).

5.3 Barrier Formation

Fish surfaces are shielded from oxygen and moisture by edible films and coatings made of polysaccharides, proteins and chitosan. Longer diffusion routes due to improved water vapor and oxygen barrier qualities prevent dehydration and drip loss during cold or frozen storage and reduce oxygen availability for microorganisms and oxidation (Umaraw *et al.*, 2020).

5.4 Enzyme Inhibition

Antioxidant-rich coatings and extracts can reduce autolytic decomposition by blocking or stabilizing endogenous enzymes such as lipases, phospholipases and lipoxygenases, lowering lipid hydrolysis and oxidation, as well as

off flavor development. Additionally, certain mechanisms inhibit prooxidant activity and texture/flavor degradation in fish products by indirectly protecting myoglobin and heme iron (Ke *et al.*, 2024).

6. Methods of Application

Fish are treated with natural extracts using surface treatments, ice and packing technologies. These methods seek to offer a regulated release of active chemicals, maintain low temperatures and optimize contact with muscle (Hussain *et al.*, 2021).

6.1 Dipping and Soaking

Whole fish or fillets are dipped or soaked in aqueous or hydroalcoholic extract solutions for a brief period of time (usually two to twenty minutes), after which they are drained and stored. In this approach, extracts from ginger, black pepper, rosemary, algae and guava leaves have been utilized to prolong shelf life under refrigerated or iced storage while lowering microbial growth and lipid oxidation. To maintain lipid quality during ice or frozen storage, antioxidant dips (such as those based on rosemary) are also applied to side-streams (heads, backbones and viscera) (Miranda *et al.*, 2018).

6.2 Coating and Edible Films

Plant extracts or essential oils are carried via edible coatings and films made of chitosan, Gelatin, myofibrillar proteins, or fungal chitosan. Fish or fillets are either wrapped in premade biopolymer films or dipped in the coating solution and dried. In comparison to uncoated controls, garlic–chitosan, pomegranate peel–chitosan, Gelatin, chitosan and rosemary systems have dramatically delayed microbiological deterioration, biogenic amine production and lipid oxidation, prolonging shelf life.

6.3 Ice Incorporation

In order to create "active ice," plant, algae, or spice extracts are dissolved in water and then frozen. Compared to ordinary ice, fish kept in this type of ice have decreased TVB N, oxidation indicators and microbial counts and their shelf life is extended by three to nine days. In chilled mackerel, anchovies, trout and seabream, extracts from *Garcinia* spp., brown algae, thyme, oregano, clove and nano encapsulated essential oils have shown promise.

6.4 Packaging Integration

Natural antioxidants and antimicrobials are directly included into films used to line or wrap fish items in active packaging. As packaging and controlled release preservative solutions, chitosan-based or composite films containing plant polyphenols, barley husk antioxidants, or borage extract minimize oxidation and microbiological development during chilled or frozen storage.

7. Benefits of Natural Extracts

Natural extracts are superior to synthetic preservatives in terms of clean label, sustainability and quality, their safety still depends on dosage and appropriate assessment.

7.1 Safe and non-toxic

Many preservatives generated from plants and microbes are thought to be safer than synthetic additives associated with toxicological and carcinogenic hazards; some of these are GRAS, or commonly used in food. Compared to certain synthetic compounds, they can also aid in reducing antimicrobial resistance. However, toxicological testing and dosage management are crucial since concentrated extracts may result in phytotoxicity or allergies and some polyphenols may be dangerous at high concentrations (Cedillo-Olivos *et al.*, 2025).

7.2 Eco-friendly and biodegradable

Natural preservatives lessen reliance on petroleum-based chemicals and promote circular economy models since they are frequently derived from renewable plant materials, food byproducts, or biobased polymers. Essential oils and plant extracts have antibacterial and antioxidant properties when added to biodegradable packaging and the material itself is extremely biodegradable or compostable, reducing environmental impact.

7.3 Shelf-Life and Nutritional Quality

In reducing microbial growth, lipid oxidation and quality loss in meats, seafood, dairy, baked goods and produce, extracts strong in antioxidants and antimicrobials reliably increase shelf life. Compared to unprotected goods or oxidized fats, they improve safety and nutritional value by preventing oxidation and spoiling reactions, which helps preserve vitamins, lipids and sensory quality.

7.4 Consumer Acceptance and Clean-Label

One of the main factors driving the usage of natural preservatives is the growing desire for "natural" and clean label foods. Herb, spice and byproduct extracts enable for the partial or complete substitution of "chemical sounding" additives, which is in line with customer aspirations for clear, less processed ingredient lists and increased perceived health.

8. Limitations and Challenges

Natural extracts have a number of drawbacks and difficulties that limit their wider use in food preservation. One significant problem is their strong flavours and scents, which can change the food's sensory profile and can have a detrimental effect on consumer approval. Standardization is challenging since the efficacy of natural extracts can vary greatly due to variations in plant sources, extraction techniques and seasonal or geographical variables. The cost of extraction and standardization is still a major obstacle; in order to increase productivity, purity and repeatability, sophisticated extraction technologies and quality control techniques are required, but they sometimes demand large investments. Commercialization is further complicated by regulatory obstacles since natural extracts must adhere to stringent safety, quality and labelling standards that differ depending on the product type and locality (Zhang *et al.*, 2018). Complexity and expense are increased by the need for advanced analytical methods to identify adulteration or contamination in order to guarantee consistent quality. Despite these obstacles, continuous developments in process automation, quality-by-design methods and green extraction technologies hold promise for lowering costs and enhancing consistency while adhering to legal requirements. However, a major obstacle to widespread application in a variety of food items continues to be striking a balance between sensory impact and preservation efficacy (Chemat *et al.*, 2020). Overall, even though natural extracts are consumer-preferred and environmentally benign substitutes for synthetic preservatives, their effective industrial application depends on resolving issues with cost, unpredictability, sensory impacts and regulatory compliance.

9. Conclusion

In offering strong antibacterial and antioxidant qualities that prevent spoiling and preserve quality without the use of artificial chemicals, natural extracts are essential for improving the safety and shelf life of fish and shellfish. By providing biodegradable, environmentally friendly substitutes that satisfy customer desire for natural, minimally processed goods, their use promotes sustainable fish preservation. Essential oils, chitosan and plant-derived chemicals are among the extracts that have shown effective in a variety of applications, including edible coatings, films and dipping solutions to prolong freshness during storage and transit. Despite encouraging outcomes, further study is required to improve formulations, comprehend mechanisms of action and handle issues with consumer acceptance and regulatory permission for wider commercialization. Overcoming these constraints will need ongoing innovation in the combination of natural extracts and cutting-edge packaging technology. In the future, using natural preservatives is a crucial step toward safer, more environmentally friendly seafood preservation that promotes public health and industrial sustainability.

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“Viral Intricacies: Dissecting Begomovirus Infection and Genomic Architecture in Cucurbits”



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Abstract

Begomoviruses are major viral pathogens of cucurbit crops, causing severe yield and quality losses. This review summarizes the characteristic symptoms induced by begomoviruses across different gourds and explains their infection cycle mediated by the whitefly *Bemisia tabaci*. The genomic features of monopartite and bipartite begomoviruses, including the roles of DNA-A, DNA-B and associated satellite molecules, are outlined. Understanding virus-host-vector interactions provides a basis for developing effective management strategies in cucurbit production.

Key words : Begomovirus, Whitefly transmission, Leaf curl disease.

Introduction

Cucurbit crops such as bitter gourd, bottle gourd, ash gourd, sponge gourd, ridge gourd, snake gourd, spine gourd and ivy gourd hold significant importance in Southern and Southeastern Asia. Although grown widely in both commercial farms and home gardens during warm seasons, their yield potential is frequently compromised by pests and diseases, particularly begomovirus infections. Begomoviruses possess a circular single-stranded DNA genome enclosed within a characteristic twinned capsid (approximately 20 × 30 nm), a defining feature of the *Geminiviridae* family. Within this family's nine genera, Begomovirus is the largest, comprising over 430 known species that infect numerous economically important crops across tropical and subtropical regions.

Symptomatology of begomovirus on different gourds

Begomovirus infection induces a wide range of characteristic symptoms in different gourd species, and the intensity of these symptoms often determines the extent of yield loss. Early-stage infection typically results in severe physiological and morphological disruptions, ultimately leading to significant reductions in fruit quality and marketable yield. Across the cucurbitaceous hosts examined, the virus produces distinct yet overlapping symptom patterns. In ash gourd, begomovirus-infected plants commonly exhibit mosaic mottling on the leaf surface along with pronounced twisting of veins. These symptomatic plants generally produce a reduced number of flowers, many of which fail to develop normally and may drop prematurely, thereby limiting fruit set.

In bitter gourd, the virus elicits a diverse set of symptoms during the vegetative phase, including upward leaf curl, twisting of the leaf blade, mottling, netting, yellowing, and mosaic. As the disease progresses to the reproductive stage, the symptoms intensify, characterized by severe leaf curling, pronounced yellowing and vein twisting, and the development of small, malformed, and deformed fruits. These abnormalities greatly impair fruit marketability. In bottle gourd, typical symptoms include chlorotic mottle, reduction in leaf size (leaf smalling), marginal and upward curling of leaves, and a pronounced stunting of the entire plant. Similar reductions in growth and leaf morphology are prominent in ivy gourd, where infected plants exhibit mosaic patterns, blistering, reduced leaf size, and overall stunted growth.

Naturally infected pointed gourd plants predominantly show mosaic, leaf curling, reduced leaf lamina, and severe deformation of fruits, accompanied by dwarfing of the whole plant. In advanced infections, plants produce fewer fruits, most of which are undersized and unsuitable for commercial use. In ridge gourd, begomovirus infection results in a broad spectrum of symptoms, beginning with light chlorotic patches on the leaf lamina. These patches appear intermingled with yellow, pale-green, and normal-green tissues. Additional symptoms include reduction in leaf size, upward curling, blistering of the leaves, stunted plant growth and the development of a limited number of malformed fruits. In snake gourd, symptoms appear initially as light green patches on the abaxial or adaxial leaf surface, which progressively develop into severe mosaic and mottling. Infected plants typically bear very few flowers and fruits due to disrupted physiological functioning.

In spine gourd, the virus induces mosaic, mottling, leaf curling, and distortion of leaves. The disease negatively affects reproductive development, resulting in fewer flowers and malformed fruits. Similarly, in sponge gourd, infection manifests as yellow specks on emerging leaves, mosaic, mild leaf curling, leaf distortion, reduced leaf size, and irregularly shaped fruits, all of which contribute to diminished yield and quality. Overall, the symptom complex associated with begomovirus infection across gourds reflects the virus's capacity to disrupt normal leaf development, photosynthetic activity, and reproductive processes, ultimately leading to considerable yield and economic losses.



Infection cycle of begomovirus

Begomoviruses infect a wide range of economically important crops and are the causal agents of leaf curl diseases that lead to substantial yield losses, especially in papaya and other horticultural crops. As obligate parasites, these viruses lack the enzymatic machinery required for independent replication and therefore rely entirely on living host cells for multiplication, survival, and persistence in nature. Since viruses cannot move autonomously, they depend on biological vectors for their spread from one host to another.

Among insect vectors, the whitefly *Bemisia tabaci* is the exclusive and most efficient natural vector responsible for transmitting begomoviruses. Transmission occurs in a persistent, circulative manner, wherein the whitefly acquires the virus during feeding on infected plants and subsequently inoculates healthy plants. The begomovirus coat protein (AV1) plays a key role in determining vector specificity; its conserved structural features facilitate precise binding of virions to receptor molecules located in the gut and salivary glands of *B. tabaci*, ensuring efficient retention and transmission.

Infections caused by Papaya leaf curl virus (PLCV) typically establish at the early growth stages of the host, disrupting several physiological and metabolic pathways. Consequently, infected plants exhibit stunted growth, malformed fruits, poor fruit quality, and severe yield deterioration. The disease expression is considerably more severe in young plants compared to mature plants. Notably, PLCV is predominantly observed under open-field

conditions rather than in nurseries, primarily due to the low availability of inoculum and the limited presence of whitefly vectors in controlled environments. Whiteflies transmit the virus while feeding primarily on the abaxial (lower) leaf surface. As sap-sucking insects, they insert their stylets into the phloem tissues, enabling them to ingest virus-laden sap from infected hosts. After acquisition, the virus traverses through the insect's alimentary canal from the oesophagus into the midgut lumen, then into the filter chamber, and finally to the primary salivary glands. During subsequent feeding on a healthy plant, viruliferous whiteflies release the virus into the phloem during salivation, completing the transmission cycle (Czosnek, 2012).

Since *B. tabaci* is the principal vector of PLCV, it can also transmit the virus to other susceptible hosts such as tomato and tobacco, where characteristic leaf curl symptoms are produced. Transmission studies conducted by Saxena *et al.* (1998) demonstrated that viruliferous whiteflies feeding exclusively on healthy papaya plants for extended periods (more than 48 hours, compared to the required 24-hour acquisition access period) exhibited high mortality, suggesting that papaya phloem sap is not a preferred or ideal food source. However, whiteflies survived better when allowed to feed alternately on papaya and other host plants, which in turn enhanced their ability to transmit the virus efficiently by inoculating healthy plants.

Genomic organization of begomovirus

Geminiviruses contain a single-stranded DNA genome housed within a unique twin-particle capsid. They infect a wide range of important crops including tomato, cassava, chilli, cotton and papaya. Their high mutation rate, adaptability to diverse hosts, and compact genome contribute to their rapid evolution and prevalence in agricultural systems.

The primary agents facilitating the dissemination of geminiviruses are insect vectors, which themselves have a broad host range, allowing efficient viral spread across diverse cropping systems. The compact genome, high mutation frequency, and wide host adaptability of these viruses contribute to their remarkable genetic variability and evolutionary flexibility. Collectively, these attributes make begomoviruses a major and persistent threat to crop cultivation, productivity and global agricultural sustainability.

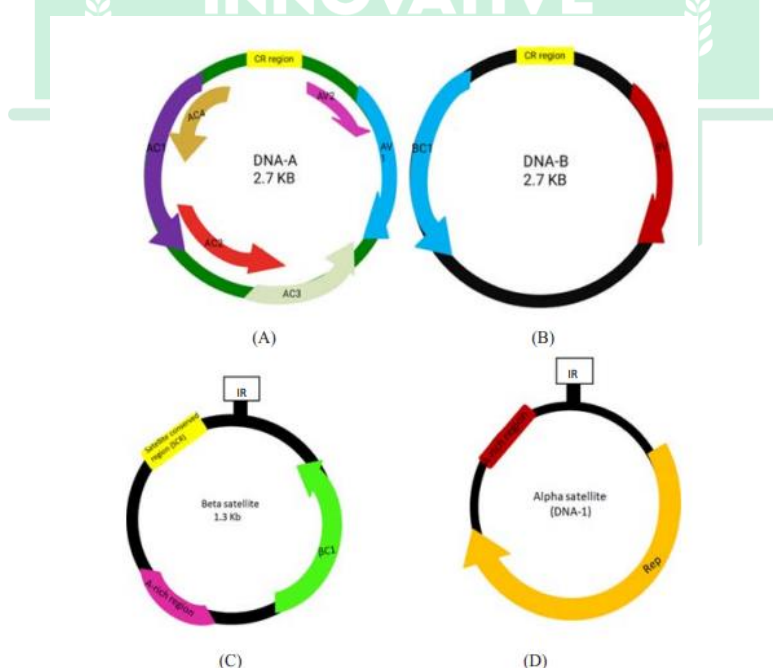


Figure 1: Genomic structure of various begomovirus components: (A) the DNA-A segment, (B) the DNA-B segment, (C) the accompanying beta-satellite molecule and (D) the associated alpha-satellite molecule

Table 1. Components of DNA-A and DNA-B of begomovirus ORF (gene) with their putative gene product(s) and their respective function

Open reading frame (DNA Component)	Protein	Functional Description
AC1 (DNA-A)	Replication initiation protein	Initiates and regulates viral DNA replication
AC2 (DNA-A)	Transcription activator protein	Activates transcription of rightward ORFs and suppresses post-transcriptional gene silencing (PTGS)
AC3 (DNA-A)	Replication enhancer protein	Enhances efficiency of viral DNA replication
AC4 (DNA-A)	—	Contributes to viral replication and functions as a PTGS suppressor
AV1 (DNA-A)	Coat protein (CP)	Responsible for virion encapsidation and essential for vector transmission
AV2 (DNA-A)	Precoat protein	Cell to cell movement protein
BC1 (DNA-B)	Movement protein (MP)	Mediates cell-to-cell movement of the virus and acts as a determinant of pathogenicity
BV1 (DNA-B)	Nuclear shuttle protein	Involved in nuclear import/export and intracellular trafficking of viral DNA

The begomovirus genome is composed of a circular ssDNA molecule. Species may be monopartite or bipartite. Bipartite begomoviruses contain two separate genomic components: DNA-A and DNA-B each roughly 2.7 kb in size. In contrast, monopartite viruses possess only the equivalent of the DNA-A component. The genus Begomovirus includes more than 192 species (Rey *et al.*, 2012), many of which have a bipartite genome whose DNA-A segment often occurs in association with satellite molecules, such as beta satellites or alpha satellites.

The DNA-A segment contains six ORFs: AV1, AV2, AC1, AC2, AC3 and AC4 (Figure. 1). AV1 (coat protein) and AV2 (pre-coat protein) are encoded on the virion-sense strand, while AC1–AC4 are encoded on the complementary strand (Patil & Fauquet, 2009). The DNA-B component encodes BV1 (nuclear shuttle protein) and BC1 (movement protein) (Figure 1B) (Rojas *et al.*, 2005). Table 1 summarizes the functional roles of the proteins encoded by DNA-A and DNA-B. A conserved intergenic region (IR) present on both components contains the nonanucleotide sequence TAATATTAC, which initiates rolling-circle replication.

For the establishment of a typical symptomatic infection, the presence of both genomic components- DNA-A and DNA-B is generally required. Nevertheless, in certain exceptional begomoviruses, the DNA-A segment alone is capable of inducing symptomatic infection independently of DNA-B. Additionally, begomoviruses are frequently associated with two types of satellite DNAs, beta satellites (DNA-β) and alpha satellites (DNA-α) (Fig. 1C and 1D). These satellites often accompany the helper virus during infection and may contribute to symptom development. In most natural infections, begomoviruses are predominantly associated with beta satellites, which are strongly linked to severe symptom expression in host plants.

Circulative pathway of begomovirus in whitefly

Begomovirus transmission occurs exclusively through feeding activities of its insect vector, *Bemisia tabaci*, which facilitates the onset of leaf curl disease in susceptible host plants. This process involves a complex tripartite interaction among the virus, the host plant, and the whitefly vector (Figure. 2). Whiteflies transmit begomoviruses in a persistent, circulative and non-propagative manner, acquiring and subsequently inoculating the virus while feeding on plant foliage (Czosnek *et al.*, 2002). Both the whitefly and its associated bacterial endosymbionts synthesize specific proteins that play essential roles in facilitating efficient viral transmission.

The infection cycle begins when the whitefly inserts its stylet into the phloem tissues of an infected plant, thereby ingesting virus-laden sap. Once acquired, the virions pass through the esophagus into the midgut and subsequently enter the filter chamber, which acts as a selective barrier for ingested materials. This initial phase constitutes the acquisition period. Following acquisition, begomoviruses accumulate and persist within the midgut for an extended duration, referred to as the latency period, during which the virions circulate within the vector's body.

During their residence in the whitefly midgut, the virions interact with host molecular chaperones such as heat shock proteins (HSP70). These interactions assist the virus in crossing the midgut epithelial barrier and

entering the haemolymph. Within the haemolymph, virions encounter GroEL proteins produced by endosymbiotic bacteria, which stabilize and protect them during transport. The virus then reaches the primary salivary glands through an endocytic mechanism. Once localized in the salivary glands, begomoviruses are introduced into a new host plant as the whitefly feeds, completing the circulative transmission pathway (Figure 3). Whiteflies generally require 15–50 minutes for effective acquisition of the virus and 15–30 minutes for its inoculation into healthy plant phloem. An approximate latency period of 8 hours is necessary before viruliferous whiteflies can successfully transmit the virus. This sequence of acquisition, movement through vector tissues, and subsequent inoculation underpins the efficiency of begomovirus spread in agricultural ecosystems.

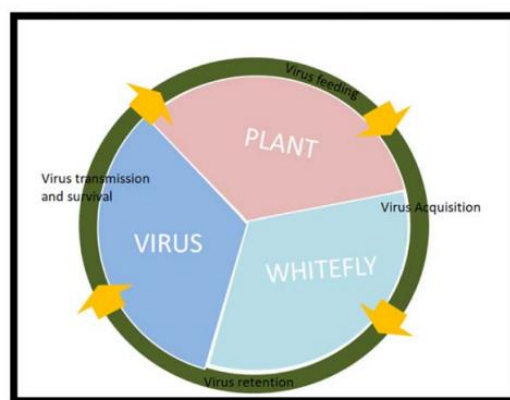


Figure 2. The diagram illustrates the three-way interaction among the whitefly, the begomovirus, and the host plant. Virus spread occurs through the whitefly vector (*Bemisia tabaci*), which acquires the virus while feeding and subsequently transfers it to healthy plants.

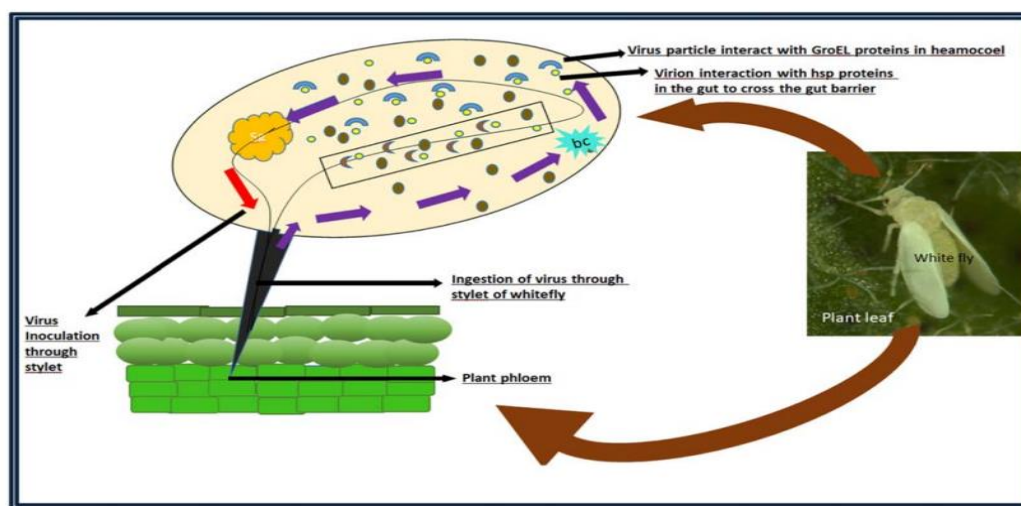
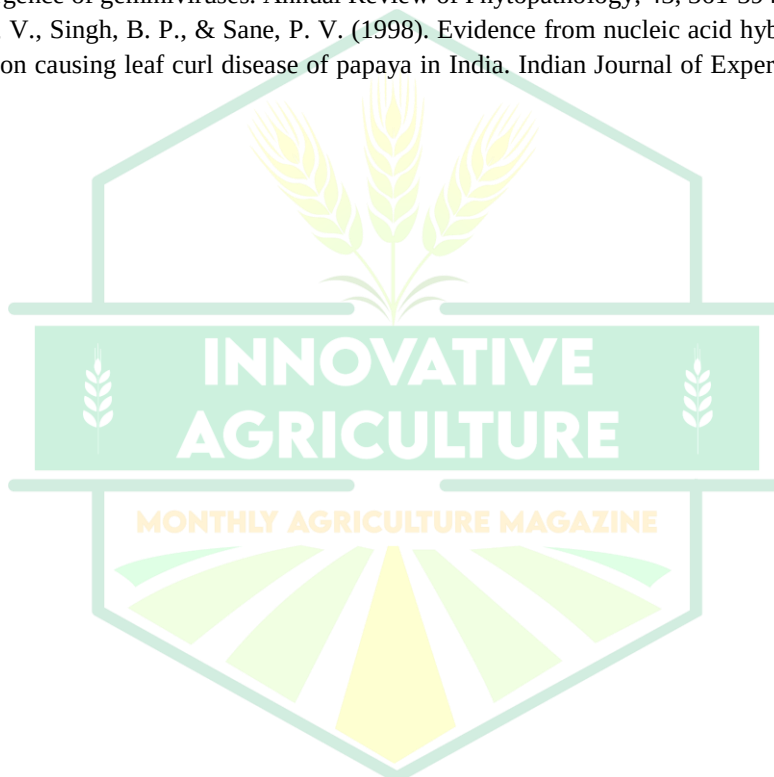


Figure 3. The figure depicts the persistent, circulative route through which whiteflies transmit the virus (shown in yellow). In this process, the whitefly (*Bemisia tabaci*) acquires begomoviruses during feeding. Once inside the insect, the virions move from the oesophagus to the midgut, where they associate with heat shock proteins (HSPs) that facilitate their passage across the midgut barrier into the haemolymph. Within the haemolymph, the virus interacts with GroEL proteins produced by endosymbiotic bacteria, which help stabilize the virions. The virus then migrates to the primary salivary glands, from where it is released into healthy plants during subsequent feeding. The whitefly's body cavity also contains secondary symbionts (represented in brown), which further aid in enhancing virus–vector compatibility and transmission efficiency.

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Impact of Women Empowerment on Child Development in Families



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Abstract

The empowerment of women has a significant impact on how children develop as a whole within households. Empowered women socially, economically and psychologically are better suited to offer a supportive, secure and stimulating environment for their children. This article investigates the influence of women empowerment on many dimensions of child development, including physical, cognitive, emotional, social and moral development. It illustrates how education, economic independence, decision-making power and knowledge among women contribute to healthy family situations and excellent kid outcomes.

Keywords:

Women Empowerment, Child Development, Family Environment, Maternal Education, Parenting Practices.

Introduction

Women empowerment is widely regarded as a crucial pillar of societal growth, personal development and family well-being. It describes the procedure that gives women equal access to opportunities, resources, rights and the ability to make decisions in both the public and private domains. Women, especially mothers, have a crucial role in families as the main caretakers, teachers and emotional support systems. The level of care, stimulation and support given to children throughout critical developmental periods is strongly impacted by their position, autonomy and ability. From the perspective of family and child development, the family is seen as a linked system where each member's health has an impact on the others. The family structure as a whole gains when women are empowered via education, economic independence, health consciousness and social engagement. Women who are empowered are more equipped to make decisions about socialization, education, healthcare and nutrition all of which are critical to a child's growth.

Children of empowered mothers exhibit improved physical health, more educational success, greater mental stability and more good social behaviors, according to several studies. On the other hand, children frequently have limited chances and unfavorable outcomes as a result of women's disempowerment, which manifests as poverty, illiteracy, gender discrimination and a lack of autonomy. Consequently, women's empowerment is a strategic investment in the holistic development of children and the future of society, in addition to being a question of gender equality. This article analyzes the impact of women empowerment on child development within households by investigating its influence on physical, cognitive, emotional and social dimensions of development. The essay emphasizes how empowering women enhances family functioning and promotes sustainable human development by using a developmental framework.

Recent empirical investigations substantially substantiate this relationship. For example, Cunningham et al. (2015) revealed that greater levels of women's empowerment are strongly connected with improved child nutrition and physical growth outcomes in South Asian nations. Similarly, Pratley (2016), in a comprehensive analysis of research from low- and middle-income countries, concluded that women's decision-making authority and educational attainment positively affect children's health, access to healthcare services and early developmental outcomes. These results show that children have superior developmental prospects when women are empowered in the home.

On the other hand, women's disempowerment, which takes the form of poverty, illiteracy, gender discrimination and limited autonomy, frequently leads to limited possibilities and unfavorable consequences for children. Children of empowered women exhibit improved physical health, more educational attainment, greater emotional stability and more good social behaviors, according to several studies (UNICEF, 2019; UNDP, 2020).

Consequently, women's empowerment is a strategic investment in children's holistic development and the future of society, in addition to being a question of gender equality.

Concept of Women Empowerment

The idea of women's empowerment is complex and extends beyond financial freedom. It refers to giving women authority over their lives, resources and choices in the home and in society. Empowerment improves children's developmental outcomes and family functioning from a developmental standpoint.

Among the main aspects of women's empowerment are:

- **Educational empowerment:** Women's knowledge, awareness and critical thinking abilities are improved by having access to both formal and informal education. Women with higher levels of education are more aware about the rights, health, nutrition and education of children.
- **Economic empowerment:** Women contribute more to home income and raise children's standards of life when they are financially independent through work, self-help organizations, or entrepreneurship.
- **Social empowerment:** Freedom from restrictive social norms, discrimination and gender bias enables women to engage fully in communal and social life.
- **Psychological empowerment:** Development of self-esteem, confidence and emotional strength permits women to handle parental stress more effectively.
- **Power to make decisions:** Involvement in family and household decisions guarantees that children's health, education and well-being requirements are given first priority.

When taken as a whole, these aspects improve a woman's ability to give her children greater care, direction, emotional support and developmental stimulation.

Understanding Child Development in Families

Child development is a lifetime and diverse process that begins at birth and continues into puberty. It comprises physical, cognitive, verbal, emotional, social and moral development. Families act as the major socializing agents and offer the first setting in which children grow and learn. Through caring techniques, emotional connection, disciplinary methods and the transfer of values, parents especially mothers have an impact on their children. While stress, conflict and deprivation can impede growth, a secure, encouraging and resource-rich home environment fosters healthy development. Women empowerment promotes family functioning by lowering stress, expanding resources and encouraging healthy parent-child relationships, so dramatically impacting children's developmental outcomes.

Impact of Women Empowerment on Physical Development of Children

Women empowerment has a direct and quantifiable influence on the physical development of children. Empowered women are more knowledgeable about illness prevention, vaccination schedules, nursing techniques, balanced eating and cleanliness. This understanding assists in lowering hunger, stunting and avoidable diseases among children.

Economic empowerment allows moms to afford healthy food, clean water, safe housing and prompt medical treatment. Additionally, empowered women are more likely to use healthcare services for mothers and children, including growth monitoring, institutional births and routine checkups. These procedures lead to better birth outcomes, better physical development and increased children's general physical well-being.

Recent research confirms this connection. Researchers used data from the National Family Health Survey of India to find that improved nutritional status for children under five years old was significantly correlated with higher levels of maternal empowerment, especially in the areas of education, financial inclusion and healthcare decision-making (Pratley, 2016; Cunningham et al., 2015). Similarly, a cross national research across low- and middle-income countries revealed that women's autonomy in health-related decisions reduced child mortality and improved child survival outcomes (Pratley, 2016).

Impact on Cognitive and Educational Development

Empowerment of women has a key role in increasing children's cognitive and intellectual development. Educated and empowered moms create a learning-friendly home atmosphere by stimulating curiosity, problem-solving and creativity. They engage youngsters in reading, storytelling, educational play and meaningful interactions, which enhance language and cognitive abilities. When it comes to early childhood education, school choice, consistent

attendance, and further education, empowered women make well-informed decisions. They are more likely to disrupt the intergenerational patterns of gender inequity by supporting sons' and daughters' equal education. Children with empowered moms typically perform better academically, are more motivated, and have favorable views about learning.

Empirical research from the past decade reveals that mother education and empowerment considerably impact children's educational performance. Children of empowered moms were more likely to attend school consistently and do better academically, according to a 2019 research by *Jejeebhoy and Sathar*. Women's involvement in home decision-making improved children's learning outcomes and decreased school dropout rates, according to another long-term research (*Malhotra & Schuler, 2020*).

Impact on Emotional and Psychological Development

Children's emotional and psychological development is greatly impacted by women's empowerment. Empowered women tend to have fewer levels of stress, worry, and helplessness, which favorably influences their parenting style. They provide their kids greater emotional support, patience and responsiveness. These moms offer emotional stability, promote candid communication and employ constructive disciplining techniques. Children learn resilience, emotional control, self-confidence and a good self-concept in this supportive setting. Strong emotional attachment with empowered caregivers also decreases behavioral difficulties and increases mental well-being among youngsters.

According to recent psychology and public health research, children's emotional adjustment is strongly correlated with mothers' autonomy and mental health. Improved mother mental health, which is frequently connected to empowerment and social support, has been linked to better emotional control and fewer behavioral issues in children, according to a research published in *The Lancet (Patel et al., 2018)*. According to a different study, empowered moms use constructive parenting techniques that help kids develop resilience and emotional stability (*Malhotra & Schuler, 2020*). Such loving surroundings help youngsters develop self-confidence, emotional control, resilience and a positive self-concept, leading to long-term mental well-being.

Impact on Social Development and Values

Empowered women have a critical role in influencing children's social development and value systems. Through regular encounters, children learn social standards, gender roles, collaboration, and respect. Within the family, empowered moms foster ideals like justice, equality, empathy and respect for one another.

Women help children especially girls develop independence and self-expression by questioning conventional gender norms. Participation of empowered women in community activities also exposes children to larger social networks, helping them develop social competence, leadership abilities and ethical responsibility.

According to recent sociological research, children's progressive gender attitudes are closely linked to women's empowerment. Children of empowered women were more likely to advocate gender equality and exhibit prosocial conduct, according to a multi-country study (*Kabeer, 2016; Malhotra & Schuler, 2020*). Children are exposed to larger social networks when empowered women participate in community and economic activities, which improves social competence and leadership abilities.

Challenges to Women Empowerment

Despite tremendous advancements, a number of obstacles still stand in the way of women's empowerment, such as poverty, illiteracy, early marriage, gender discrimination, domestic abuse and restricted access to jobs and healthcare. These obstacles limit women's capacity to give their kids the best possible care and stimulation. As a result, children may endure poor health outcomes, low educational attainment, mental stress, and restricted social exposure, so perpetuating cycles of deprivation throughout generations.

Role of Society and Policy in Promoting Women Empowerment

Government regulations and societal support are essential for empowering women and enhancing the development of children. Stronger families are a result of initiatives that support women's employment, education for girls, maternity and child health, legal rights, and social safety programs. Initiatives for family life education, self-help organizations, and community awareness programs all contribute to changing perceptions of women's responsibilities in households and society.

Conclusion

Strong family structures and the development of healthy children depend on the empowerment of women. Empowered women contribute significantly to children's physical health, cognitive growth, emotional stability, social competence and moral development. From a developmental standpoint, women's empowerment improves family dynamics, lessens disadvantages across generations and fosters long-term human growth. Long-term advantages for children, families, and society as a whole result from investing in women's education, economic prospects, psychological health and decision-making authority. As a result, society should promote women empowerment in their family so that the better development of children, stronger family values and overall social progress can be ensured.

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Neuroendocrine Biomarkers in Fish: A Novel Approach to Precision Aquaculture Management



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Abstract:

The rapid expansion of aquaculture demands innovative and sensitive monitoring strategies to ensure sustainable production, environmental safety, and optimal fish health. Conventional water quality assessments and disease diagnostics often detect stress responses only after physiological damage or production losses have occurred. In this context, neuroendocrine biomarkers in fish offer a promising early-warning system for precision aquaculture management.

The neuroendocrine system in fish plays a central role in regulating stress adaptation, pigmentation, metabolism, growth, and immune responses. Environmental fluctuations, chemical contaminants, nutritional imbalances, and handling stress can disrupt hormonal and neurotransmitter-mediated pathways long before visible clinical symptoms appear. Monitoring neuroendocrine indicators—such as pigment cell responses, hormonal modulation patterns, and stress-related signaling alterations—provides a sensitive measure of sub-lethal stress in cultured fish populations.

Among these indicators, melanophore pigment dynamics represent a rapid and visually quantifiable response to neurohormonal regulation. Alterations in pigment aggregation and dispersion patterns reflect underlying disturbances in adrenergic and hormonal control mechanisms. Such cellular responses can serve as real-time indicators of water quality deterioration, toxic exposure, or chronic stress conditions within aquaculture systems. Integrating neuroendocrine biomarkers into routine farm management supports the development of precision aquaculture practices. Early detection of physiological imbalance enables timely intervention, reduces mortality risk, enhances feed efficiency, and promotes sustainable aquatic food production. By combining cellular-level biomarkers with environmental monitoring tools, aquaculture can transition toward more predictive, responsive, and climate-resilient management strategies.

This approach highlights the transformative potential of neuroendocrine biomarker research in advancing innovative and sustainable aquaculture systems within the broader scope of life sciences.

Keywords: Neuroendocrine Biomarkers, Precision Aquaculture, Melanophore Dynamics, Fish Stress Physiology, Water Quality Monitoring, Sustainable Fish Farming, Aquatic Health

Introduction:

Aquaculture has emerged as one of the fastest-growing sectors of global food production, contributing significantly to nutritional security, livelihood generation, and rural economic development. With increasing demand for aquatic protein and declining capture fisheries, modern aquaculture systems are evolving toward intensified and technology-driven production models. However, intensification also increases vulnerability to environmental fluctuations, water quality deterioration, disease outbreaks, and stress-related growth suppression. Ensuring fish health under such dynamic conditions requires monitoring tools that are not only accurate but also capable of detecting early physiological imbalance before irreversible damage occurs.

Traditional aquaculture management practices primarily rely on physico-chemical assessment of water parameters such as dissolved oxygen, pH, ammonia, and temperature. While these indicators are essential, they often fail to reflect the biological stress experienced by cultured organisms. Similarly, clinical symptoms and mortality rates represent late-stage manifestations of underlying physiological disturbances. Therefore, there is a growing need for sensitive biological markers that can signal sub-lethal stress at its earliest stages.

The neuroendocrine system in fish plays a pivotal role in maintaining homeostasis and coordinating responses to environmental challenges. Hormones and neurotransmitters regulate critical processes including stress adaptation, pigmentation, metabolism, immune modulation, growth, and reproduction. Even minor environmental

perturbations—such as fluctuations in water quality, exposure to contaminants, nutritional imbalance, or handling stress—can alter neuroendocrine signaling pathways. These changes often precede visible signs of disease or production decline, making them valuable early indicators of health status.

Neuroendocrine biomarkers, therefore, offer a promising framework for precision aquaculture management. By assessing hormone-regulated physiological responses at the cellular or systemic level, it becomes possible to monitor fish well-being in real time. Among the emerging cellular indicators, pigment cell dynamics—particularly melanophore responses—provide a rapid and visually detectable measure of neurohormonal regulation. Alterations in pigment aggregation and dispersion patterns can reflect disturbances in adrenergic and hormonal pathways, serving as sensitive markers of stress and environmental imbalance.

Integrating neuroendocrine biomarkers into aquaculture systems aligns with the principles of precision agriculture, where data-driven and biologically informed decisions enhance productivity while minimizing environmental impact. Such approaches support sustainable aquaculture by enabling early intervention, reducing disease incidence, optimizing feed utilization, and promoting overall system resilience. Within the broader scope of life sciences, the application of neuroendocrine biomarkers represents an innovative intersection of physiology, environmental biology, and agricultural biotechnology.

2. Neuroendocrine Regulation in Fish:

The neuroendocrine system integrates nervous and hormonal signals to maintain internal balance. Key components include:

2.1. Hypothalamic–pituitary–interrenal (HPI) axis: The Hypothalamic–Pituitary–Interrenal (HPI) axis is the central stress-regulating system in fish, comparable to the HPA axis in mammals. In response to environmental stressors such as poor water quality, crowding, or toxic exposure, the hypothalamus releases corticotropin-releasing hormone (CRH), which stimulates the pituitary to secrete adrenocorticotrophic hormone (ACTH). ACTH then activates interrenal cells in the head kidney to produce cortisol.

Cortisol serves as the primary stress hormone in teleost fish. While short-term activation supports adaptive processes like energy mobilization and osmoregulation, chronic activation can impair growth, immunity, reproduction, and metabolism. Therefore, changes in HPI axis activity act as early indicators of stress in aquaculture systems.

2.2. Adrenergic signaling pathways: Adrenergic signaling involves the release of catecholamines such as adrenaline (epinephrine) and noradrenaline (norepinephrine) during acute stress. These neurotransmitters bind to specific adrenergic receptors present in various tissues, including pigment cells, cardiovascular tissues, and metabolic organs.

In fish, adrenergic signaling plays a crucial role in rapid physiological adjustments, including modulation of heart rate, blood flow, ion regulation, and pigment cell responses. Melanophores, for example, respond to adrenergic stimulation by altering melanosome aggregation or dispersion. Disruption of adrenergic pathways due to environmental contaminants or chronic stress can impair these rapid adaptive responses, serving as a sensitive marker of neuroendocrine imbalance.

2.3. Cortisol-mediated stress response: Cortisol functions as the central mediator of the stress response in fish. Following HPI axis activation, cortisol facilitates energy mobilization by stimulating gluconeogenesis, protein catabolism, and lipid metabolism. It also regulates osmoregulation and immune function.

Under controlled conditions, cortisol helps fish cope with temporary environmental challenges. However, persistently elevated cortisol levels—often resulting from chronic stressors in intensive aquaculture—can suppress immune responses, reduce disease resistance, impair growth performance, and decrease reproductive efficiency. Therefore, cortisol dynamics serve as a critical biomarker for assessing physiological stress in aquaculture systems.

2.4. Hormonal regulation of metabolism and growth: Beyond stress regulation, the neuroendocrine system influences growth and metabolic balance through hormones such as growth hormone (GH), insulin-like growth factors (IGFs), thyroid hormones, and metabolic regulators.

Environmental stress can alter hormonal secretion patterns, affecting nutrient utilization, feed conversion efficiency, and somatic growth. For example, chronic stress may suppress growth hormone activity, leading

to reduced weight gain and poor productivity. Similarly, metabolic imbalance caused by neuroendocrine disruption can compromise feed efficiency and energy allocation.

Understanding hormonal regulation mechanisms enables aquaculture managers to interpret physiological signals that precede production losses, thereby supporting timely intervention and optimized farm management.

When fish encounter environmental stressors such as poor water quality, toxic exposure, handling, or overcrowding, the HPI axis is activated. This leads to cortisol release and modulation of various physiological pathways. While acute responses may be adaptive, chronic activation disrupts growth, immune competence, feed conversion efficiency, and reproductive performance.

Because neuroendocrine responses occur rapidly and at early stages of stress, they provide a valuable window for early detection.

3. Neuroendocrine Biomarkers: Concept and Significance:

A biomarker is a measurable biological response indicating physiological or pathological processes. Neuroendocrine biomarkers include:

- Hormonal fluctuations (e.g., cortisol levels)
- Altered neurotransmitter-mediated responses
- Cellular indicators regulated by neurohormonal pathways

Among cellular indicators, melanophore pigment dynamics provide a visually observable and rapid response to adrenergic and hormonal regulation. Melanophores are pigment-containing cells capable of bidirectional melanosome movement—aggregation and dispersion—under neuroendocrine control. Disturbances in this regulation reflect underlying stress and environmental imbalance.

Such cellular-level responses occur before gross pathological symptoms, making them valuable tools in precision aquaculture.

4. Application in Precision Aquaculture Management:

Precision aquaculture integrates biological monitoring, environmental data, and technological tools to optimize production efficiency and sustainability. Neuroendocrine biomarkers can support precision management in several ways:

4.1 Early Stress Detection: Monitoring neuroendocrine indicators allows identification of sub-lethal stress before growth retardation or disease outbreaks occur.

4.2 Water Quality Assessment: Biological responses may detect contamination or imbalance that conventional chemical testing may overlook.

4.3 Improved Feed Efficiency: Stress reduction enhances metabolic stability and feed conversion ratios.

4.4 Disease Prevention: Chronic neuroendocrine stress suppresses immunity; early intervention prevents pathogen proliferation.

4.5 Sustainable Production: Reduced mortality and optimized health contribute to environmentally responsible aquaculture.

5. Advantages Over Conventional Monitoring:

Compared to traditional aquaculture monitoring methods, neuroendocrine biomarkers provide several significant advantages that enhance precision and sustainability in fish farming systems.

Higher Sensitivity to Subtle Stress

Conventional monitoring primarily focuses on physico-chemical water parameters such as dissolved oxygen, ammonia, pH, and temperature. While these factors are important, they do not always reflect the biological stress experienced by fish. Neuroendocrine biomarkers detect physiological disturbances at the hormonal and cellular levels, often before visible behavioral changes, disease symptoms, or mortality occur. This heightened sensitivity allows for early identification of sub-lethal stress conditions that might otherwise go unnoticed.

Rapid Response Detection

Neuroendocrine responses, particularly those mediated through hormonal and adrenergic pathways, occur rapidly following exposure to environmental stressors. Changes in cortisol levels, pigment cell dynamics, or

neurotransmitter signaling can manifest within a short time frame. This enables timely intervention, reducing the risk of chronic stress, growth retardation, and disease outbreaks in aquaculture systems.

Biological Relevance to Fish Health

Unlike purely chemical measurements, neuroendocrine biomarkers directly reflect the physiological state of the organism. They provide insight into internal homeostatic balance, metabolic stability, immune competence, and stress adaptation capacity. Because these indicators are closely linked to growth performance, feed efficiency, and disease resistance, they offer a more comprehensive understanding of fish health and overall farm productivity.

Potential Integration with Automated Systems

With advancements in aquaculture technology, neuroendocrine monitoring can be integrated into smart farming platforms. Automated sampling systems, biosensors, digital imaging tools, and data analytics can be used to monitor hormonal levels or pigment cell responses in real time. Such integration supports data-driven decision-making, enabling predictive management strategies aligned with precision aquaculture practices.

Collectively, these advantages position neuroendocrine biomarkers as powerful tools within innovative agriculture, bridging the gap between environmental monitoring and biological health assessment in modern aquaculture systems.

6. Challenges:

Despite their significant potential, the practical implementation of neuroendocrine biomarkers in routine aquaculture management presents several challenges that must be systematically addressed.

Standardization of Protocols

One of the primary limitations is the absence of universally standardized protocols for biomarker assessment. Variations in sampling techniques, environmental conditions, analytical methods, and interpretation criteria can lead to inconsistent results. Establishing standardized experimental frameworks and reference ranges for hormonal and cellular responses is essential to ensure reliability and reproducibility across aquaculture systems.

Species-Specific Validation

Fish species differ in their physiological responses, stress tolerance levels, and endocrine regulation patterns. A biomarker validated in one species may not directly apply to another. Therefore, species-specific baseline studies and validation trials are necessary before large-scale adoption. Such research will help define threshold values and response patterns appropriate for different aquaculture species.

Integration with Digital Aquaculture Technologies

Modern aquaculture increasingly relies on automated monitoring systems and digital platforms. Integrating neuroendocrine biomarkers into these systems requires technological innovation, including sensor development, imaging tools, and data management software. Bridging the gap between biological monitoring and digital infrastructure remains a key developmental area for precision aquaculture.

Farmer Awareness and Capacity Building

Successful implementation also depends on awareness and technical training among farmers and aquaculture professionals. Many production systems still rely primarily on traditional monitoring practices. Educating stakeholders about the benefits of early physiological monitoring and providing user-friendly diagnostic tools will facilitate wider adoption.

7. Future Prospects:

Advancements in biotechnology and digital agriculture offer promising avenues for the future. Development of non-invasive biosensors capable of detecting hormonal fluctuations, automated imaging systems to monitor pigment cell responses, and portable diagnostic kits could make neuroendocrine monitoring more accessible and practical.

Furthermore, integration with artificial intelligence and data analytics platforms may enable real-time interpretation of biomarker data, predictive modeling of stress events, and automated decision-support systems. Such innovations would enhance early warning capacity, optimize feeding and stocking strategies, and reduce disease incidence.

As aquaculture adapts to climate variability, environmental uncertainty, and increasing production demands, incorporating neuroendocrine biomarker-based monitoring can significantly strengthen system resilience. By enabling proactive rather than reactive management, this approach supports sustainable growth, improved fish welfare, and long-term productivity in innovative aquaculture systems.

8. Conclusion:

Neuroendocrine biomarkers represent a transformative advancement in precision aquaculture management, shifting the focus from reactive problem-solving to proactive health surveillance. By identifying early physiological imbalances at hormonal, cellular, and metabolic levels, these biomarkers provide a predictive and biologically meaningful framework for assessing fish well-being before visible symptoms or production losses occur.

Unlike conventional monitoring systems that primarily evaluate environmental parameters, neuroendocrine approaches directly reflect the internal adaptive state of the organism. This enables more accurate evaluation of stress load, growth performance, immune competence, and overall metabolic stability. Consequently, farmers and aquaculture managers can implement timely corrective measures related to water quality, stocking density, feeding regimes, and environmental management.

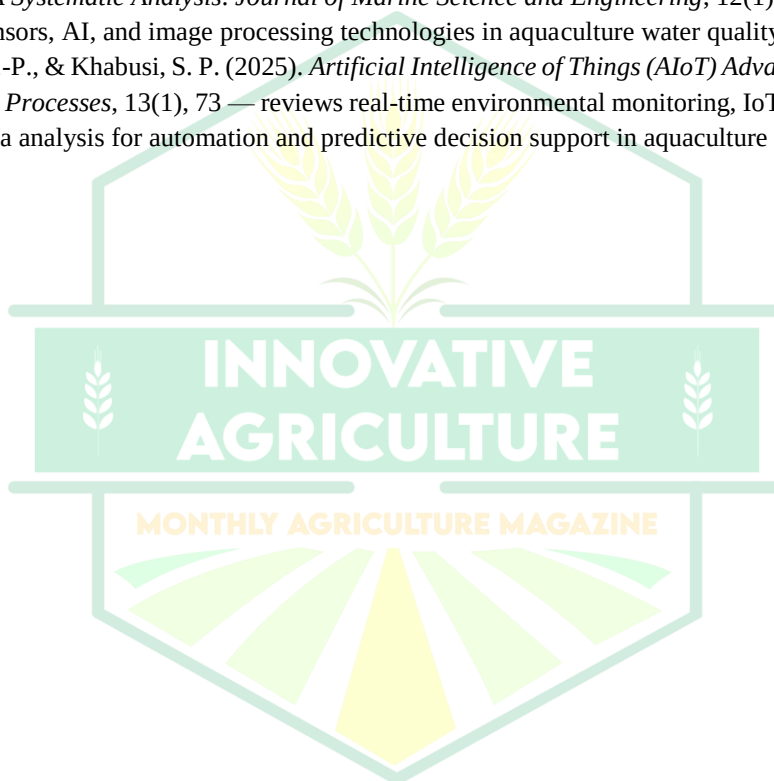
The integration of neuroendocrine monitoring into aquaculture systems aligns strongly with the principles of innovative agriculture, emphasizing sustainability, efficiency, animal welfare, and environmental responsibility. By combining biological indicators with digital technologies, automated monitoring platforms, and data-driven decision-making tools, aquaculture can evolve toward a smarter and more resilient production model.

Continued interdisciplinary research, technological innovation, and field-level validation will be essential to translate this promising approach into routine practice. As global demand for aquatic food resources increases and environmental challenges intensify, neuroendocrine biomarker-based strategies will play an increasingly vital role in shaping the future of sustainable, life sciences-driven aquaculture systems.

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Software Used in Social Science Research: Tools Transforming Modern Inquiry



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Abstract

The use of software in social science research has significantly transformed the way researchers collect, analyze, and interpret data. Modern tools such as statistical packages, qualitative data analysis software, and Geographic Information Systems (GIS) have enhanced the efficiency, accuracy, and depth of research. These tools enable researchers to handle complex datasets, perform advanced analyses, and present findings in a visually appealing and understandable manner. This article discusses the major software used in social science research, their applications, advantages, and relevance, particularly in areas such as fisheries and rural development.

Introduction

Social science research is concerned with the systematic study of human behaviour, social relationships, and economic systems. In earlier times, researchers relied heavily on manual methods of data collection and analysis, which were time-consuming and often prone to errors. However, with the advancement of technology, software tools have become an integral part of research processes. Today, researchers use software at every stage of their work, including questionnaire design, data collection, data analysis, and presentation of results. These technological advancements have not only improved the speed and accuracy of research but also enabled the analysis of large and complex datasets that were previously difficult to manage. For instance, in fisheries research, software tools can be used to study fishermen's livelihoods, analyse policy impacts, and map coastal resources efficiently.

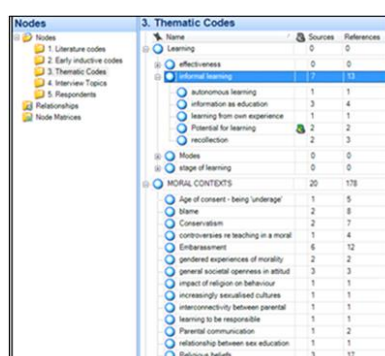
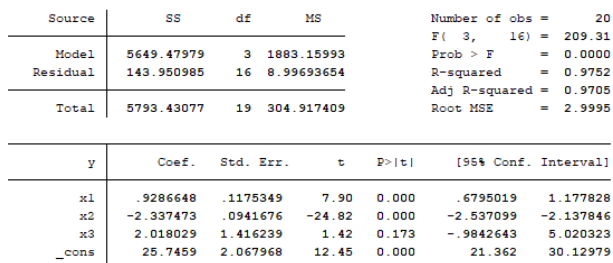
Role and Importance of Software in Research

Software plays a crucial role in enhancing the quality and reliability of social science research. One of the primary advantages of using software is the ability to process large volumes of data quickly and accurately. Statistical software reduces the chances of human error and allows researchers to perform complex analyses such as regression, correlation, and hypothesis testing. Additionally, software tools improve data visualization by converting numerical data into charts, graphs, and dashboards, making it easier for researchers and policymakers to understand the findings. According to Field (2018), the use of statistical software has greatly improved the precision and validity of research outcomes. Furthermore, software facilitates efficient data storage and management, ensuring that research data is organized and easily accessible.

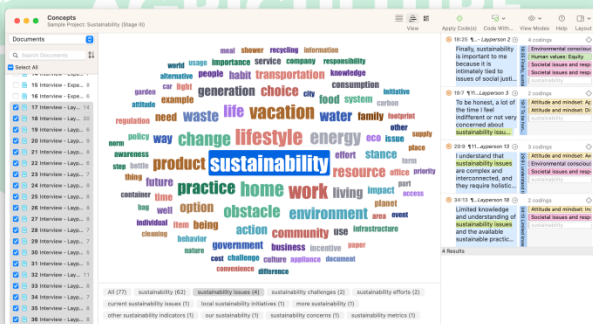
Statistical Software in Quantitative Research

Quantitative research involves the analysis of numerical data, and statistical software plays a vital role in this process. Popular tools such as SPSS, R, Stata, and SAS are widely used by researchers to perform statistical analyses.

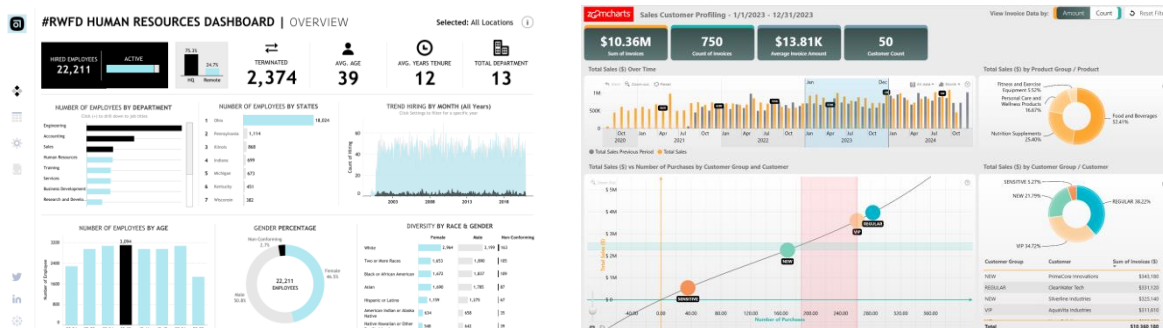
These tools allow researchers to calculate descriptive statistics, conduct correlation and regression analyses, and test hypotheses. For example, in a study on fishermen's income, statistical software can be used to determine average income levels, examine the relationship between education and income, and evaluate the impact of government welfare schemes. SPSS, in particular, is widely preferred due to its user-friendly interface and powerful analytical capabilities (Pallant, 2020). The use of such tools enables researchers to draw meaningful conclusions from data and support their findings with statistical evidence.



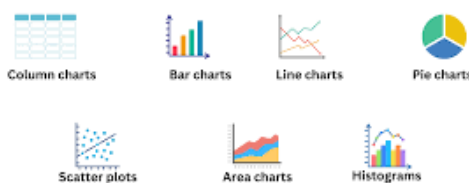
Code book A codebook is a guide to help researchers consistently apply codes to qualitative data.



fishermen or a bar graph to compare different districts. Visualization not only makes data more understandable but also helps in identifying trends and patterns. Knaflic (2015) highlights that effective data visualization is crucial for storytelling and decision-making in research.

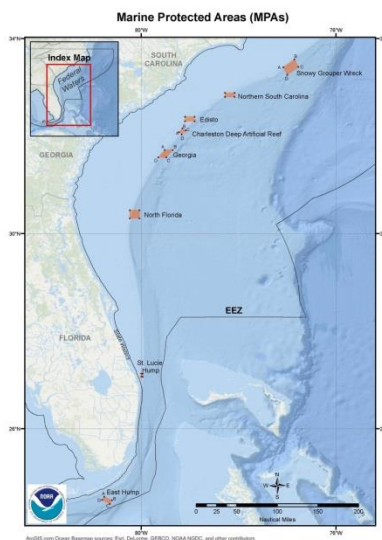
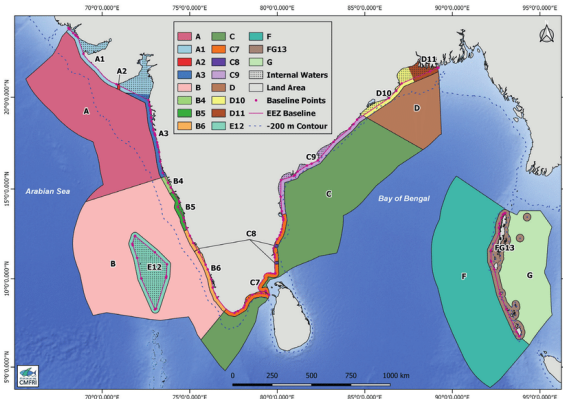


Types of Data Visualizations in Excel



GIS Software in Social Science Research

Geographic Information Systems (GIS) have become increasingly important in social science research, particularly in studies involving spatial data. Software such as QGIS and ArcGIS allows researchers to map and analyze geographical information. In fisheries research, GIS can be used to map fishing zones, analyze resource distribution, and study the impact of environmental changes on coastal communities. For example, researchers can map coastal districts such as Nagapattinam and Cuddalore to identify fishing areas and assess resource availability. According to Longley et al. (2015), GIS plays a critical role in spatial analysis and supports informed decision-making in environmental and social research



Applications in Fisheries and Rural Development Research

Software tools are highly relevant in fields such as fisheries and rural development. In livelihood analysis, statistical software can be used to analyze income and employment data. For policy evaluation, researchers can assess the effectiveness of government schemes using quantitative methods. Value chain analysis can be conducted using a combination of statistical and qualitative tools to understand the roles of different stakeholders. GIS tools are useful for mapping coastal areas and analyzing environmental changes, while qualitative software helps in understanding the experiences and challenges faced by fishermen. These applications demonstrate the importance of software in conducting comprehensive and impactful research.

Challenges in Using Research Software

Despite the numerous advantages, the use of software in research also presents certain challenges. One of the major issues is the lack of technical knowledge and skills among researchers, which may limit the effective use of advanced tools. Additionally, some software packages are expensive and may not be accessible to all researchers. There is also a need for proper training to ensure accurate data analysis. Data privacy and security concerns are another important consideration when using digital tools. However, the availability of open-source software such as R, QGIS, and KoboToolbox has helped address some of these challenges by providing cost-effective alternatives.

Conclusion

In conclusion, software has become an indispensable component of modern social science research. It enhances the efficiency, accuracy, and quality of research by enabling advanced data analysis, effective visualization, and systematic data management. For researchers in fields such as fisheries and rural development, the use of software tools is essential for understanding complex social and economic issues. By integrating statistical, qualitative, and spatial tools, researchers can generate comprehensive insights and contribute to evidence-based policymaking. As technology continues to evolve, the role of software in research is expected to grow, making it increasingly important for researchers to develop the necessary skills to utilize these tools effectively.

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Entomopathogenic Nematodes: A Green Weapon Against Soil Pests



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ABSTRACT

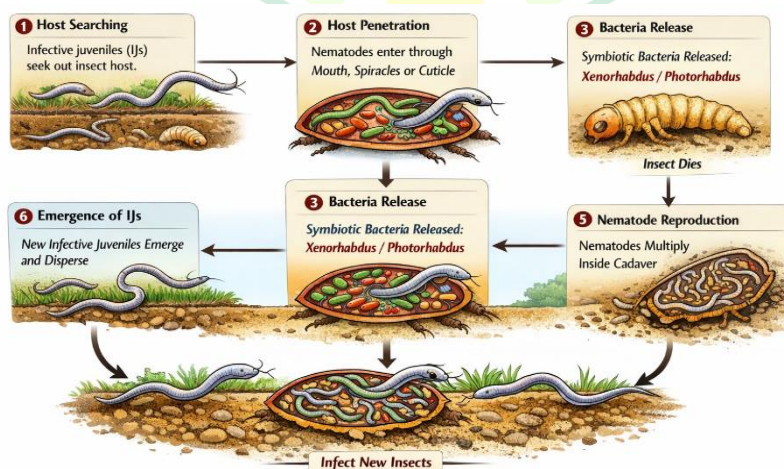
Soil-dwelling insect pests cause substantial agricultural damage by attacking root systems, leading to significant yield loss and a historical over-reliance on harmful synthetic pesticides. As an eco-friendly alternative, entomopathogenic nematodes (EPNs) function as highly effective biological control agents that naturally inhabit soil ecosystems. These microscopic roundworms operate via a lethal symbiosis with specialized bacteria, which release toxins to rapidly kill insect hosts within 24 to 72 hours of infection. Unlike chemical interventions, EPNs are safe for humans, plants, and beneficial organisms, making them ideal for integrated pest management (IPM) programs. By cycling through host cadavers and persisting in the environment, they provide a self-sustaining defense mechanism against underground pests. Utilizing EPNs reduces chemical dependency, protects soil biodiversity, and supports long-term agricultural productivity. Consequently, these nematodes are increasingly recognized as a premier "green" technology for modern, sustainable farming.

INTRODUCTION

Soil insect pests like white grubs and wireworms are notoriously difficult to manage due to their hidden, underground nature, leading to significant crop loss and a historical over-reliance on harmful synthetic pesticides. As an eco-friendly alternative, entomopathogenic nematodes (EPNs) from the genera *Steinernema* and *Heterorhabditis* have become essential tools in sustainable Integrated Pest Management. These microscopic worms, in symbiosis with lethal bacteria, infect and kill soil-dwelling hosts within 24 to 72 hours before reproducing and seeking out new prey. Because they are highly effective, safe for non-target organisms, and leave no chemical residues, EPNs provide a powerful biological solution for protecting plant health while maintaining environmental integrity.

• Mode of Action of Entomopathogenic Nematodes (EPNs)

Entomopathogenic nematodes (EPNs) control insect pests through a symbiotic relationship with specific bacteria. The infective juvenile stage of the nematode actively searches for insect hosts in the soil and initiates infection. The process involves several steps that ultimately lead to the death of the insect host.



Mode of Action of Entomopathogenic Nematodes in Controlling Soil Insect Pests

1. Host Searching

The infective juvenile (IJ) stage of EPNs moves through soil in search of insect hosts. Different species use different strategies:

- Ambushers wait near the soil surface to attack mobile insects.
- Cruisers actively move through the soil to locate sedentary hosts.

2. Host Penetration

Once a suitable host is located, the nematode enters the insect body through natural openings such as:

- Mouth
- Spiracles (breathing openings)
- Anus

In some cases, species of *Heterorhabditis* can also penetrate directly through the insect cuticle.

3. Release of Symbiotic Bacteria

After entering the insect body cavity (hemocoel), the nematode releases symbiotic bacteria:

- *Xenorhabdus* bacteria in *Steinernema*
- *Photorhabdus* bacteria in *Heterorhabditis*

These bacteria multiply rapidly inside the insect body.

4. Killing of the Insect Host

The bacteria produce toxins, enzymes, and antibiotics that:

- Suppress the insect immune system
- Cause septicemia (blood infection)
- Kill the insect within 24–72 hours

5. Reproduction inside the Host

- After the insect dies, the nematodes feed on the bacteria and degraded insect tissues. Several generations of nematodes develop inside the insect cadaver.

6. Emergence of New Infective Juveniles

- When nutrients inside the dead insect are depleted, thousands of new infective juveniles emerge from the cadaver and disperse in the soil to infect new hosts.

• Major Soil Pests Controlled by Entomopathogenic Nematodes (EPNs)

Soil Pest	Scientific Examples	Nature of Damage	Crops Affected	Role of EPNs in Control
White grubs	<i>Holotrichia</i> spp., <i>Phyllophaga</i> spp.	Larvae feed on plant roots causing wilting, yellowing, and plant death. Severe infestations can destroy entire fields.	Sugarcane, groundnut, maize, vegetables, turfgrass	EPNs infect the larvae in the soil and release symbiotic bacteria that kill the grub within 48–72 hours, reducing root damage.
Cutworms	<i>Agrotis ipsilon</i> , <i>Agrotis segetum</i>	Larvae cut seedlings at the soil surface during night, causing sudden plant loss in early crop stages.	Vegetables, cotton, maize, tobacco	Infective juveniles enter the larval body and rapidly kill the pest, preventing further seedling damage.
Wireworms	<i>Agriotes</i> spp., <i>Melanotus</i> spp.	Larvae bore into roots, tubers, and underground stems causing holes and reduced plant vigor.	Potato, maize, wheat, sugarcane	EPNs actively search for wireworms in soil and infect them, reducing population levels.
Root weevils	<i>Otiorhynchus</i> spp., <i>Diaprepes abbreviatus</i>	Larvae feed on roots and root bark, weakening plants and reducing nutrient uptake.	Citrus, strawberry, ornamental plants	EPNs penetrate larvae in soil and cause mortality through bacterial toxins.
Fungus gnats	<i>Bradysia</i> spp.	Larvae feed on roots and organic matter, damaging seedlings and nursery plants.	Nursery crops, greenhouse vegetables, ornamental plants	EPNs infect larvae in moist soil and kill them quickly, reducing nursery losses.

• Application Methods

EPNs are usually applied in **moist soil conditions** because they require water films in soil pores to move and locate insect hosts. Several application techniques are commonly used in agriculture.

1. Soil Drench Application

Water-based suspensions applied directly to the root zone, ideal for nurseries and vegetables.

2. Spray Application

Using conventional equipment (knapsack or tractor-mounted) to treat the soil surface or crop base.

3. Irrigation System Application

Distribution through drip or sprinkler systems for uniform coverage in large fields or greenhouses.

4. Seed Treatment and Root Dip

Dipping seedlings or treating seeds prior to planting to provide early-stage protection.

• Formulations of EPNs

Formulation plays an important role in maintaining the **viability, shelf life, and field performance** of entomopathogenic nematodes. Several formulations have been developed to facilitate storage, transportation, and field application.

1. Aqueous Suspension Formulation

Simple water-based storage; requires refrigeration and has a shorter shelf life.

2. Sponge and gel Formulation

Nematodes are held in moist sponges or polymer gels to maintain hydration during transport.

3. Granular Formulation

Mixed with carriers like clay or vermiculite, allowing for easy application via fertilizer spreaders.

4. Alginate Capsule Formulation

This modern technique encapsulates nematodes in calcium alginate beads. These capsules protect nematodes from environmental stress and allow slow release into the soil, improving field effectiveness.

Proper application and formulation technologies greatly improve the success of entomopathogenic nematodes in managing soil insect pests.

• Advantages and Challenges of Entomopathogenic Nematodes in Pest Management

Aspect	Advantages of Entomopathogenic Nematodes	Challenges / Limitations
Environmental Impact	Eco-friendly and safe for humans, animals, and beneficial organisms	Sensitive to extreme environmental conditions such as high temperature and UV radiation
Pest Control Efficiency	Highly effective against many soil-dwelling insect pests like white grubs, cutworms, and root weevils	Effectiveness may decline under unfavorable soil moisture or temperature
Mode of Action	Rapid insect mortality within 24–72 hours due to symbiotic bacteria	Requires proper environmental conditions for successful infection
Compatibility	Compatible with Integrated Pest Management (IPM) programs and some pesticides	Limited compatibility with certain chemical pesticides
Residue and Safety	Leaves no toxic residues in soil, water, or crops	Requires careful handling during storage and transportation
Reproduction	Capable of reproducing inside host insects, providing natural pest suppression	Persistence in soil may vary depending on host availability
Application	Can be applied through sprayers, irrigation systems, or soil drenching	Proper application techniques and equipment are necessary
Farmer Adoption	Promotes sustainable and organic farming practices	Limited awareness and relatively higher initial cost for farmers

Conclusion

Entomopathogenic nematodes (EPNs) are effective and eco-friendly biological agents for controlling important soil insect pests such as white grubs, cutworms, wireworms, root weevils, and fungus gnats. Their ability to locate hosts and kill them through symbiotic bacteria makes them valuable tools in sustainable pest management. With improved formulations, farmer awareness, and integration into IPM programs, EPNs have strong potential for future sustainable crop protection.

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Seed Sovereignty: Can the Seeds of the Past, Save the Future of Food?



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Seed sovereignty is the primary entitlement of farmers and communities to conserve, utilize, share, and manage their own seed supplies, and be in charge of one of the most basic inputs of agrarian production. Farmers have been custodians of seed diversity and have carefully chosen and preserved the best varieties that are best suited to their own ecosystems over centuries. Not only has this traditional stewardship been able to support livelihoods, but it has created a deep pool of genetic variation in domesticated species, which has helped not only to make our food systems more resilient. However, the introduction of industrial agribusiness and the development of patented hybrid varieties have increasingly subjugated this independence making farmers more dependent on the outside seed sources. The relevance of seed sovereignty as a concept has never been as acute in the modern environment of climatic instability and increasing nutritional needs. It strengthens the cultivation of agronomically resilient crops, protects native agronomic heritage and makes agricultural activities ecologically and socially inclusive. Finally, seed sovereignty is not just a commodity but a source of empowerment to producers, protection of biodiversity, and strengthening world food security in the future.

Indigenous Seeds: Nature's Genetic Treasure:

Crop	Wild Relative / Indigenous Variety	Stress Type	Specific Trait / Resistance
Rice (<i>Oryza sativa</i>)	<i>Oryza nivara</i>	Pest (Brown planthopper)	Resistance genes (BPH resistance)
Rice (<i>Oryza sativa</i>)	<i>Oryza rufipogon</i>	Abiotic (Flood)	Submergence tolerance (SUB1 gene source)
Wheat (<i>Triticum aestivum</i>)	<i>Aegilops tauschii</i>	Disease (Rust)	Leaf & stem rust resistance genes
Wheat (<i>Triticum aestivum</i>)	<i>Triticum dicoccoides</i>	Abiotic (Drought)	Deep root system, water-use efficiency
Tomato (<i>Solanum lycopersicum</i>)	<i>Solanum pimpinellifolium</i>	Disease (Bacterial wilt)	Natural disease resistance
Potato (<i>Solanum tuberosum</i>)	<i>Solanum demissum</i>	Disease (Late blight)	Resistance genes (R genes)
Maize (<i>Zea mays</i>)	Teosinte (<i>Zea mays ssp. parviglumis</i>)	Abiotic (Drought)	Stress tolerance & adaptability
Barley (<i>Hordeum vulgare</i>)	<i>Hordeum spontaneum</i>	Abiotic (Salinity)	Salt tolerance genes
Chickpea (<i>Cicer arietinum</i>)	<i>Cicer reticulatum</i>	Abiotic (Drought)	Drought tolerance traits
Pigeon pea (<i>Cajanus cajan</i>)	<i>Cajanus scarabaeoides</i>	Pest (Pod borer)	Insect resistance
Brinjal (<i>Solanum melongena</i>)	<i>Solanum incanum</i>	Disease (Fusarium wilt)	Disease resistance
Groundnut (<i>Arachis hypogaea</i>)	<i>Arachis duranensis</i>	Abiotic (Drought)	Water stress tolerance
Mustard (<i>Brassica juncea</i>)	<i>Brassica nigra</i>	Disease (Alternaria blight)	Disease resistance
Sugarcane (<i>Saccharum officinarum</i>)	<i>Saccharum spontaneum</i>	Abiotic (Drought, salinity)	Stress tolerance, vigor
Pearl millet (<i>Pennisetum glaucum</i>)	Wild <i>Pennisetum spp.</i>	Abiotic (Heat, drought)	Heat & drought tolerance

Landraces are native or indigenous seeds, which form an indispensable genetic storehouse that has been maintained by ecological processes and generations of agrarian farmers. These seeds are not the homogenized varieties that are grown in modern day agriculture, but, through natural selection and centuries-old methods of cultivation, have developed into systems of traits that are highly adapted to particular climatic regimes, edaphic

conditions and pest pressures of their original habitats. Genetically, landraces have a wide range of allele spectrums and this allows them to have a greater ability to endure environmental pressures like droughts, floods and epidemics. Many traditional cultivars have been reported to have high levels of critical micronutrients, antioxidant activity, and an assortment of bioactive phytochemicals as compared to the contemporary high-yielding varieties. Essentially, the indigenous seed systems serve as biological repositories of information because they can preserve both biological diversity and at the same time provide meaningful and sustainable solutions to the future agricultural systems with the prevailing global climate change.

From Heritage to Hybrid: What Changed?

Farming has long been based on heritage seeds; these are the varieties that have been carefully chosen, preserved and passed down by farmers in their localities. This change started with the Green revolution that saw the introduction of high-yielding varieties (HYVs) and hybrid seeds. Modern seed technologies have been designed to be more productive and uniform with support of chemical fertilizers, irrigation and pesticides. Although this revolution significantly boosted food production and reduced hunger. The hybrid breeding concept had both advantages and trade-offs as the heritage breeding was replaced. On the one hand, more food was grown, and this led to national food security; on the other hand, genetic erosion followed, making the crops more vulnerable to the pests and diseases and climatic changes. Further, the economic performance of the farmers increased as more relied on external inputs and seed market. The inconsistency between heritage and hybrid systems today has become a thorny issue as the question is how to balance between productivity and sustainability. Although hybrids will never be eliminated to nourish a growing population, there is a revival in the use of native seeds, which are important due to their robustness, nutritional quality, and environmental diversity. The future of agriculture may not therefore lie in favouring one system against the other but in balancing the traditional wisdom with modern science so as to develop a more secure and sustainable food system.

Corporate Control & Farmer Dependency:

Feature	Farmer-Managed Seed System	Centralized/Corporate Seed System
Seed Type	Heterogeneous landraces, saved and exchanged by farmers.	Uniform modern cultivars; often hybrids that cannot be saved.
Control	Local, in the hands of farmers and communities.	Centralized, controlled by institutions (like ICARDA) and large, often multinational, corporations.
Goal	Resilience, diversity, and local adaptation.	High yield, uniformity, and market integration.
Legality	Based on informal exchange and tradition.	Governed by formal laws, certification, and property rights.
Benefit	Benefits small farmers, local communities, and local production chains; secures nutritionally complete goods impacting public health.	Business owners and foreign trading firms controlling global seed markets, often huge multinational corporations.

Role of Farmers as “Seed Guardians”:

Farmers have traditionally become the custodians of the seeds and thus they are the inalienable custodians of farm biodiversity. Through maintaining strict methods of seed gathering, preservation, and sharing, they maintain a dynamic genetic vault which makes crops resilient. Through generations, farmers have carefully chosen the high-quality germplasm, preserved the seed stocks before harvest and traded seed with other regions. These sorts of deliberations guarantee that beneficial phenotypic traits, including, but not limited to, greater yield potential and organoleptic traits, are passed on to the later generations of plant populations. The long-term, farmer-based phenotypic selection is an informal, but very effective plant-breeding regime. This natural selection of breeding causes the phenotypes of crops to be in accord with aboriginal weather and soil conditions, and as a result, ecological niche-specific selection occurs without formal breeding lines. Importantly, female agrarians often play a central role in this continuum especially with seed selection, preservation, and spreading germplasm of information in domestic and communal spheres. Through the communal seed repositories and the local seed banks, farmers become stronger when it comes to their seed sovereignty and independence over their operations, thus reducing their reliance on unnecessary agronomic inputs. This networked strategy promotes ecological and the economic resilience. Finally, farmers as custodians are not only food producers, but also biocultural providers,

creators of crop resilience, the main drivers of agrarian system sustainability at the global level. Their custodianship is still important in securing the future viability of global food security.

Policies & Legal Framework:

- The **Convention on Biological Diversity** (CBD, 1992) supports the idea of national sovereignty in terms of biological resources and at the same time promotes fair distribution of benefits of the said resources.
- Farmers have their rights acknowledged by the **International Treaty on the Rights of plant genetic resources to food and agriculture** (ITPGRFA, 2001), which formally acknowledges the right of Farmers to save, use, exchange, and sell seed that has been saved on their own farms. However, it offers the national governments the power to decide the boundaries within which such rights can be exercised.
- The **World Trade Organization** (WTO) administers the Agreement on **Trade-Related Aspects of Intellectual Property Rights** (TRIPS, 1995) which requires member states to offer intellectual-property protection to plant varieties either by patent or other sui generis means. This has been criticized as favouring corporate interests too much and neglecting traditional seed-sharing by way of this provision.
- **Navdanya** (India) - an association started by Vandana Shiva in 1987 - is a movement that founded over 150 community seed banks and is vociferously opposed to the aspects of genetic modification and biopiracy of crops.
- **La Via Campesina** is a global union that includes millions of small-scale farmers and promotes food as well as seed sovereignty as human rights.
- In the United States, **Seed Savers Exchange** serves the aim of preserving heirloom and open-pollinated varieties by motivating home gardeners and small farmers to preserve such germplasm.
- **African and Latin American seed networks** are networks that support the sharing of traditional seed, local cooperative and conservation of genetic diversity at community level.
- The **Protection of Plant Varieties and Farmers Rights Act** (PPVFR, 2001) was passed in India as a measure to balance the rights of breeders versus farmers so that the rights of farmers and the rights of biodiversity can be legally recognized.
- **Bharat Beej Swaraj Manch**: An alliance of farmers and activists (100+ committees across 18 states) saving and promoting traditional seeds to preserve genetic diversity and cultural heritage.

Challenges to Seed Sovereignty:

- **Corporate Concentration**: A small number of transnational agricultural corporations such as Bayer-Monsanto, Corteva, Syngenta and BASF control over sixty per cent of the global seed market thus limiting competition and diversity of cultivars.
- **Laws on Intellectual Property**: The establishment of patent protection and the legal principle of plant breeder's rights deny agrarian producers the right to store or transfer seed material of patented varieties, thus making them dependent on the regular use of new seed progeny.
- **Traditional Varieties Erosion**: The spread of genetically homogeneous and high-yielding hybrids has triggered the extinction of local landraces and erosion of genetically homogeneous, which erode the resistance and adaptability of crops to heterogeneous agro-ecological situations.
- **Genetically Modified Organisms (GMOs)**: Genetically engineered food, which is supposed to have pest resistance or be resistant to herbicides, is often surrounded by strict legal regulations and environmental issues, such as the possibility of cross-contamination with native plants.
- **Climate Change**: The high frequency of extreme weather conditions endangers agricultural output and upsets the traditional seed systems making the prioritisation of hardy and locally adapted varieties a higher priority.
- **Policy and Regulatory Barriers**: In many jurisdictions, legislation that regulates the sale of seed varieties requires certification and registration of commercial varieties, a process which usually excludes traditional and indigenous seed varieties of commercial transaction.

Future of Seed Sovereignty:

Seed sovereignty is being viewed as the cornerstone to sustainable food systems as the world transforms to climate change, population expansion, and globalisation of the market in agriculture. New priority areas entail:

- Strengthening seed banks and community breeding of plants.
- Building non-patent open-source seed programs, in which varieties are given freely.
- Bridging the gap between science and traditional knowledge to grow climate-resistant crops.
- Reforming national and international seed policies in order to safeguard the rights of farmers and the biodiversity.



Agricultural Strategies for the Restoration of Desertified and Degraded Lands



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ABSTRACT:

Land systems emerge from the interplay between human activities and the natural environment, with land degradation posing threats to economies, food production, biodiversity, and ecosystem services, thereby endangering the sustainability of these systems. Soil and water are crucial natural resources that are integral to the Sustainable Development Goals (SDGs), addressing societal issues such as climate resilience, poverty reduction, and biodiversity conservation. Degradation negatively impacts soil health, diminishes ecosystem functions, and worsens global challenges like desertification, primarily driven by human actions and climate change. Geospatial technology and precision agriculture aid restoration efforts through practices like agroforestry, diverse cropping, and pasture management. These strategies help curb deforestation and illegal mining, boosting carbon sequestration and biodiversity. Achieving land degradation neutrality (LDN) by restoring 1.5 billion hectares of degraded land by 2030 is essential for restoring ecosystem services and mitigating the effects of climate change. Halting degradation and rehabilitating land are crucial for maintaining ecosystems and human well-being.

KEYWORDS: Anthropogenic, Biodiversity, Desertification, Land degradation, Restoration

1. INTRODUCTION

Desertification and land degradation are pressing global challenges impacting one-sixth of the world's population and vast areas of drylands and land. These phenomena pose threats to food security, economic stability, and environmental quality by causing soil erosion and nutrient depletion. The international Convention to Combat Desertification seeks to tackle issues of poverty, drought, and food insecurity in the affected dryland regions.

1.1 WHAT IS LAND DEGRADATION AND DESERTIFICATION

Desertification is a multifaceted issue marked by numerous characteristics. The significance of two main attributes—land, vegetation, and soil—is further divided into sub-attributes related to the deterioration of vegetation and the decay of soil (Grainger, 2015). Land degradation can be described as a decline in the land's ability to deliver ecosystem goods and perform functions and services essential for both society and nature (Millennium Ecosystem Assessment, 2005). Desertification represents a type of land degradation where fertile land transforms into desert. According to the UNCCD, desertification is "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UN, 1994). In degraded regions, native ecosystems are often destroyed, leading to reduced agricultural yields, diminished livestock production, and a loss of ecosystem complexity, which is frequently associated with severe soil degradation. Soil degradation is a global land degradation issue caused by overgrazing, deforestation, unsuitable agricultural practices, excessive fuelwood use, urbanization, and other human activities. The soil in degraded areas has a diminished capacity to support plant growth, leading to a decline in vegetation and economic productivity. In dry regions, soil degradation occurs through processes such as wind erosion, water erosion, compaction, waterlogging, salinization, and alkalinization.

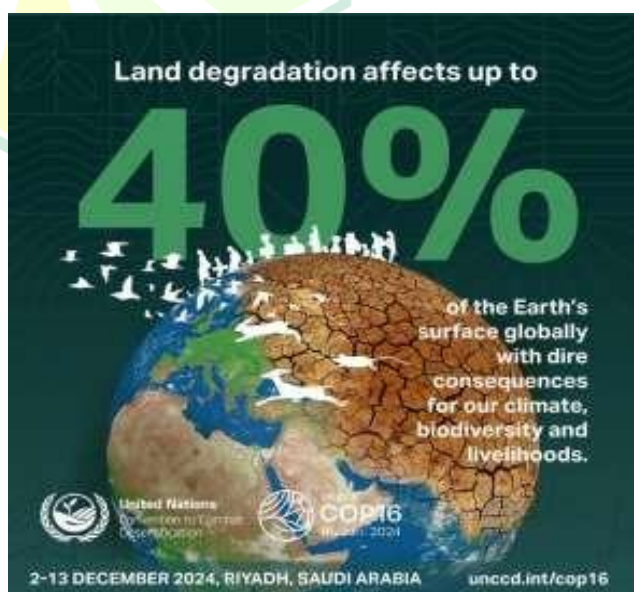
2. DETERMINANTS AND TYPES OF LAND DEGRADATION PROCESSES

Land degradation is a persistent issue caused by both natural and human-induced factors. Natural contributors include adverse climatic conditions, large temperature variations, inconsistent precipitation, and challenges in water distribution, all of which promote drought and desertification (Al-Kulabi, 2022). Drilling wells for irrigation on farmland without considering hydrological aspects can significantly lower the water table and increase groundwater and soil salinity, exacerbating desertification and land degradation. Climate change intensifies these issues by increasing the frequency and severity of droughts, aridity, wind events, intense rainfall, flooding, sea-level rise, heat stress, and permafrost thaw. The relationship between climate change, land degradation, and land use is complex, with climate change significantly affecting the hydrological cycle, leading to heavier rainfall and more severe soil erosion. Climate change not only worsens land degradation in managed ecosystems like croplands and pastures but also opens new pathways for degradation in natural and semi-natural ecosystems. This issue also facilitates species invasion and its associated degradation by enhancing the transport, colonization, establishment, and ecological impact of invasive species while hindering control measures. Human activities often exacerbate land degradation, with human actions having the most direct and indirect impacts on environmental conditions (Ahmed et al., 2021). Direct drivers include land-use change, conversion of forests to agriculture or urban areas, cultivation on marginal lands, deforestation, and unsustainable land management practices. Soil compaction, salinity, alkalinity, and altered water cycles are significant contributors to land degradation. Human factors include excessive irrigation, interference with natural drainage, improper use of heavy machinery, and insufficient soil conservation practices. Unsustainable agricultural practices significantly contribute to sand and dust storms (SDSs), especially in areas experiencing vegetation loss. These storms often reduce land productivity, while wind-driven erosion accelerates the depletion of soil organic carbon. Such processes create a vicious cycle: SDSs degrade land, and the resulting deterioration further increases the frequency and intensity of future SDS events, perpetuating a downward spiral in soil quality. Breaking this cycle requires a shift toward more sustainable agricultural resource management and land-use strategies (FAO., 2022).

3. IMPACT OF LAND DEGRADATION

Land degradation is defined as a negative trend in land condition arising from anthropogenic impact, climate change, expressed as long-term reduction or loss of at least one of the biological productivity, ecological integrity, or value to humans. Land degradation not only impacts the land surface itself but also affects marine and freshwater systems, as well as people and ecosystems far away from the local sites of degradation. IPCC states that destabilizing India's agricultural productivity and food security threats are posed by land degradation and desertification.

Land areas with degraded ecosystems have seen a reduction in their capacity to regenerate biomass, achieving only 30–40% of the productivity of more pristine lands. In contrast, severely damaged lands have lost essential metabolic functions and produce less than 10% of the biomass compared to healthier lands. When grazing exceeds the land's carrying capacity, it accelerates soil erosion and desertification. Land degradation affects soil quality by depleting soil organic carbon, essential nutrients, water retention and regulation, and underground biodiversity. As a result, due to habitat destruction, these degraded lands struggle to sustain vegetation biomass, and sensitive species may become extinct. Unhealthy soils fail to provide balanced nutrition, negatively impacting both the quantity and quality of food production.



4. AGRICULTURAL SOLUTIONS TO LAND DEGRADATION

While land degradation and desertification can sometimes be reversed, this is not always the case. Addressing desertification involves implementing a range of sustainable land-use practices designed to prevent or mitigate land degradation, restore partially degraded areas, and reclaim regions that have been more severely affected by desertification. In this regard, land degradation neutrality is a multi-sectoral effort that emphasizes the prevention and reduction of land degradation to maintain land functions. Research has shown that sustainable land management techniques can effectively preserve or enhance soil characteristics, such as its carbon storage capacity (EPRS, 2020). Intensive agricultural practices, including excessive machinery use, tillage, and pesticide application, have a significant impact on essential soil properties like organic matter, structure, cover, biodiversity, and water content, contributing to land degradation. Changing farming practices is crucial to addressing this issue. A range of innovative methods, such as Agroforestry Systems, Conservation Agriculture (CA), Sustainable Grazing Management, soil and water conservation techniques, and Zai pits, aim to restore soil health and develop more resilient and productive agroecosystems.

According to research evidence, restoring 26 million hectares of degraded cropland could potentially cut the yield gap by up to 50% for oil crops and enable cereal, root, and tuber crops to reach their maximum yield potential in the Arab region (Ziadat et al., 2025). Cultivating Bael (*Aegle marmelos*) using the clean tilled with halfmoon technique is not only highly appropriate but also a profitable fruit for conservation horticulture in the long-term degraded ecosystem of the Chambal ravines (Meena et al., 2023). Land degradation in rangelands is among the most prevalent land use changes globally, and grass cover could enhance overall soil functionality. Under Tri-Specific Hybrid (TSH: *Pennisetum glaucum* x *Pennisetum purpureum* x *Pennisetum squamulatum* and *Heteropogon contortus* (HC), soil functionality was 83% and 22% greater than with *Megathyrus maximus* (MM), respectively. The carbon accumulation capability of TSH, MM, and HC was approximately 2.23, 2.17, and 2.07 times higher than that of fallow land. These soil functions boost ecosystem services, including climate regulation, biomass production, nutrient recycling, and water and air flow services (Patidar et al., 2023). Planting 3–5-year-old jatropha contributed about 4000 kg of plant biomass annually, equating to 1450 kg C ha⁻¹—800 kg C from leaves, 150 kg C from pruned twigs, and 495 kg C as deoiled Jatropha cake to the soil, along with biodiesel C replacement in fossil fuels. The added biomass and active plant roots increased microbial activity, enhanced soil physical properties, recycled plant nutrients, improved soil fertility, and reduced erosion, aiding in the rehabilitation of degraded lands (Wani et al., 2012).

5. CONCLUSION

Desertification and land degradation (DLD) are acknowledged as major global challenges that impede the delivery of ecosystem goods and services vital to both society and nature. The structure and function of land ecosystems, when aligned with natural processes, dictate crucial sustainability outcomes. Human activities frequently exacerbate land degradation, diminishing the land's capacity to support vegetation biomass and causing greater imbalances in ecosystem services. Restoration seeks to initiate and expedite the recovery of land. Agricultural practices that restore land will enhance ecosystem services, such as carbon sequestration, biodiversity conservation, and water management, thereby playing a pivotal role in mitigating climate change.

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Soil Microbiome: Structure and Function



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Abstract

The soil microbiome represents one of the most complex biological systems on Earth, composed of bacteria, archaea, fungi, protists, viruses, and microfauna interacting within heterogeneous soil matrices. These microorganisms regulate essential ecosystem processes such as nutrient cycling, organic matter decomposition, soil aggregation, plant growth promotion, and disease suppression. Advances in molecular ecology and high-throughput sequencing have revolutionized understanding of microbial diversity, revealing that soil function depends not only on microbial abundance but also on community structure, functional genes, and ecological interactions. This chapter discusses the structure, diversity, ecological drivers, functional roles, plant interactions, and modern analytical approaches to soil microbiome research, highlighting its importance for sustainable agriculture, environmental resilience, and climate change mitigation.

1. Introduction: Soil as a Biological System

Soil represents one of the most complex biological systems on Earth, functioning simultaneously as a living ecosystem, a biogeochemical reactor, and a reservoir of biodiversity. A single gram of soil may contain billions of microorganisms belonging to thousands of species, forming what is collectively termed the soil microbiome. The soil microbiome comprises bacteria, archaea, fungi, protozoa, algae, and viruses interacting within a heterogeneous matrix of minerals, organic matter, water, and gases. These microbial communities regulate ecosystem productivity and sustainability by mediating nutrient cycling, soil formation, plant health, and atmospheric gas exchange (Fierer, 2017). Rather than acting independently, these organisms form complex networks in which metabolites produced by one species serve as substrates for another, creating a tightly connected biological system.

Historically, soil fertility was attributed mainly to its chemical composition; however, advances in microbial ecology and molecular biology have revealed that biological processes drive most soil functions. Microorganisms are not passive inhabitants but active engineers shaping soil structure and ecosystem stability (van der Heijden *et al.*, 2008). The development of high-throughput sequencing technologies has revolutionized the understanding of microbial diversity, demonstrating that less than 1% of soil microbes are culturable using traditional laboratory methods (Torsvik & Øvreas, 2002). Consequently, soil science has shifted from chemistry-centric to biology-centric paradigms, recognizing soil microbiomes as essential regulators of global biogeochemical cycles.

The concept of the soil microbiome refers not only to microbial diversity but also to functional genes, metabolic pathways, and ecological interactions operating within the soil environment. Modern sequencing technologies have demonstrated that more than 90% of soil microorganisms cannot be cultured in laboratory media, indicating that traditional microbiology underestimated soil biodiversity (Prosser, 2015). Consequently, soil fertility is now understood as a biological property emerging from microbial activity rather than simply a chemical attribute. The soil microbiome is now considered the biological engine of terrestrial ecosystems because it determines plant productivity, carbon sequestration, and resilience to environmental stress (Bardgett and van

der Putten, 2014). This chapter discusses in detail the structure, composition, ecological interactions, and functional roles of the soil microbiome, integrating classical microbiology with modern molecular ecology. Microbial communities determine whether nutrients remain immobilized in organic matter or become available to plants. Therefore, plant productivity depends on microbial transformations rather than fertilizer presence alone. This paradigm shift forms the foundation of biological soil management.

2. Soil as a Microbial Habitat

Soil is not a uniform medium but a spatially structured environment consisting of aggregates, pores, and interfaces that create numerous ecological niches. Microorganisms inhabit soil aggregates where mineral particles are bound together by organic matter and microbial exudates. These aggregates provide microhabitats differing in oxygen concentration, moisture availability, and nutrient gradients (Young and Crawford, 2004). As a result, aerobic and anaerobic microorganisms coexist within millimeter-scale distances.

The rhizosphere, the narrow region of soil influenced by plant roots, is particularly significant for microbial colonization. Root exudates such as sugars, amino acids, and organic acids serve as substrates for microbial growth and lead to microbial densities several orders of magnitude higher than in bulk soil (Philippot *et al.*, 2013). This region forms a dynamic interface where plant and microbial metabolisms interact, influencing nutrient uptake and plant health.

Soil texture also influences microbial distribution. Clay soils tend to protect microorganisms from predation and desiccation by providing small pore spaces, whereas sandy soils allow rapid diffusion but less protection (Six *et al.*, 2004). Organic matter further enhances microbial colonization by providing energy sources and buffering environmental fluctuations.

Moisture content regulates microbial metabolism because water acts as a solvent for nutrients and enzymes. At optimal water potential, microbial respiration and enzymatic activity reach maximum levels, whereas drought conditions induce dormancy or sporulation in many microbial taxa (Schimel *et al.*, 2007). Therefore, soil microbiome structure reflects a balance among physical protection, nutrient availability, and environmental stress.

3. Diversity and Composition of the Soil Microbiome

The soil microbiome consists primarily of bacteria, archaea, fungi, protists, and viruses, each contributing specialized ecological functions.

Bacteria

Bacteria represent the most abundant microbial group and perform diverse metabolic reactions including decomposition, nitrogen cycling, and mineral weathering. Their distribution is strongly influenced by soil pH, which acts as the dominant environmental filter controlling bacterial diversity worldwide (Lauber *et al.*, 2009). Neutral soils typically support high bacterial diversity, whereas acidic soils favor specialized groups adapted to low pH conditions. Bacteria constitute the most abundant component of the soil microbiome and dominate metabolic processes such as decomposition and nutrient transformation. Major bacterial phyla commonly detected in soils include Proteobacteria, Actinobacteria, Acidobacteria, Firmicutes, and Bacteroidetes (Janssen, 2006). Each group occupies distinct ecological niches. Proteobacteria generally thrive in nutrient-rich environments and respond rapidly to organic inputs, whereas Acidobacteria dominate nutrient-poor soils and exhibit oligotrophic lifestyles (Fierer *et al.*, 2007).

Actinobacteria play an important role in decomposition of complex organic compounds such as cellulose, lignin, and chitin. They can colonize stable soil aggregates and play a major role in the creation of humus thanks to their filamentous growth and extracellular enzyme synthesis (Goodfellow and Williams, 1983). Many actinobacteria also produce antibiotics that regulate microbial competition.

Nitrogen-fixing bacteria, including symbiotic *Rhizobium* and free-living *Azotobacter* species, convert atmospheric nitrogen into biologically available forms, making them essential for plant nutrition (Galloway *et al.*, 2008). Nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter* mediate the oxidation of ammonia to nitrate, linking microbial metabolism to agricultural productivity and environmental sustainability.

Archaea

Archaea were once thought to inhabit only extreme environments but are now recognized as abundant members of soil communities. Ammonia-oxidizing archaea contribute substantially to nitrification processes, particularly

in acidic soils where bacterial nitrifiers are less competitive (Kuypers *et al.*, 2018). Their metabolic versatility enables them to function at low nutrient concentrations, indicating adaptation to oligotrophic soil conditions. Methanogenic archaea occur in anaerobic microsites such as waterlogged soils and wetlands, producing methane as a by-product of organic matter decomposition (Conrad, 2009). Conversely, methanotrophic microorganisms oxidize methane, creating a biological control on greenhouse gas emissions.

Fungi

Fungi constitute a large proportion of soil biomass and play a key role in decomposition of complex plant polymers such as lignin and cellulose. Their filamentous hyphae connect soil particles into aggregates, improving soil structure and water retention (de Boer *et al.*, 2005). Mycorrhizal fungi establish symbiotic associations with plant roots, exchanging mineral nutrients for plant carbon and enhancing plant growth (van der Heijden *et al.*, 2008). Saprophytic fungi break down cellulose and lignin, while mycorrhizal fungi form symbiotic associations with plant roots.

Arbuscular mycorrhizal fungi enhance phosphorus uptake and improve plant tolerance to drought and pathogens (Smith and Read, 2008). In exchange, plants supply carbohydrates to fungal partners. This mutualistic relationship is estimated to occur in more than 80% of terrestrial plant species, highlighting its ecological significance.

Protozoa and Nematodes

Protozoa and nematodes function as microbial predators, regulating bacterial populations and stimulating nutrient mineralization through grazing (Bonkowski, 2004). By consuming bacteria, protozoa release nitrogen in plant-available forms, enhancing soil fertility. Thus, higher trophic levels indirectly control nutrient availability. Protists function as microbial predators, regulating bacterial populations and releasing nutrients immobilized in microbial biomass. Through grazing activity they accelerate mineralization and nutrient turnover (Geisen *et al.*, 2018). Soil viruses, particularly bacteriophages, influence microbial community structure through infection and gene transfer, thereby shaping ecosystem stability (Emerson *et al.*, 2018)

Viruses

Soil viruses, particularly bacteriophages, influence microbial population dynamics by infecting and lysing host cells. Viral lysis releases intracellular nutrients and contributes to the microbial loop, a process that redistributes carbon and nitrogen within the soil ecosystem (Williamson *et al.*, 2017). Although often overlooked, soil viruses represent a major reservoir of genetic diversity.

These organisms occupy microscale habitats rather than being uniformly distributed. Root-associated zones contain dense microbial populations, while bulk soil supports slower metabolic activity. Microorganisms are not randomly distributed in soil but occupy highly structured microhabitats. The region immediately surrounding plant roots, known as the rhizosphere, contains the highest microbial activity because roots release organic compounds that serve as energy sources. The detritusphere, formed around decomposing plant residues, represents another hotspot of microbial activity. In contrast, bulk soil contains fewer available nutrients and supports slower microbial metabolism. Within soil aggregates, oxygen gradients create aerobic and anaerobic niches, allowing diverse metabolic processes to occur simultaneously.

4. Spatial Organization and the Rhizosphere Effect

Microbial communities vary dramatically across soil microenvironments. The rhizosphere, the narrow region surrounding plant roots, contains the highest microbial activity because roots release organic compounds that serve as microbial substrates (Philippot *et al.*, 2013). Root exudates include sugars, amino acids, and organic acids that selectively recruit beneficial microorganisms. Soil aggregates act as ecological islands where microbial consortia develop specialized metabolic cooperation. Within aggregates, oxygen gradients create aerobic outer zones and anaerobic inner cores, allowing simultaneous nitrification and denitrification processes (Sexstone *et al.*, 1985).

The rhizosphere further increases spatial complexity by forming chemical gradients around roots. Plants actively manipulate microbial populations by altering exudate composition in response to environmental conditions. For example, pathogen attack triggers recruitment of antagonistic microbes that suppress disease, a

phenomenon described as microbiome-mediated plant defense (Bais *et al.*, 2006). This demonstrates that plants and microbes form an integrated biological system sometimes referred to as the plant holobiont.

Biofilms represent another structural component of the soil microbiome. Microorganisms embedded in extracellular polymeric substances adhere to mineral surfaces and roots, forming cooperative communities that enhance nutrient exchange and stress tolerance (Flemming and Wingender, 2010). Biofilms protect microbes from environmental stress and antibiotics, enabling stable long-term colonization. Within soil aggregates, oxygen availability varies, creating aerobic and anaerobic niches that support different metabolic pathways simultaneously. Such spatial heterogeneity allows processes like nitrification and denitrification to occur in close proximity.

5. Environmental Drivers of Microbial Community Structure

The structure of soil microbial communities is not static but dynamically regulated by environmental conditions operating across spatial and temporal scales. Among these factors, soil pH has consistently emerged as one of the strongest predictors of microbial community composition. Across global soil surveys, bacterial diversity shows a unimodal relationship with pH, with maximal diversity occurring near neutral conditions, while acidic soils select for specialized taxa such as Acidobacteria and certain archaeal nitrifiers (Lauber *et al.*, 2009). The sensitivity of microbial enzymes and membrane stability to hydrogen ion concentration explains why small shifts in pH can reorganize entire microbial networks. Organic matter content regulates energy availability, with high carbon soils supporting larger microbial biomass and faster nutrient cycling.

Soil organic matter provides the primary energy source for heterotrophic microorganisms. High organic carbon content supports greater microbial biomass and activity, leading to rapid nutrient turnover. Conversely, nutrient-poor soils favor slow-growing organisms adapted to limited resources. Soil texture also plays a significant role by influencing pore size distribution, water retention, and protection from predation. Clay soils often protect microorganisms within microaggregates, whereas sandy soils expose them to environmental stress. Clay particles protect microorganisms within aggregates, whereas sandy soils expose them to desiccation and temperature fluctuations (Six *et al.*, 2004). Climate also plays a major role, as temperature and moisture regulate enzymatic activity and decomposition rates. Climate conditions, particularly temperature and moisture, regulate metabolic rates. Temperature represents another dominant ecological filter. Microbial metabolic rates increase exponentially with temperature up to an optimum, after which enzyme denaturation reduces activity. Long-term warming experiments have demonstrated shifts toward faster-growing bacterial taxa and reduced fungal dominance, altering carbon turnover rates and accelerating soil respiration. These findings suggest that climate warming may destabilize soil carbon reservoirs through microbial physiological responses rather than purely chemical processes.

Soil moisture regulates oxygen availability and diffusion of soluble substrates. Under dry conditions microorganisms enter dormancy, whereas saturated soils promote anaerobic metabolism including denitrification and methanogenesis (Schimel, 2018). Seasonal wetting and drying cycles therefore generate pulsed microbial activity known as the “Birch effect,” in which rapid mineralization occurs after rewetting dry soil (Birch, 1958). This phenomenon contributes significantly to nitrogen and carbon fluxes in agricultural systems. Warm and moist environments stimulate microbial respiration and decomposition, while dry or cold conditions reduce activity and promote dormancy. Agricultural practices further modify microbial communities. Intensive tillage disrupts fungal networks and exposes protected organic matter to rapid decomposition, whereas organic amendments increase microbial diversity by providing energy sources. Agricultural practices significantly alter microbial communities. Intensive tillage disrupts fungal networks and accelerates organic matter loss, whereas organic amendments increase microbial abundance and diversity (Lori *et al.*, 2017). Crop rotation stabilizes microbial communities and reduces pathogen dominance. Crop rotation promotes functional diversity, while monoculture systems often reduce microbial stability and increase disease risk.

Organic matter quantity and quality further determine microbial composition. Labile substrates favor copiotrophic organisms capable of rapid growth, whereas recalcitrant organic matter selects for fungi and slow-growing oligotrophs (Fontaine *et al.*, 2003). Thus, plant litter chemistry indirectly structures microbial communities by controlling resource availability.

Vegetation type is also a major ecological driver. Plant species release distinct root exudate profiles, recruiting specific microbial consortia that may persist even after crop rotation. This legacy effect demonstrates that plants actively engineer soil microbiomes, creating feedbacks that influence ecosystem succession and productivity (Bever *et al.*, 2010).

6. Functional Roles in Biogeochemical Cycles

Carbon Cycling

Microorganisms perform essential ecosystem processes collectively referred to as biogeochemical cycling. Carbon cycling begins with the decomposition of plant residues and root exudates. Microbial enzymes break down complex polymers into simpler compounds that microorganisms assimilate for growth and respiration. Some carbon is released as carbon dioxide, while another fraction becomes stabilized within soil aggregates as humus. Importantly, dead microbial cells contribute significantly to long-term soil carbon storage, demonstrating that microbial biomass itself forms a major component of soil organic matter (Gougoulas *et al.*, 2014). Thus, microbial biomass contributes substantially to long-term carbon sequestration.

Nitrogen Cycling

Nitrogen cycling is almost entirely mediated by microorganisms. Atmospheric nitrogen gas is biologically fixed into ammonia by specialized bacteria and archaea. Organic nitrogen in plant residues is converted into ammonium through ammonification. Nitrifying microorganisms oxidize ammonium to nitrate, which plants readily absorb but is also susceptible to leaching. Under low oxygen conditions, denitrifying bacteria reduce nitrate to gaseous forms, returning nitrogen to the atmosphere. These processes determine fertilizer efficiency and environmental nitrogen losses. (Kuypers *et al.*, 2018).

Phosphorus Mobilization

Most soil phosphorus occurs in insoluble mineral forms unavailable to plants. To improve plant uptake and solubilize phosphorus, microorganisms release phosphatase enzymes and organic acids (Richardson and Simpson, 2011). This process reduces dependency on phosphate fertilizers.

Soil Aggregation

Soil structure formation is another major microbial function. Bacteria produce sticky extracellular polymers, and fungal hyphae physically bind soil particles into aggregates. These aggregates improve aeration, water retention, and resistance to erosion. Thus, microorganisms act as ecosystem engineers that create the physical habitat supporting plant growth. Microbial exopolysaccharides and fungal hyphae bind soil particles together, forming stable aggregates that improve aeration and water infiltration (Six *et al.*, 2004). Therefore, microorganisms function as ecosystem engineers shaping soil physical structure.

7. Plant–Microbiome Interactions

The soil microbiome functions as an extended plant immune system. Beneficial microbes suppress pathogens through competition for nutrients and niches, production of antimicrobial compounds, and stimulation of plant defense pathways (Berendsen *et al.*, 2012). This phenomenon forms the basis of disease-suppressive soils, where pathogens fail to establish despite favorable environmental conditions. Plants actively shape the soil microbiome by releasing root exudates that selectively recruit beneficial microorganisms. These plant-associated microbes, often called plant growth-promoting rhizobacteria, enhance plant development through multiple mechanisms. Some fix atmospheric nitrogen, others solubilize phosphorus, and many produce hormones that stimulate root growth. Certain microbes also reduce plant stress hormones, enabling plants to tolerate drought or salinity. Plants rely heavily on associated microorganisms for growth and survival. Plant growth-promoting rhizobacteria enhance nutrient uptake, produce phytohormones, and reduce plant stress hormone levels (Vessey, 2003). Mycorrhizal fungi extend root surface area and improve nutrient acquisition, particularly phosphorus (van der Heijden *et al.*, 2008).

The soil microbiome also provides biological disease control. In suppressive soils, microbial communities prevent pathogens from establishing through competition for nutrients, production of antimicrobial compounds, and activation of plant immune responses. In disease-suppressive soils, beneficial microorganisms outcompete pathogens and activate plant immune responses (Mendes *et al.*, 2011). Induced systemic resistance occurs when root-associated microbes activate plant defense genes, increasing resistance to foliar pathogens and insect pests

(Pieterse *et al.*, 2014). Unlike chemical pesticides, this biological protection is durable and environmentally safe. Such natural disease suppression reduces the need for chemical pesticides and represents a key component of sustainable agriculture. This natural biological control represents an important alternative to chemical pesticides. Furthermore, microbial symbioses increase plant resilience to environmental stress. Mycorrhizal fungi improve water uptake during drought, while endophytic bacteria enhance tolerance to heavy metals and temperature extremes. These interactions demonstrate that plant adaptation to environmental conditions often depends on associated microbial communities rather than plant genetics alone. Microbes also increase plant tolerance to abiotic stress. Certain bacteria reduce ethylene accumulation during drought, while fungal symbionts improve water uptake, demonstrating that plant adaptation often depends on microbial partnerships rather than plant genetics alone (Pieterse *et al.*, 2014).

Conversely, disturbance of microbial balance may lead to dysbiosis, facilitating pathogen outbreaks. Intensive agriculture, heavy pesticide use, and soil degradation often reduce microbial diversity and resilience, increasing plant disease susceptibility (van Bruggen and Semenov, 2000). Maintaining microbial diversity therefore represents a key strategy for sustainable crop protection.

8. Soil Microbiome and Climate Change

Soil microorganisms play a central role in regulating greenhouse gases. Microbial respiration releases carbon dioxide, while denitrification produces nitrous oxide and methanogenic archaea generate methane in anaerobic environments (Conrad, 2009). Denitrifying bacteria emit nitrous oxide, a potent greenhouse gas (Butterbach-Bahl *et al.*, 2013). Changes in temperature and moisture alter microbial metabolism, potentially accelerating carbon loss from soils. Conversely, promoting microbial processes that stabilize organic matter can enhance carbon sequestration. Therefore, managing soil microbiomes is increasingly viewed as a strategy for climate change mitigation. (Kuypers *et al.*, 2018). Environmental changes affecting microbial metabolism can therefore influence global climate.

Climate warming accelerates organic matter decomposition, potentially creating positive feedback loops that amplify global warming (Crowther *et al.*, 2016). However, microbial adaptation may partially offset this effect through community shifts toward more carbon-efficient taxa.

Drought conditions reduce microbial activity but may increase emissions after rewetting events. Similarly, elevated atmospheric CO₂ alters plant root exudation, indirectly reshaping microbial communities (Kassem *et al.*, 2008). These complex feedbacks highlight the need to incorporate microbiome processes into climate models.

9. Molecular and Omics Approaches in Soil Microbiome Research

Traditional microbiology relied on culturing techniques that revealed only a small fraction of microbial diversity. The introduction of molecular ecology transformed soil science by enabling culture-independent analysis of microbial communities.

The first breakthrough involved ribosomal RNA gene sequencing, particularly the 16S rRNA marker for bacteria and archaea and ITS regions for fungi. These markers allow taxonomic identification and phylogenetic reconstruction of microbial communities (Woese, 1987). However, marker genes provide limited functional insight, prompting the development of metagenomics.

Metagenomics involves direct sequencing of total environmental DNA, enabling reconstruction of metabolic pathways and detection of previously unknown microbial taxa (Handelsman, 2004). Soil metagenomic studies have revealed extraordinary genetic diversity and identified novel enzymes involved in carbon degradation and antibiotic synthesis.

Metatranscriptomics further examines actively expressed genes by sequencing RNA, providing a snapshot of functional activity rather than potential capacity (Carvalhais *et al.*, 2013). This approach distinguishes dormant microbes from metabolically active populations, revealing that only a subset of soil microbes contributes to immediate ecosystem processes.

Metaproteomics and metabolomics extend analysis to proteins and metabolites, linking genetic potential to biochemical function. By integrating these techniques, researchers can reconstruct nutrient cycling pathways and microbial interactions in situ (Prosser, 2015). Collectively, these approaches form the basis of systems microbial ecology, where soils are studied as integrated biological networks rather than isolated species assemblages.

Bioinformatics plays a crucial role in interpreting large datasets generated by high-throughput sequencing. Computational pipelines cluster sequences into operational taxonomic units or amplicon sequence variants, enabling quantitative comparison across ecosystems (Callahan *et al.*, 2017). Machine learning models increasingly predict microbial function from sequence data, advancing predictive soil ecology.

10. Agricultural Management and Microbiome Engineering

Agricultural management strongly influences soil microbiome composition and activity. Practices that minimize disturbance and increase organic inputs promote microbial diversity and stability. Conservation agriculture, organic amendments, and diversified cropping systems enhance beneficial microbial populations and improve nutrient cycling efficiency. Sustainable agriculture increasingly focuses on managing microbial communities rather than relying solely on chemical inputs. Agricultural management practices exert strong selective pressure on soil microbiomes. Tillage disrupts soil aggregates and exposes organic matter to rapid decomposition, reducing fungal networks and favoring bacterial dominance (Six *et al.*, 2006). In contrast, no-till systems preserve aggregate structure and promote mycorrhizal abundance, improving soil stability and nutrient retention. Fertilizer application alters microbial metabolism by modifying nutrient availability. High nitrogen inputs suppress biological nitrogen fixation while stimulating nitrifiers and denitrifiers, increasing nitrous oxide emissions (Ramirez *et al.*, 2010). Excess phosphorus reduces symbiotic mycorrhizal colonization because plants become less dependent on fungal nutrient acquisition.

Organic amendments such as compost and manure introduce diverse microbial communities and enhance functional redundancy. These amendments increase microbial biomass, enzyme activity, and disease suppression capacity (Bonanomi *et al.*, 2010). The suppressive effect arises from competition, antibiosis, and induced systemic resistance in plants. Organic amendments, reduced tillage, and crop diversification enhance microbial diversity and nutrient cycling efficiency (Lori *et al.*, 2017). Biofertilizers containing beneficial microorganisms are being developed to improve nutrient acquisition and plant resilience.

Biological inoculants, commonly known as biofertilizers, aim to manipulate soil microbiomes intentionally. Rhizobial inoculants improve legume nitrogen fixation, while phosphate-solubilizing bacteria enhance nutrient availability. However, field performance varies because introduced microbes must compete with native communities (Bashan *et al.*, 2014). Understanding ecological compatibility is therefore essential for successful microbiome engineering.

Recent research aims to intentionally manipulate soil microbiomes to improve crop productivity. Biofertilizers containing beneficial bacteria and fungi are applied to seeds or soil to enhance nutrient acquisition. Synthetic microbial consortia are being designed to perform complementary functions, such as nitrogen fixation combined with disease suppression. This approach represents a shift from chemical-based agriculture toward biological management. Future research aims to predict soil fertility based on microbiome composition using ecological modeling and artificial intelligence. Plant breeding programs are beginning to select crop varieties capable of recruiting beneficial microbiomes, indicating a transition toward microbiome-assisted agriculture.

11. Future Perspectives

Advances in microbial ecology have opened possibilities for designing beneficial soil microbiomes. Strategies include synthetic microbial consortia, targeted stimulation of native microbes, and precision agriculture guided by microbial indicators (Toju *et al.*, 2018). Such approaches aim to enhance nutrient use efficiency, reduce chemical inputs, and improve resilience to climate stress.

The concept of “soil health” now integrates biological parameters alongside physical and chemical metrics. Microbial diversity indices and functional gene abundance are emerging as diagnostic tools for ecosystem sustainability (Lehmann *et al.*, 2020). In the future, farmers may manage soils using microbiome-based decision support systems similar to medical diagnostics.

Nevertheless, challenges remain in predicting microbial behavior due to ecological complexity and context dependence. Long-term interdisciplinary research combining ecology, genomics, agronomy, and modeling will be required to translate microbiome knowledge into practical applications.

Future agriculture will likely rely on microbiome-guided practices. Advances in artificial intelligence and ecological modeling may allow prediction of soil fertility based on microbial composition. Plant breeding

programs are beginning to select crop varieties capable of recruiting beneficial microbiomes. Precision agriculture technologies may deliver tailored microbial inoculants to specific soil conditions. Understanding functional redundancy and identifying keystone species will be essential for maintaining ecosystem stability under changing environmental conditions.

12. Conclusion

The soil microbiome represents the biological foundation of terrestrial ecosystems. Its structure is shaped by environmental conditions, plant interactions, and management practices, while its functions regulate nutrient cycling, plant productivity, soil structure formation, and climate processes. Modern research demonstrates that sustainable agriculture depends not on replacing microbial processes with chemical inputs but on managing and enhancing them. By integrating microbial ecology into soil management strategies, it is possible to improve crop yields, reduce environmental impacts, and build resilient agroecosystems capable of supporting future food security. Sustainable land management depends on preserving and enhancing microbial diversity rather than replacing it with synthetic inputs. Understanding soil microbial ecology therefore represents a central component of future food security and environmental sustainability.

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“Year-Round Production of Berry Crops Using Advanced Hydroponic Systems”



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Abstract

Hydroponics, a soilless cultivation technique, has emerged as a sustainable and efficient alternative to conventional agriculture. By using nutrient-enriched water solutions, this system enables precise control of plant growth conditions, resulting in higher productivity and greater resource-use efficiency. Amid increasing challenges such as land degradation, water scarcity, and climate change, hydroponics offers significant potential, particularly for fruit crop production. This article examines the principles, types, advantages, and limitations of hydroponics, as well as its applications in fruit crops such as strawberries, melons, and papaya. Recent research findings and prospects are also discussed to highlight its role in sustainable horticulture.

1. Introduction

Agriculture is facing significant challenges due to rapid urbanization, declining soil fertility, and increasing demand for food. Conventional soil-based farming often struggles with issues such as pest infestations, nutrient imbalances, and environmental constraints. In this context, hydroponics has gained attention as an innovative method for efficient crop production.

Hydroponics is defined as the cultivation of plants without soil, where nutrients are supplied directly through water solutions. The roots may be suspended in the solution or supported by inert media such as cocopeat, perlite, or vermiculite. This system enables better control of plant nutrition and environmental factors, resulting in improved growth and yield (Resh, 2013).

The technology is particularly useful for fruit crops grown in controlled environments, including strawberries, melons, and certain fruit seedlings. Its adaptability to urban agriculture and protected cultivation systems makes it an important tool for future food production.

2. History of Hydroponics

The concept of hydroponics dates back to ancient civilizations. The Hanging Gardens of Babylon and floating gardens in China are often cited as early examples of soilless cultivation. However, scientific research in hydroponics began in the early 20th century.

The term “hydroponics” was coined by William Gericke in the 1930s, who demonstrated large-scale plant growth using nutrient solutions. In India, hydroponics was introduced in 1946 by W.J. Shalto Douglas in Kalimpong, West Bengal. Since then, the technology has evolved significantly and is now widely adopted in countries such as the Netherlands, Israel, and Japan (Trejo-Téllez and Gómez-Merino, 2012).

3. Principles of Hydroponics

Plants require water, nutrients, oxygen, sunlight, and physical support for growth. In hydroponics, soil is replaced by nutrient solutions that contain essential macro- and micronutrients. The roots absorb these nutrients directly, ensuring efficient uptake and reduced energy expenditure.

The success of hydroponics depends on maintaining:

- Optimal nutrient concentration
- Proper pH (usually 5.5–6.5)
- Adequate oxygen supply to roots

- Suitable temperature and light conditions

Because nutrients are readily available, plants grow faster and produce higher yields compared to soil-based systems (Savvas and Gruda, 2018).

4. Types of Hydroponic Systems

4.1 Solution Culture Systems

In these systems, plant roots are directly exposed to nutrient solutions. Common types include:

- Nutrient Film Technique (NFT)
- Deep Flow Technique (DFT)
- Floating raft system

NFT is widely used in commercial production due to its efficient nutrient delivery and water conservation.

4.2 Solid Media Culture Systems

Plants are grown in inert substrates such as cocopeat, perlite, or vermiculite. These media provide physical support while allowing nutrient solutions to pass through.

Examples include:

- Grow bag technique
- Pot culture
- Trench or trough systems

4.3 Aeroponics

In aeroponics, plant roots are suspended in air and sprayed with a fine mist of nutrient solution. This method provides maximum oxygen availability and promotes rapid growth.

4.4 Passive and Active Systems

- Passive systems rely on capillary action (e.g., wick system)
- Active systems use pumps and timers for nutrient delivery (e.g., drip and NFT systems)

5. Advantages of Hydroponics

5.1 Efficient Resource Utilization

Hydroponics uses significantly less water compared to conventional agriculture, as nutrient solutions are recirculated. This makes it suitable for water-scarce regions (Savvas and Gruda, 2018).

5.2 Higher Productivity

Plants grow faster due to optimal nutrient availability and controlled conditions, resulting in higher yields per unit area (Resh, 2013).

5.3 Year-Round Production

Hydroponics allows continuous cultivation regardless of seasonal changes, especially when combined with greenhouse technology.

5.4 Reduced Pest and Disease Incidence

The absence of soil eliminates many soil-borne pathogens and weeds, reducing the need for pesticides (Trejo-Téllez and Gómez-Merino, 2012).

5.5 Space Efficiency

Plants can be grown in vertical systems, maximizing space utilization in urban areas.

6. Limitations of Hydroponics

6.1 High Initial Investment

Hydroponic systems require significant capital for infrastructure, equipment, and maintenance.

6.2 Technical Complexity

Proper management of nutrient solutions, pH, and environmental conditions requires skilled knowledge.

6.3 Risk of System Failure

Power outages or equipment malfunction can disrupt nutrient supply, leading to crop loss.

6.4 Disease Spread

Waterborne pathogens can spread rapidly in recirculating systems if not properly managed (Savvas and Gruda, 2018).

7. Application of Hydroponics in Fruit Crops

7.1 Suitable Crops

Hydroponics is widely used for:

- Strawberry
- Melon
- Papaya
- Tomato (fruit vegetable)
- Seedlings of citrus, grape, guava, and peach

Small-sized plants with short growth cycles are more suitable for hydroponic systems.

7.2 Hydroponic Production of Fruit Seedlings

Hydroponics is highly effective for producing disease-free, uniform seedlings. Benefits include:

- Faster growth
- Better root development
- Early establishment in the field

8. Achievements in Hydroponic Cultivation

A hydroponic cultivation system for Strawberry, Blueberry, and Raspberry in Bengaluru demonstrated remarkable improvements in fruit production and quality under controlled greenhouse conditions. Using Nutrient Film Technique (NFT) and drip systems with cocopeat as a growing medium, the study maintained optimal pH and nutrient levels, resulting in yield increases of 35–45% compared to soil cultivation. Fruits exhibited better uniformity, higher sugar content, and longer shelf life. The system also achieved up to 90% water savings through efficient nutrient recycling and significantly reduced soil-borne diseases and pesticide use. Additionally, the controlled environment enabled year-round production, allowing farmers to access off-season markets and secure premium prices. Despite initial setup costs and the need for technical expertise, the system increased overall profitability by 50–60%, confirming hydroponics as a sustainable and economically viable approach for modern berry cultivation (Resh, 2013; Savvas et al., 2013)



Fig.1: Hydroponic in Strawberry

9. Role in Sustainable Agriculture

Hydroponics contributes to sustainability by:

- Reducing water consumption
- Minimizing chemical inputs
- Enabling urban and peri-urban farming
- Reducing land dependency

It is particularly useful in regions facing environmental stress and limited arable land.

10. Future Scope

The future of hydroponics is promising, driven by technological advancements and increasing demand for high-quality food. Key developments include:

- Integration with automation and artificial intelligence
- Expansion of vertical farming systems
- Adoption in urban agriculture

- Government support and subsidies

In India, hydroponics is expected to grow rapidly due to increasing awareness and policy support.

11. Conclusion

Hydroponics represents a transformative approach to modern agriculture. Its ability to enhance productivity, conserve resources, and enable year-round cultivation makes it a vital tool for sustainable food production. In fruit crops, particularly strawberry and seedling production, hydroponics has shown significant potential.

Although challenges such as high cost and technical complexity exist, ongoing research and innovation are expected to overcome these limitations. With proper implementation, hydroponics can play a crucial role in ensuring food security and improving agricultural sustainability.

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Nature-Based Solutions in Fisheries Management: Harnessing Ecosystems for Sustainable Fisheries



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Abstract

Nature-Based Solutions (NbS) are widely acknowledged as sustainable alternatives to solving fisheries' complex difficulties, such as overfishing, habitat loss, pollution and climate change. NbS improves ecological integrity while promoting human well-being and livelihoods by collaborating with natural ecosystems rather than working against them. Because they provide nursery habitats, sustain food webs and enhance water quality through nutrient cycling and pollution filtering, aquatic ecosystems including freshwater, marine and coastal environments are essential to fisheries. With keystone species controlling ecological balance and sustaining sustainable fish populations, biodiversity in these habitats is crucial for preserving fish productivity, ecosystem stability and resilience. Mangrove restoration, coral reef protection, wetland and estuary rehabilitation, sustainable aquaculture methods and the creation of marine protected areas are important NbS measures in fisheries. greater fish harvests, improved livelihoods for fishing communities and greater biodiversity are just a few advantages of these tactics. Widespread adoption is hampered by issues including low awareness, financial limitations, policy gaps and technological difficulties. It is crucial to remove these obstacles via inclusive government, sustained investment and efficient oversight. All things considered, NbS offer a comprehensive route toward fisheries that are resilient, productive and sustainable in the face of environmental change on a global scale.

Keywords- Nature-Based Solutions, Sustainable Fisheries, Ecosystem Restoration, Biodiversity, Climate Resilience

Introduction

Fisheries management include managing fishing operations to maintain fish populations and habitats, which are critical for food security, livelihoods and biodiversity. The rapid changes in the globe pose a threat to the contemporary marine and coastal systems that offer humanity a wide range of ecological services and goods. Rising human pressures exacerbated by climate change have been shown to cause habitat degradation and declines in plant and animal populations in freshwater, marine and terrestrial systems around the globe. The resilience and productivity of fisheries are now threatened by overfishing, habitat degradation and climate change. Overfishing, wetland degradation, dam construction, deforestation, urbanization and industrialization are some of the factors contributing to low productivity. Management strategies might concentrate on issues like employing a watershed or ecosystem viewpoint, generating income for conservation initiatives and distributing duties and benefits among regional stakeholders in order to potentially overcome the aforementioned challenges. Nature-Based Solutions (NbS) are becoming more and more well-known around the world as creative methods that concurrently solve environmental, social and economic issues by preserving, restoring, and sustainably managing ecosystems. By improving habitats like wetlands, floodplains and mangroves that offer vital ecosystem services like water filtering, fish nurseries and carbon sequestration, NbS can benefit fisheries. Research demonstrates the potential of NbS in freshwater and marine environments. For instance, restoring wetlands in Ethiopian fisheries or combining mangrove restoration with shrimp farming in Indonesia can enhance sustainability while promoting local communities and biodiversity conservation (Mekonen *et al.*, 2025; Le Gouvello *et al.*, 2022). In the face of

shifting environmental conditions, ecosystem-based fisheries management strategies that include NbS concepts provide workable means to strike a balance between ecological health and economic demands (Howell *et al.*, 2021).

Concept of Nature-Based Solutions (NbS)

The novel concept of NbS was initially put out by the World Bank in 2008. The International Union for Conservation of Nature (IUCN) defines Nature-Based Solutions (NbS) as measures to preserve, sustainably manage and restore natural or modified ecosystems that effectively and adaptively address societal challenges while benefiting biodiversity and human well-being. Working with nature rather than against it, NbS emphasizes ecological processes to provide a number of co-benefits, including increased biodiversity, better livelihoods and climate resilience. The eight guiding principles of the IUCN Global Standard—which address societal challenges, landscape scale of intervention, biodiversity gain, economic viability, governance capability, equitable trade-off balancing, adaptive management and mainstreaming within an appropriate jurisdictional context—form its cornerstone. NbS uses natural processes to produce affordable, sustainable results at landscape scales, in contrast to typical engineering solutions that frequently rely on gray infrastructure and may have limited ecological advantages. Being motivated and inspired by nature, tackling social issues holistically, providing several advantages at once and incorporating inclusive governance with local stakeholder engagement are all important tenets. Urban green infrastructure that promotes biodiversity and human health, as well as the restoration of wetlands and forests, are examples of NbS in environmental management. Unlike isolated or strictly technological interventions, these solutions are flexible, incorporated into policy frameworks and made to be egalitarian and context-specific (Sowińska-čwierkosz *et al.*, 2022; Albert *et al.*, 2021).

Importance of Fisheries Ecosystems

Aquatic Ecosystems and Their Role

Fisheries and human well-being are supported by vital ecosystem services provided by freshwater, marine and coastal ecosystems. These ecosystems support intricate food webs that control species interactions, operate as nursery grounds for young fish and filter contaminants and cycle nutrients to help purify water. Sustainable fisheries management and biodiversity conservation depend on healthy aquatic ecosystems because they maintain fish populations and improve ecosystem resilience (Pownkumar *et al.*, 2022).

Biodiversity and Fish Productivity

The productivity and health of fish stocks are intimately related to biodiversity in fisheries ecosystems. While keystone species are essential for preserving ecological balance by controlling prey numbers and habitat conditions, high species variety promotes ecosystem resilience and stability. Food security and ecosystem services depend on continuous fish recruitment and productivity, which are ensured by protecting biodiversity (Meinam *et al.*, 2023).

Major Challenges in Fisheries Management

Overfishing and Resource Depletion

Overfishing caused by irresponsible harvesting techniques depletes valuable fish species and affects long-term fisheries viability. Fish populations diminish as a result of increased fishing without sufficient management, creating questions about the availability of resources in the future and the health of ecosystems (Ameyaw *et al.*, 2021).

Habitat Destruction

Fish reproduction and survival depend on vital nursery and feeding areas, which are lost when mangroves disappear and coral reefs deteriorate. Fisheries that rely on robust coastal ecosystems are threatened by these habitat changes, which lower fish production and biodiversity (Fenner *et al.*, 2012).

Pollution and Climate Change

Aquatic habitats are deteriorated by water pollution from plastics, industrial waste and agricultural runoff, while fish breeding cycles are disturbed and species ranges are changed by ocean warming and acidification. Together, these factors weaken catch stability and jeopardize the resilience of fisheries.

Socio-economic Pressures

Many fishing communities rely significantly on fisheries for a living, leaving them vulnerable to resource depletion and management failures. Due to issues including poor governance, a lack of funding and disputes over access, small-scale fisheries are more susceptible to changes in the environment and the economy (Arthur *et al.*, 2022).

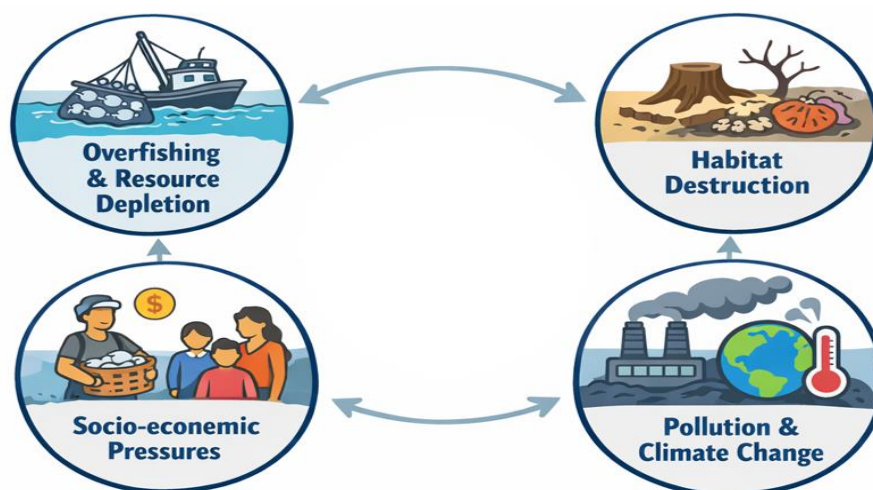


Fig. 1. Major Challenges in Fisheries Management

Types of Nature-Based Solutions in Fisheries

NbS might use permeable pavement to control their fisheries. The forms of NbS for fisheries are thus discussed in this section after these insights.

Mangrove Restoration

Mangrove restoration is an important nature-based approach because it restores fish nurseries, which promote juvenile fish development and biodiversity. By stabilizing shorelines and reducing erosion through their intricate root systems that trap sediments and lessen wave energy, mangroves also offer coastal protection. Examples from the Caribbean and the coast of Guiana show how successful restoration initiatives differ depending on the geography, where customized strategies restored circulation and sediment collection to revitalize mangrove ecosystems. Through carbon sequestration, these initiatives improve local fisheries production and ecological resilience while also providing advantages for climate mitigation (Winterwerp *et al.*, 2025).

Coral Reef Conservation

Coral reefs are important for marine biodiversity because they provide habitat complexity that supports various fish populations, which are necessary for fisheries. Reef restoration and the installation of artificial reefs to repair damaged habitats are examples of conservation initiatives that can boost fish productivity and abundance. These actions support sustainable fishing and storm protection along the shore by preserving ecosystem services including shelter and feeding grounds (Perricone *et al.*, 2023).

Wetland and Estuary Restoration

Wetlands and estuaries play important roles in inland fisheries by providing breeding and feeding areas for several fish species. By buffering floods and improving water quality through nitrogen cycling, restoration of these ecosystems enhances floodplain management. In addition to offering extra ecosystem services like carbon storage and water purification, these natural solutions promote the sustainability of fish populations.

Sustainable Aquaculture Practices

Integrated Multi-Trophic Aquaculture (IMTA) integrates species from several trophic levels to imitate natural ecosystems, hence increasing resource efficiency and lowering environmental impact. By reducing pollution and encouraging nutrient recycling in aquaculture systems, the use of natural feeds promotes ecological balance. By

reducing reliance on wild fish supplies and reducing adverse effects on nearby habitats, these methods improve sustainability (Riisager-Simonsen *et al.*, 2022).

Marine Protected Areas (MPAs)

MPAs are areas set aside to limit fishing in order to protect marine ecosystems and biodiversity. The spillover effect, in which protected populations replenish nearby fishing grounds and increase overall fisheries production, is encouraged by well-designed MPAs. By including local stakeholders in conservation efforts, community-managed reserves frequently improve compliance and socioeconomic advantages (Riisager-Simonsen *et al.*, 2022).

Seagrass and Algal Ecosystems

Algae habitats and seagrass beds play a major role in carbon sequestration, or "blue carbon," which lessens the effects of climate change. They promote early life stages that are vital to maintaining fish populations by giving young fish vital habitat. Furthermore, by stabilizing sediments and maintaining water quality, these ecosystems boost fisheries resilience and safeguard coastal biodiversity (Perricone *et al.*, 2023).

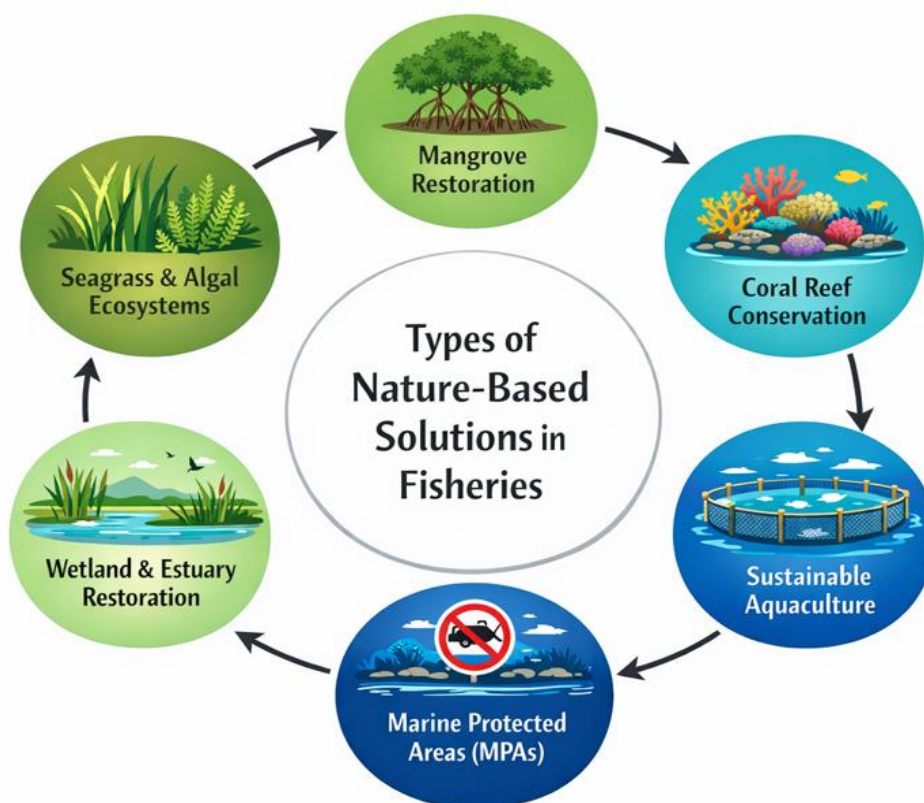


Fig. 2. Types of nature-based solution in fisheries

Benefits of Nature-Based Fisheries Management

Ecological Benefits

Nature-based fisheries management improves biodiversity by protecting habitats and maintaining ecological interactions essential for healthy fish populations. By strengthening ecosystem resilience, this strategy makes aquatic systems more resilient to environmental shifts and human demands. It promotes trophic linkages and habitat complexity, which are essential for long-term fisheries sustainability, by emphasizing ecosystem-based management over single-species exploitation (Tripathy *et al.*, 2025).

Economic Benefits

Nature-based fisheries management can boost fish yields by encouraging sustainable harvests and better fish populations. By stabilizing revenue streams and lowering the danger of resource depletion, it promotes sustainable livelihoods for fishing communities. Economic benefits result from striking a balance between fishing production

and conservation, frequently through integrated management techniques that maximize both ecological health and financial profits (Sachdeva *et al.*, 2024).

Social Benefits

Community engagement is essential for successful nature-based fisheries management, since it fosters local ownership and compliance with conservation measures. Adaptability and fair resource usage are improved by fusing traditional ecological knowledge with contemporary methods. According to (Sachdeva *et al.*, 2024), inclusive governance enhances the sustainability of communities that depend on fisheries, empowers stakeholders and fosters social cohesion.

Challenges in Implementing NbS

One of the main obstacles to the implementation of nature-based solutions (NbS) is the general lack of knowledge among stakeholders regarding the advantages and possibilities of NbS, which restricts their adoption and incorporation into planning procedures. Funding constraints are important because NbS programs usually need long-term commitment and consistent financial support; however, available finances are generally insufficient or fragmented, making scale difficult (Martin *et al.*, 2025). Another obstacle is policy gaps; many current rules prioritize traditional designed solutions over NbS and there is sometimes a dearth of explicit legislation or policy drivers that particularly assist NbS deployment (Martin *et al.*, 2025). Monitoring and evaluation challenges exacerbate implementation since quantitative data on NbS efficacy are either insufficient or inconsistently provided, making it difficult to develop a solid evidence foundation that can educate adaptive management and justify expenditures. Operational difficulties after installation are also a result of technological complexity and a lack of experience with NbS design, operation and maintenance. To overcome these obstacles, better governance frameworks that encourage inclusive stakeholder participation, enhanced knowledge exchange, longer-term funding sources and integrated monitoring techniques are needed to consistently show the advantages of NbS and foster confidence among practitioners and policymakers (Martin *et al.*, 2025).

Conclusion

Nature-based solutions (NbS) are a promising integrated strategy to addressing climate change, biodiversity loss and sustainable development that relies on natural ecosystems to provide many social and environmental advantages. However, their efficacy is contingent upon careful design that upholds the rights of Indigenous peoples, safeguards natural ecosystems and enhances rather than substitutes swift efforts to reduce the use of fossil fuels. NbS are becoming more widely acknowledged and many nations have included them into plans for climate adaptation and mitigation under frameworks such as the Paris Agreement. However, there are still few quantifiable objectives and evidence-based implementation. The potential of NbS to improve resilience to climate effects while offering co-benefits including better biodiversity, air and water quality and social well-being makes their adoption urgent. Achieving these benefits requires collective action involving policymakers, researchers, practitioners and local communities to ensure inclusive governance, adequate funding and robust monitoring. Coordinated efforts can help scale up NbS effectively to meet global sustainability goals and build resilient societies in the face of accelerating environmental challenges.

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Millet and Other Forgotten Foods: Rediscovering Nature's Nutritional Powerhouses



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Introduction:

In the modern global food system, dietary patterns are increasingly dominated by a narrow range of staple crops primarily wheat, rice and maize. While these cereals have played a critical role in ensuring food security, their overwhelming dominance has led to the marginalization of a vast diversity of traditional crops once central to human diets. Among these underutilized resources, millets and other “forgotten foods” stand out as nutritionally superior, environmentally resilient and culturally significant alternatives. Reintroducing these foods into mainstream consumption is not merely a matter of nostalgia it is a strategic response to contemporary challenges such as malnutrition, climate change, and declining agricultural biodiversity.

The resurgence of millet:

Millets are a group of small seeded grasses that have been cultivated for over 7,000 years, particularly across Asia and Africa. Historically, they formed the backbone of traditional diets in regions with challenging agro-climatic conditions. Today, millets are regaining attention due to their remarkable adaptability and nutritional richness.

Agronomic advantages:

Millets are inherently climate resilient crops.

- Thrive in low rainfall and poor soil conditions
- Require minimal external inputs
- Exhibit short growing cycles, making them suitable for marginal lands
- Resistant to many pests and diseases

These characteristics make millets highly relevant in the context of climate change and sustainable agriculture.

Nutritional superiority:

Millets are often referred to as “nutri-cereals” due to their exceptional nutrient profile.

- **High dietary fiber:** Supports digestion and helps manage obesity
- **Rich in protein:** Important for muscle development and repair
- **Micronutrient dense:** Contains iron, calcium, magnesium, phosphorus and zinc
- **Low glycemic index:** Beneficial for diabetic patients

Major Types and Their Benefits:

- **Pearl millet (Bajra):** Rich in iron and energy, ideal for combating anemia
- **Finger millet (Ragi):** Exceptionally high in calcium, supports bone health
- **Foxtail millet:** Good for heart health and blood sugar regulation
- **Little millet:** High in antioxidants and fiber, aids digestion

Additionally, millets are naturally gluten free, making them suitable for individuals with gluten intolerance or celiac disease.

Other forgotten foods worth rediscovering:

Beyond millets, numerous traditional crops once sustained civilizations and offer immense potential today.

1. Amaranth: A pseudo cereal revered by ancient civilizations such as the Aztecs

- Rich in high quality protein, including lysine (rare in cereals)

- Packed with iron, calcium and antioxidants
 - Useful in porridges, baked goods and popped snacks
- 2. Sorghum (Jowar):** A staple in semi-arid regions
- High in fiber and antioxidants
 - Supports heart health and digestion
 - Widely used in flatbreads, porridges, and gluten-free baking
- 3. Fonio:** An ancient West African grain
- One of the fastest maturing cereals (as little as 6-8 weeks)
 - Rich in essential amino acids and micronutrients
 - Easy to cook and highly digestible
- 4. Teff:** A tiny grain central to Ethiopian cuisine
- Extremely rich in iron and calcium
 - Used to prepare injera, a fermented flatbread
 - Promotes gut health due to fermentation
- 5. Taro, Cassava and Yam (root crops):**
- Complex carbohydrates for sustained energy
 - Vitamins like B6 and C
 - Versatility in cooking (boiling, roasting, frying, flour production)
- 6. Breadfruit:** A highly productive tropical crop
- Rich in fiber and potassium
 - Can be used as a rice or potato substitute
 - Supports food security due to high yield per tree

Importance/need of rediscover forgotten foods:

1. Nutritional Security:

Modern diets often lack diversity, leading to “hidden hunger” (micronutrient deficiencies). Traditional crops are more nutrient dense and naturally balanced in essential vitamins and minerals

2. Environmental Sustainability:

Forgotten foods support ecological balance, require less water and chemical inputs, enhance soil health and promote agro biodiversity.

3. Climate Resilience:

With increasing climate variability drought-tolerant crops like millets and sorghum provide stable yields and reduce dependency on climate sensitive crops like rice and wheat

4. Food Security:

Diversifying crops reduces risk of crop failure, strengthens local food systems and ensures availability in adverse conditions.

5. Cultural and economic value:

Reviving traditional foods preserves indigenous knowledge and culinary heritage, supports local farmers and rural economies and encourages farm to table and organic movements

Challenges in revival:

Despite their benefits, forgotten foods face several barriers.

- Lack of consumer awareness
- Limited market infrastructure and value chains
- Perception as “poor man’s food”
- Insufficient policy and research support

Probable solutions:

- Awareness campaigns
- Inclusion in government nutrition programs
- Promotion through food industries and startups

Way forward:

India, for instance, has already taken significant steps by promoting millets as “Shree Anna” and observing the International Year of Millets (2023), which has substantially enhanced public awareness, production and consumption of these nutritive cereals. However, to ensure the sustained revival and mainstreaming of millets and other forgotten foods, a coordinated and multi-institutional approach is essential.

- Integrate them into daily diets (e.g., millet based rotis, porridge, snacks)
- Promote processing technologies for ready to eat products
- Encourage institutional support (schools, hospitals, government schemes)
- Strengthen research and extension services

Conclusion:

The rediscovery of millets and other forgotten foods represents a powerful convergence of nutrition, sustainability, and cultural revival. Far from being relics of the past, these traditional crops offer practical and forward looking solutions to some of the most pressing challenges of our time, including malnutrition, climate change, and declining agro biodiversity. By reintroducing them into mainstream agriculture and diets, we can move toward a food system that is inherently more diverse, resilient, and health-oriented. Embracing these nutrient rich crops is not merely a return to tradition, but a strategic step toward the future. Their integration into daily diets can significantly enhance nutritional security, while their cultivation supports sustainable farming practices and reduces environmental stress. Moreover, promoting these foods helps preserve indigenous knowledge, cultural heritage and local food traditions that have sustained communities for generations. Thus, incorporating millets and other ancient foods into modern food systems is more than a dietary adjustment, it is a transformative pathway toward achieving long term food and nutritional security, strengthening climate resilience and maintaining ecological balance. In doing so, we not only nourish present populations but also safeguard resources and traditions for future generations.



Bioluminescent Biosensors: Harnessing Living Light to Decode Aquatic Toxicity



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Abstract

Aquatic pollution caused by persistent toxic contaminants, particularly heavy metals, has intensified the need for rapid and biologically relevant monitoring approaches. Bioluminescent biosensors have emerged as advanced analytical tools that utilize light-emitting biochemical reactions of living organisms to detect environmental toxicity. These systems operate by translating pollutant-induced metabolic stress into measurable optical signals, enabling sensitive and real-time assessment of water quality. Bacterial luminescent assays, firefly luciferase-based platforms, and recently engineered biosensor architectures have significantly enhanced detection efficiency and field applicability. Integration with nanomaterials and portable sensing technologies has further improved analytical sensitivity and operational feasibility under diverse environmental conditions. By reflecting the bioavailable fraction of contaminants rather than total chemical concentration, bioluminescent biosensors provide ecologically meaningful insights into aquatic toxicity. Consequently, these innovative sensing strategies represent sustainable and cost-effective solutions for modern environmental surveillance and proactive pollution management.

Key words: Bioluminescent biosensors, Heavy metals, Portable sensing technologies

Introduction

Water pollution has emerged as one of the most pressing environmental challenges of the modern era, driven by rapid industrialization, urban expansion, and intensified agricultural practices. The release of toxic contaminants, particularly persistent heavy metals and complex chemical residues, has significantly altered the stability of the aquatic ecosystems and posed serious risks to environmental and public health. Conventional analytical methods used for monitoring water quality often involve sophisticated instrumentation, extensive sample preparation and delayed data interpretation, which may limit their effectiveness in rapid environmental decision-making contexts (Hui et al., 2022; Lopreside et al., 2021). There exists an increasing scientific demand for innovative monitoring approaches capable of providing both timely and sensitive detection of toxic substances in aquatic systems. In this context, biosensors have gained prominence as advanced analytical tools that integrate biological recognition elements with signal transduction mechanisms to detect environmental contaminants. Among the diverse biosensing strategies currently under development, Bioluminescent biosensors represent a promising technological advancement. The integration of naturally occurring light-producing systems into biosensor platforms has opened new avenues for rapid, sensitive, and field-deployable water toxicity monitoring, marking a significant shift toward sustainable environmental surveillance technologies.

Fundamentals of Bioluminescence

Bioluminescence is the emission of light resulting from enzyme-mediated biochemical reactions in living organisms. The interaction between luciferase enzymes and their substrates produces quantifiable light signals that can be modulated by environmental stressors or toxic compounds, enabling real-time detection of pollution events (Reyes et al., 2025; Viviani et al., 2022). Bioluminescence is widely distributed across diverse taxonomic groups, including both marine and terrestrial bacteria, fungi, insects and other aquatic organisms. The evolutionary persistence of bioluminescence across multiple biological kingdoms highlights its ecological and physiological importance as a functional adaptive trait (Ge et al., 2025; Reyes et al., 2025). In microbial communities, luminescent bacteria belonging to genera such as *Vibrio* and *Photobacterium* are commonly associated with marine environments, where light emission may contribute to communication, symbiosis, or defense mechanisms (Thacharodi et al., 2019). Bioluminescence has also been documented in fungi such as

Neonothopanus gardneri, where metabolically regulated light emission pathways contribute to ecological interactions and emerging biotechnological applications. (Ge et al., 2025).

At the molecular level, bioluminescence is primarily governed by the luciferin–luciferase reaction mechanism. In this process, the enzyme luciferase catalyzes the oxidation of a substrate molecule known as luciferin in the presence of molecular oxygen and, in some systems, cofactors such as adenosine triphosphate. This reaction results in the formation of an electronically excited intermediate that releases energy in the form of photons as it returns to the ground state, producing visible light (Lopreside et al., 2021; Viviani et al., 2022). Unlike conventional light generation processes that involve substantial heat loss, bioluminescent reactions are highly energy-efficient and are therefore often described as producing “cold light.” Biologically, light emission serves multiple ecological functions, including mate attraction, prey capture, camouflage, and interspecies signaling.

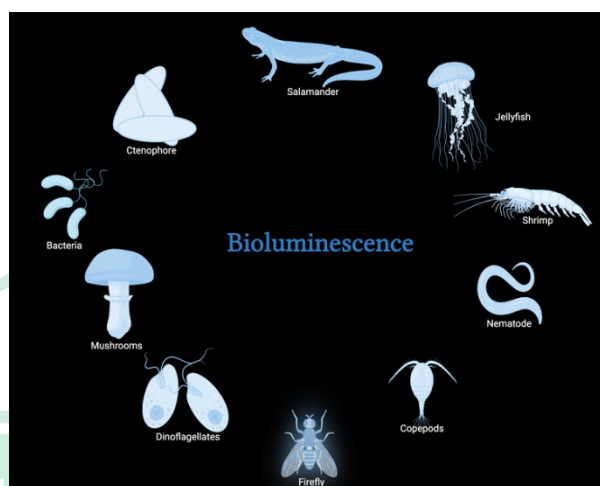


Figure 1: Bioluminescence in Nature (Source: Lopreside et al., 2021)

Principle of Bioluminescent Biosensors

Bioluminescent biosensors operate on the fundamental principle that exposure to toxic environmental contaminants can influence the physiological and metabolic activity of light-emitting biological systems. In whole-cell biosensor configurations, living microorganisms engineered or naturally capable of bioluminescence respond to toxicants through alterations in cellular respiration, enzyme activity, and gene expression pathways. These metabolic disturbances directly affect the biochemical reactions responsible for light production, thereby enabling toxicity detection through measurable luminescent responses (Hui et al., 2022; Lopreside et al., 2021). One of the primary sensing mechanisms in such systems involves modulation of light intensity. Under optimal environmental conditions, luminescent organisms emit a stable and quantifiable light signal. However, the presence of toxic substances such as heavy metals or organic pollutants may inhibit enzymatic activity or disrupt intracellular homeostasis, leading to a reduction in emitted light. Conversely, in certain genetically engineered biosensor designs, pollutant-responsive regulatory elements can trigger enhanced expression of luciferase enzymes, resulting in increased luminescence output. These contrasting responses are generally classified as “light-OFF” and “light-ON” sensing mechanisms, respectively, depending on whether the signal decreases or increases upon toxic exposure (Viviani et al., 2022; Abbas et al., 2018). The optical signals generated through these biological reactions are detected using sensitive photometric instrumentation, including photomultiplier tubes, photodiodes, and advanced imaging sensors. Such optical detection systems allow rapid quantification of luminescent intensity changes, facilitating real-time assessment of environmental toxicity without extensive laboratory processing (Reyes et al., 2025).

Bioluminescent Systems Used in Toxicity Monitoring

A variety of bioluminescent biological systems have been successfully adapted for environmental toxicity monitoring due to their sensitivity to chemical stressors and rapid signal generation. Among these, bacterial bioluminescent systems represent one of the most widely applied approaches. Naturally luminescent marine

bacteria belonging to genera such as *Vibrio* and *Photobacterium* produce light through enzyme-mediated oxidation reactions involving reduced flavin mononucleotide and long-chain aldehyde substrates. When exposed to toxic pollutants, disruption of cellular respiration and redox balance leads to measurable inhibition of light emission, forming the basis of widely used ecotoxicity bioassays (Abbas et al., 2018; Thacharodi et al., 2019). In addition to bacterial systems, firefly luciferase-based sensing platforms have gained considerable attention in biosensor engineering. The firefly luciferin–luciferase reaction, which requires molecular oxygen, adenosine triphosphate, and magnesium ions, produces highly sensitive luminescent signals that can be modulated by environmental stressors. Recent studies have demonstrated that firefly luciferases exhibit spectral and intensity variations in response to toxic metal ions such as mercury and cadmium, enabling their application as enzymatic and intracellular toxicity indicators (Viviani et al., 2022; Gabriel & Viviani, 2016).

Advances in molecular biotechnology have further facilitated the development of engineered luciferase platforms with enhanced stability, brightness, and specificity. Novel variants such as compact luciferase enzymes and genetically optimized reporter systems provide improved analytical sensitivity and enable the design of customized biosensing assays for targeted pollutant detection (England et al., 2016). More recently, the integration of bioluminescent reactions with nanomaterials and miniaturized sensing architectures has led to the emergence of portable and paper-based biosensors. These systems allow rapid field-level toxicity assessment using lightweight optical detectors or smartphone-based signal acquisition, thereby expanding the practical applicability of bioluminescent biosensing technologies for real-time environmental monitoring (Martínez-Pérez-Cejuela et al., 2023; Lopreside et al., 2021).

Table 1. Representative bioluminescent systems used for environmental toxicity monitoring (adapted from Abbas et al., 2018)

Source of Luminescence	Application	Mechanism
Recombinant <i>Escherichia coli</i> with lux gene	Detection of mutagenic compounds (acids, DMS, hydrogen peroxide, formaldehyde)	Light induction in the presence of toxicants
<i>Vibrio fischeri</i> and lux-modified <i>Pseudomonas fluorescens</i>	Detection of salinity toxicity, chromium and phenol contamination	Luminescence inhibition
<i>Vibrio fischeri</i> (ToxAlert system)	Detection of volatile chloro-organic pollutants in river water	Luminescence inhibition
<i>Vibrio logei</i>	Detection of heavy metals, organic chemicals (benzene, toluene, xylene) and pesticides	Luminescence inhibition
<i>Vibrio fischeri</i> (LUMISTox assay)	Monitoring of processed industrial effluents and textile dye auxiliaries	Luminescence inhibition
<i>Vibrio harveyi</i> mutant strain	Detection of mutagenic environmental pollutants	Luminescence induction
<i>Vibrio campbellii</i> STF1	Detection of heavy metals such as lead, cadmium, copper and mercury	Luminescence inhibition
Dinoflagellates (<i>Gonyaulax polyedra</i> , <i>Pyrocystis lunula</i>)	Detection of toxic metals and organic pollutants including phenanthrene and SDS	Luminescence inhibition

Detection of Heavy Metal Toxicity in Water

Heavy metal contamination in aquatic environments has become a major global concern due to the persistence, non-biodegradable nature, and bioaccumulative potential of metals such as mercury (Hg), cadmium (Cd), lead (Pb), and chromium (Cr). These toxic elements can enter water bodies through industrial effluents, mining activities, agricultural runoff, and urban wastewater discharge, leading to long-term ecological degradation and potential risks to human health. Unlike many organic pollutants, heavy metals cannot be metabolically degraded and therefore tend to accumulate within aquatic food webs, intensifying their toxicological impacts over time (Hui et al., 2022). Bioluminescent biosensor systems offer an effective approach for detecting heavy metal toxicity by exploiting the sensitivity of cellular metabolic processes and enzymatic light-producing reactions to metal-induced stress. Exposure to toxic metal ions can disrupt intracellular redox balance, inhibit enzyme activity, and interfere with energy metabolism, resulting in measurable reductions in luminescent intensity in bacterial or enzymatic biosensor platforms. In addition to intensity-based responses, certain luciferase systems exhibit

spectral shifts in emitted light when interacting with specific metal ions, enabling more refined ratiometric detection strategies for toxicity assessment (Viviani et al., 2022; Gabriel & Viviani, 2016). Furthermore, biological sensing approaches provide insight into the bioavailable fraction of metals, the portion that actively interacts with living cells rather than merely quantifying total elemental concentration. This distinction is critical because chemical analytical techniques may detect metals that are environmentally inert, whereas biosensors reflect biologically relevant toxicity levels (Thacharodi et al., 2019). Consequently, bioluminescent biosensors represent a powerful tool for real-time assessment of heavy metal pollution and ecological risk in aquatic systems.

Technological Advancements in Biosensor Platforms

Recent progress in biosensor engineering has significantly enhanced the analytical performance and practical applicability of bioluminescent toxicity monitoring systems. Whole-cell systems utilize metabolically active microorganisms that respond dynamically to environmental toxicants through physiological stress responses, enabling biologically relevant toxicity assessment. In contrast, cell-free biosensors rely on isolated enzymatic components or immobilized bioluminescent reaction systems, offering improved operational stability, reduced biosafety concerns, and simplified calibration requirements (Lopreside et al., 2021). Advances in nanobiotechnology have further contributed to the improvement of bioluminescent biosensor sensitivity and durability. The incorporation of nanostructured materials such as metal-organic frameworks and nanoparticle-based supports has enabled enhanced enzyme stabilization, signal amplification, and efficient analyte interaction. These nanomaterial-integrated sensing architectures facilitate the development of highly sensitive analytical platforms capable of detecting low concentrations of environmental contaminants under diverse field conditions (Martínez-Pérez-Cejuela et al., 2023; Reyes et al., 2025). Another significant technological trend is the emergence of portable field-deployable biosensor devices designed for on-site environmental monitoring. Miniaturized photodetection systems and compact optical modules allow rapid quantification of luminescent signals without the need for centralized laboratory infrastructure. More recently, smartphone-based sensing strategies have been explored as cost-effective analytical solutions, wherein mobile imaging sensors and dedicated software applications are used to capture and interpret luminescence data. Such innovations are transforming bioluminescent biosensors into accessible and scalable tools for real-time water quality surveillance and environmental risk management (Reyes et al., 2025).

Advantages and Practical Significance

Bioluminescent biosensors offer several practical advantages that make them highly suitable for contemporary environmental monitoring applications. One of the most significant benefits is their **rapid response** capability. Unlike conventional analytical techniques that may require extensive sample preparation and laboratory processing, bioluminescent systems can generate measurable luminescent signals within a short duration following exposure to toxic substances. (Lopreside et al., 2021). Another important advantage lies in the **eco-friendly nature of biological sensing approaches**. Bioluminescent biosensors rely on naturally occurring biochemical reactions and living or biologically derived components, thereby reducing dependence on hazardous reagents or energy-intensive instrumentation. This biological compatibility enhances their suitability for sustainable environmental surveillance strategies aimed at minimizing ecological disturbance during monitoring processes (Reyes et al., 2025). From an economic perspective, these biosensor systems can also provide **cost-effective monitoring solutions**, particularly when integrated into portable analytical platforms or simplified assay formats. The use of miniaturized optical detection devices and scalable biosensor configurations reduces operational expenses associated with routine water quality assessment. Furthermore, the ability of bioluminescent biosensors to facilitate real-time pollution surveillance represents a major practical advantage, thereby improving risk evaluation and environmental decision-making efficiency (Thacharodi et al., 2019).

Conclusion

Bioluminescent biosensors have emerged as innovative analytical tools that bridge fundamental biological phenomena with modern environmental monitoring needs. By utilizing the natural light-emitting capabilities of living systems, these biosensors enable rapid, sensitive, and biologically relevant detection of toxic contaminants in aquatic environments. Their ability to provide real-time insights into pollutant toxicity, particularly heavy metal stress, highlights their growing significance in contemporary water quality surveillance and ecological risk

assessment frameworks. Beyond analytical performance, the sustainability dimension of bioluminescent biosensing further strengthens its scientific relevance. As research continues to integrate advances in synthetic biology, nanotechnology, and digital sensing systems, the future of bioluminescent biosensors is expected to expand toward intelligent environmental monitoring networks capable of supporting proactive pollution management strategies.

“Monitoring aquatic toxicity through biological light is not merely a technological advancement, but a critical step toward safeguarding the integrity of aquatic ecosystems”

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IoT-Based Cold Food Chain Monitoring and Intelligent Management for Reducing Post-Harvest Losses

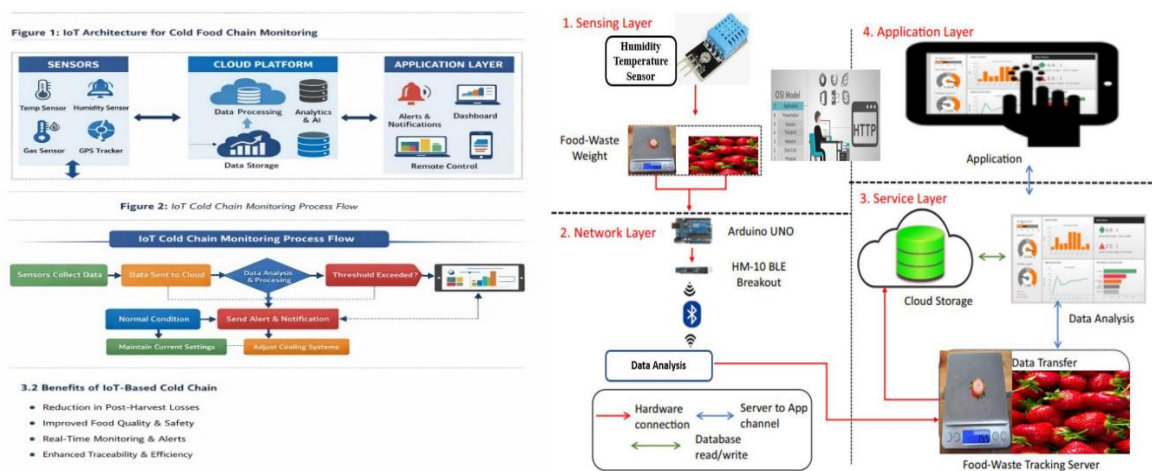
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Abstract

The preservation of perishable food commodities through an efficient cold chain system is essential for ensuring food quality, safety, and economic sustainability. In India, post-harvest losses of fruits, vegetables, dairy, and meat products remain significantly high due to inadequate monitoring and inefficient cold storage infrastructure. The integration of Internet of Things (IoT) technology into cold chain management provides a smart and automated solution for real-time monitoring and intelligent decision-making. IoT systems utilize sensors, communication networks, cloud computing, and data analytics to continuously track environmental parameters such as temperature, humidity, and gas composition. This paper presents a comprehensive overview of IoT-based cold chain monitoring systems, including system architecture, working mechanisms, applications, advantages, challenges, and future prospects. The study highlights how IoT-enabled intelligent management can reduce spoilage, improve supply chain transparency, and enhance food safety standards.

Keywords: IoT, Cold Chain Management, Smart Sensors, Food Safety, Post-Harvest Losses, Supply Chain

1. Introduction

India is one of the largest producers of fruits, vegetables, milk, and other perishable commodities. Despite high production levels, the country faces substantial post-harvest losses, estimated to be around 15–30% due to poor storage, transportation, and lack of real-time monitoring systems. The cold food chain, which includes storage, transportation, and distribution under controlled temperature conditions, is crucial for maintaining the quality and extending the shelf life of perishable products.

Traditional cold chain systems rely on manual monitoring and lack real-time data tracking, which often leads to temperature fluctuations and product spoilage. The emergence of IoT technology has revolutionized this sector by enabling automated, data-driven, and intelligent monitoring systems.

IoT refers to a network of interconnected physical devices embedded with sensors, software, and communication technologies that collect and exchange data. In cold chain management, IoT facilitates continuous

monitoring, predictive analysis, and automated control, ensuring optimal storage conditions throughout the supply chain.

2. Materials and Methods / System Architecture

2.1 Overall System Design

The IoT-based cold chain system is composed of multiple layers:

- ❖ Sensing Layer – Data collection using sensors
- ❖ Network Layer – Data transmission
- ❖ Processing Layer – Cloud computing and analytics
- ❖ Application Layer – User interface and control systems

2.2 Sensing Layer (Data Acquisition)

Sensors are the backbone of IoT systems. Common sensors used include:

- **Temperature Sensors:** Monitor storage temperature (critical for perishables)
- **Humidity Sensors:** Maintain moisture levels
- **Gas Sensors:** Detect CO₂, ethylene (important for fruit ripening)
- **Light Sensors:** Monitor exposure conditions
- **GPS Modules:** Track location of transport vehicles

These sensors continuously collect environmental data at defined intervals.

2.3 Network Layer (Communication Technologies)

The collected data is transmitted through various communication technologies:

- **Wi-Fi:** Suitable for short-range indoor monitoring
- **GSM/4G/5G:** Used in transportation systems
- **LoRaWAN:** Ideal for long-range, low-power rural applications
- **Bluetooth & Zigbee:** Used for short-range connectivity

2.4 Processing Layer (Cloud and Data Analytics)

- Data is stored in cloud servers
- Real-time processing and analysis
- Historical data storage for trend analysis
- Integration with Artificial Intelligence (AI) and Machine Learning (ML)

2.5 Application Layer (User Interface)

- Mobile apps and dashboards
- Real-time alerts (SMS, email)
- Decision support systems
- Automated control (cooling systems)

2.6 Working Mechanism

- Sensors collect environmental data continuously
- Data is transmitted via network to cloud servers
- Cloud platform processes and analyzes the data
- Alerts are generated if parameters exceed safe limits
- Automated systems adjust cooling or notify operators

3. Results and Discussion

3.1 Applications of IoT in Cold Food Chain

3.1.1 Cold Storage Units

- Smart refrigeration systems
- Automated temperature control
- Inventory management

3.1.2 Transportation Systems

- Refrigerated trucks with real-time monitoring
- GPS-based route optimization
- Condition tracking during transit

3.1.3 Retail and Distribution

- Smart refrigerators in supermarkets
- Quality monitoring at retail points

3.1.4 Dairy and Fisheries Sector

- Milk chilling units monitoring
- Fish preservation using temperature sensors

3.2 Benefits of IoT-Based Cold Chain

- Reduction in Post-Harvest Losses: Continuous monitoring prevents spoilage
- Improved Food Quality: Maintains optimal conditions
- Real-Time Alerts: Immediate response to system failures
- Traceability: Track product from farm to consumer
- Cost Efficiency: Reduces waste and energy consumption
- Data-Driven Decisions: Improves operational efficiency

3.3 Challenges and Limitations

- High Initial Cost: Installation and maintenance
- Connectivity Issues: Rural and remote areas
- Data Security Risks: Cybersecurity concerns
- Technical Knowledge Gap: Farmers and stakeholders need training
- Power Supply Issues: Reliable electricity is required

3.4 Case Example (India Context)

- In India, dairy cooperatives and cold storage facilities are increasingly adopting IoT technologies. For example:
- Milk collection centers use temperature sensors to ensure milk quality
- Fruit exporters use IoT-enabled containers for maintaining export quality
- Fisheries sector uses smart monitoring for fish preservation
- These implementations have shown a significant reduction in spoilage and improved product **quality**.

4. Conclusion

IoT-based cold chain monitoring systems represent a significant advancement in the agricultural and food supply sector. By enabling real-time monitoring, predictive analysis, and intelligent decision-making, these systems help reduce post-harvest losses and improve food safety. Despite challenges such as cost and connectivity, the future of IoT in cold chain management is promising, especially with increasing government support and technological advancements. Adoption of these systems will play a crucial role in ensuring food security and enhancing farmer income in India.

5. Future Scope

- Integration with Artificial Intelligence (AI) for predictive analytics
- Use of Blockchain technology for transparency
- Development of low-cost IoT devices for farmers
- Smart packaging with embedded sensors
- Government-supported digital agriculture programs.

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Enhanced production technology of Groundnut through integrated crop management



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A methodical strategy for closing the "yield gap" between research findings and actual farm productivity is Integrated Crop Management (ICM) in Groundnut using Cluster Frontline Demonstrations (CFLD) during Kharif-2024. When compared to conventional farming methods, these demonstrations usually produce a 20% to 35% increase in production by applying a whole package of better agronomic approaches.

Background information about farmer field: Previous crop was Cumin and Mustard, Nitrogen (N) and Phosphorus (P) status was low and Potassium (K) status was medium.

Details of technology demonstrated:

- (1) Use of improved variety GJG-32 (2018) @ 100 kg/ha.
- (2) Seed treatment with Carbendazim (50% WP) @ 3 g /kg seed.
- (3) Line sowing in 30x10 cm row and plant spacing.
- (4) Use of recommended Nitrogen (N) @ 20 kg/ha and Phosphorus (P) @ 40 kg/ha.
- (5) Application of Fipronil (0.3%GR) @ 12.5 kg/ha for termite management.
- (6) Application of Zinc sulphate (33%) @ 6.25 kg/ha, Sulphur (80% WDG) @ 6.25 kg/ha and NPK (18:18:18) @ 2.5 kg/ha for nutrient management.
- (7) Use of Waste decomposer @ 50g/ha.
- (8) Use of Imidacloprid (17.8% SL) @ 250 ml/ha for management of sucking pest.

Institutional involvement: KVK, Nagaur-I performed CFLD in Kharif-2024 on Groundnut under NFSM-oilseed. Shri Kheta ram participated in KVK trainings to learn about the technologies for higher productivity of Groundnut crop. KVK provided critical inputs. KVK scientists provided advisory for technical guidance as per need. He was urged to save the produce as seed for the next season by KVK experts.



Training and inputs distribution to CFLD partner farmers at KVK, Nagaur-I

Success point: Increase in yield and got good market price due to bright bold seed.

Farmer feedback:

- ❖ Farmers appreciated the Groundnut variety GJG-32 due to better yield.
- ❖ Training and distribution of inputs had been done before sowing of groundnut crop.
- ❖ Low insect-pest incidences due to seed treatment and pesticides application.



Field visit on CFLD- Groundnut at Madhaniyon ki dhani

Outcome yield: Potential yield of variety is 33.92 qtls/ha, District average yield is 17.58 qtls/ha and State average is 19.66 qtls/ha

Table: 1 Performance of technology vis-a-vis Local check (Increase in productivity and returns)

Specific Technology	Yield (q/ha)	Gross cost (Rs/ha)	Gross income (Rs/ha)	Net income (Rs/ha)	B:C ratio
Farmer practices	21.64	41054	154578	113524	3.77
Demonstration	27.65	42300	198485	156185	4.69
% Increase/different	27.77%	1246	43907	42661	0.92

Conclusion: Local adoption is sparked by the CFLD programs, which are frequently run by Krishi Vigyan Kendra (KVK) in the area. They show a large "Extension Gap" (gap between demonstration and farmer yields), emphasizing that ignorance rather than environmental limitations is the primary cause of low productivity. Successful demonstrations often result in "horizontal spread," when other farmers adopt the new variety with Integrated crop management (ICM) after observing the cluster plots' profitability.

Agronomic Practices to Improve Seed Quality and Germination

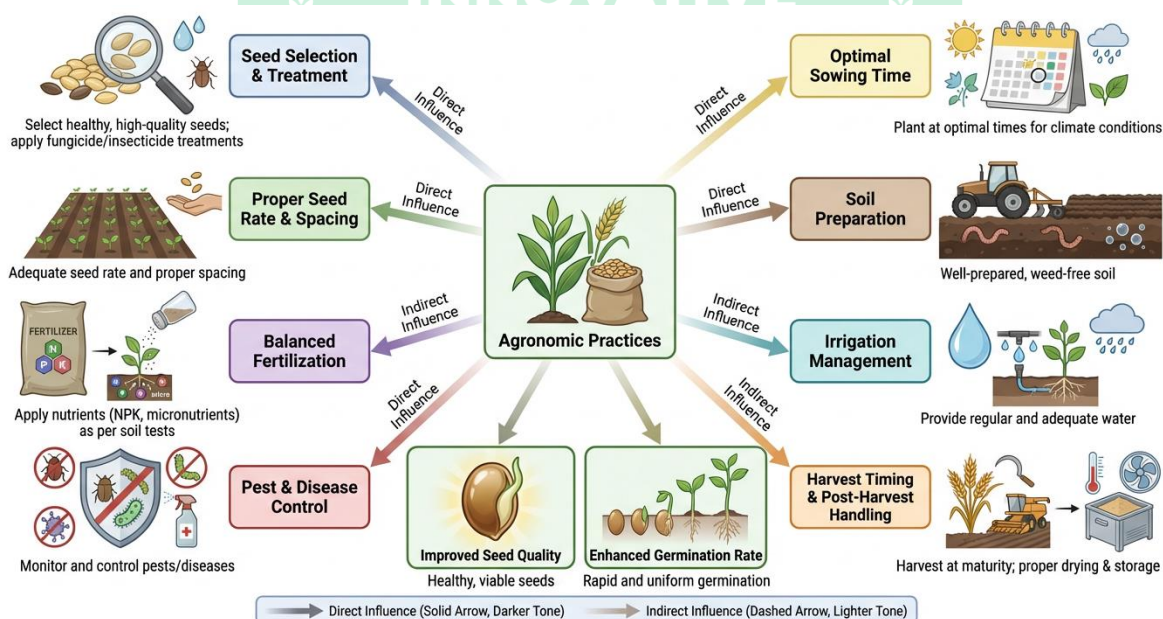


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1. Introduction

Seed quality and germination are fundamental determinants of successful crop establishment, uniformity, and overall agricultural productivity. High-quality seeds possess intrinsic attributes such as viability, vigor, purity, and physiological integrity, which collectively ensure rapid and uniform emergence, robust seedling growth, and resilience under diverse environmental stresses. Seed quality directly influences crop stand uniformity, stress tolerance, and yield potential, making it a critical focus in agronomic management. Enhancing seed quality involves not only selecting genetically superior and physiologically sound seeds but also implementing integrated agronomic practices such as seed treatments, optimized soil and environmental management, precise sowing techniques, and vigilant post-sowing care. These practices improve germination rates, protect seeds from pathogens and pests, and create favorable conditions for seedling establishment. Additionally, innovations in seed technology, including advanced coatings, biological treatments, and precision agriculture tools, further elevate seed performance. Addressing challenges such as environmental variability, resource limitations, and knowledge gaps through education, infrastructure development, and policy support is essential for maximizing the benefits of improved seed quality. This comprehensive approach underpins resilient cropping systems and sustainable agricultural intensification, ultimately contributing to global food security.



2. Seed Quality: Definition and Components

Seed quality is a multidimensional attribute that determines a seed's ability to germinate and develop into a healthy seedling under variable conditions. It includes:

- Viability:** The intrinsic ability of a seed to germinate and produce a normal seedling.
- Vigor:** The capacity for rapid, uniform emergence and robust seedling growth, reflecting seed metabolic activity and resilience.

- 3) **Purity:** The proportion of seed free from contaminants such as weed seeds, inert matter, or damaged seeds.
- 4) **Physical Integrity:** Absence of mechanical damage, cracks, or deformities that impede water uptake or embryo development.
- 5) **Physiological Integrity:** Optimal moisture content, metabolic readiness, and genetic stability.
- 6) **Genetic Purity:** Maintenance of varietal characteristics ensuring desired agronomic traits.

3. Seed Selection and Genetic Improvement

The foundation for improving seed quality and germination lies in selecting genetically superior and physiologically sound seeds:

- 1) **Certified Seeds:** Use of certified seeds guarantees genetic purity, high germination percentage, and freedom from seed-borne diseases. Certification protocols ensure adherence to stringent quality standards.
- 2) **Hybrid Seeds:** Hybrids exhibit heterosis, leading to enhanced vigor, uniformity, and stress tolerance, thereby improving germination and seedling establishment.
- 3) **Seed Source and Storage:** Seeds harvested at physiological maturity from reputable sources and stored under optimal conditions (cool, dry, pest-free) maintain viability and vigor over extended periods.
- 4) **Genetic Improvement Programs:** Breeding efforts focus on traits affecting seed performance, such as dormancy regulation, seed coat permeability, and abiotic stress tolerance (drought, salinity, temperature extremes), enhancing germination success under variable environments.
- 5) **Adaptation to Local Conditions:** Selecting seeds adapted to specific agro-climatic zones improves compatibility with environmental factors, reducing germination failures.

4. Seed Treatments to Enhance Germination and Seedling Establishment

Seed treatments are pre-sowing interventions aimed at overcoming dormancy, accelerating metabolic activation, and protecting seeds from pathogens and pests.

4.1 Physical Treatments

- 1) **Scarification:** Mechanical (abrasion, nicking) or chemical (acid) scarification breaks hard seed coats, facilitating water imbibition and gas exchange, crucial for species with impermeable seed coats.
- 2) **Soaking and Priming:** Controlled hydration initiates enzymatic and physiological processes without radicle protrusion, improving germination speed and uniformity. Methods include:
 - Hydropriming (soaking in water)
 - Osmopriming (using osmotic solutions like polyethylene glycol)
 - Matrix priming (using solid carriers)
- 3) **Thermal Treatments:** Exposure to heat (hot water treatment) or cold stratification breaks dormancy and reduces pathogen load.

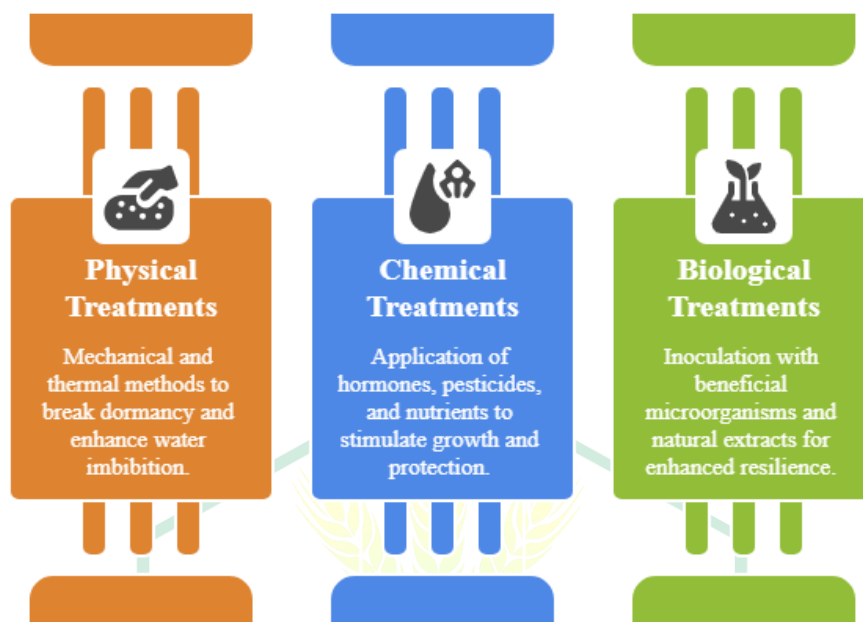
4.2 Chemical Treatments

- 1) **Growth Regulators:** Application of hormones such as gibberellic acid (GA₃), cytokinins, and auxins stimulates germination and seedling growth by modulating physiological pathways.
- 2) **Fungicides and Insecticides:** Protect seeds from soil-borne pathogens and pests during germination and early growth, reducing seedling mortality.
- 3) **Nutrient Coatings:** Application of micronutrients (zinc, boron, manganese) on seeds supplies essential elements during critical early growth phases, enhancing enzymatic activity and stress tolerance.

4.3 Biological Treatments

- 1) **Bio-priming:** Inoculation with beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, or *Trichoderma* spp. enhances nutrient uptake, disease resistance, and abiotic stress tolerance.
- 2) **Biostimulants:** Application of natural extracts (seaweed, humic acids) or microbial metabolites improves seed metabolism, vigor, and stress resilience.

Seed Treatment Strategies



5. Soil and Environmental Management for Optimal Germination

Seed germination and seedling establishment are highly sensitive to soil and environmental conditions, which can be optimized through targeted agronomic practices.

5.1 Soil Preparation

- 1) **Tillage:** Proper seedbed preparation creates a fine, firm seedbed ensuring good seed-soil contact, aeration, and moisture retention, critical for imbibition and radicle emergence. Conservation tillage can be adapted to maintain soil structure and microbial activity while reducing erosion.
- 2) **Soil Moisture Management:** Irrigation scheduling and moisture conservation techniques such as mulching, cover cropping, and conservation tillage maintain optimal soil moisture for germination.
- 3) **Soil Temperature Regulation:** Mulching and timing sowing to coincide with favorable temperature ranges support metabolic activity essential for seed germination.

5.2 Nutrient Management

- 1) **Pre-sowing Fertilization:** Application of basal nutrients based on soil testing ensures nutrient availability during early seedling growth, supporting enzymatic functions and growth.
- 2) **Micronutrient Supplementation:** Addressing deficiencies (e.g., zinc, iron) through soil amendments or seed coatings enhances enzymatic activity and stress tolerance during germination.

5.3 Weed, Pest, and Disease Control

- 1) **Weed Management:** Pre-sowing herbicides and mechanical control reduce competition for water, nutrients, and light during seedling establishment.
- 2) **Soil Sanitation:** Removal of crop residues and pathogen inoculum limits disease incidence.
- 3) **Integrated Pest Management (IPM):** Combining biological, cultural, and chemical controls protects seedlings from pests and diseases.

6. Sowing Techniques and Depth

Accurate sowing methods optimize seed placement, depth, and spacing, directly influencing germination success and seedling vigor.

- 1) **Optimal Sowing Depth:** Seeds must be placed at depths that provide adequate moisture and oxygen while preventing seedling smothering or energy depletion. For maize and similar crops, depths typically range from 2 to 5 cm.
- 2) **Sowing Density and Spacing:** Appropriate seed rates and spacing prevent overcrowding, reduce intra-specific competition, and promote uniform emergence.
- 3) **Precision Sowing Equipment:** Use of calibrated mechanical planters ensures accurate seed placement, minimizes seed damage, and enhances stand uniformity.
- 4) **Site-Specific Adjustments:** Precision agriculture technologies allow dynamic adjustment of sowing depth and density based on spatial soil variability and historical yield data.

7. Post-Sowing Management for Seedling Establishment

Post-sowing agronomic practices are essential to support seedling survival, growth, and resilience during the vulnerable early stages.

- 1) **Irrigation Management:** Maintaining consistent soil moisture during emergence prevents seedling desiccation and promotes uniform growth.
- 2) **Mulching:** Conserves soil moisture, moderates temperature fluctuations, suppresses weed growth, and improves soil microbial activity.
- 3) **Early Nutrient Application:** Foliar feeding or side dressing supplies readily available nutrients to rapidly growing seedlings, enhancing metabolic functions and stress tolerance.
- 4) **Field Monitoring and Early Intervention:** Regular scouting enables timely detection and management of pests, diseases, or abiotic stresses, reducing seedling mortality and supporting robust crop establishment.

Table 1: Agronomic and Post-Harvest Practices for Enhancing Seed Quality and Germination

Practice	Approach Type	Mechanism of Action	Impact on Seed Quality/Germination (%)	Outcome
Seed Treatment (Chemical/Biological)	Protective	Controls seed-borne pathogens	15–30% increase in germination	Healthy seedlings
Proper Drying	Post-harvest	Reduces seed moisture content	10–25% improvement	Enhanced storage life
Optimal Storage Conditions	Storage management	Maintains low temperature and humidity	20–40% viability retention	Reduced deterioration
Priming Techniques (Hydro/Osmo-priming)	Physiological	Activates metabolic processes	10–30% faster and uniform germination	Improved emergence
Use of Growth Regulators	Chemical	Enhances enzyme activity	10–20% improvement	Better seedling vigor
Grading and Sorting	Physical	Removes damaged and small seeds	10–15% increase	Uniform germination
Use of Biofertilizers	Biological	Enhances early nutrient uptake	10–20% improvement	Strong seedling growth

8. Storage and Handling Practices to Maintain Seed Quality

Proper seed storage and handling preserve seed viability and vigor prior to sowing.

- 1) **Moisture Control:** Maintaining seed moisture below critical thresholds (usually 8-12%) prevents fungal growth and deterioration.
- 2) **Temperature Management:** Cool, stable storage temperatures reduce metabolic activity, prolonging seed shelf life.
- 3) **Pest Protection:** Use of sealed containers, fumigation, or natural repellents prevents insect damage.
- 4) **Handling Practices:** Minimizing mechanical damage during transportation and loading preserves seed integrity.

9. Innovations in Seed Technology and Precision Agriculture

Emerging technologies enhance seed quality and germination through improved treatment, monitoring, and management.

- 1) **Advanced Seed Coatings:** Incorporate nutrients, biostimulants, protective agents, and microbial inoculants to enhance seed performance and stress tolerance.
- 2) **Nanotechnology:** Nanoparticles improve targeted delivery of nutrients and pesticides, reducing environmental impact and enhancing efficacy.
- 3) **Molecular Breeding and Biotechnology:** Genetic engineering and marker-assisted selection develop varieties with improved dormancy control, vigor, and abiotic stress tolerance.
- 4) **Sensor-Based Monitoring:** Imaging, spectroscopy, and biochemical sensors provide real-time assessment of seed health, viability, and germination potential.
- 5) **Automation and Precision Agriculture:** Robotics, artificial intelligence, and data analytics enable precise seed sorting, treatment, and sowing, improving uniformity and reducing labor.

10. Overcoming Challenges through Education, Infrastructure, and Accessibility

Despite advances, several challenges affect adoption and effectiveness of agronomic practices for seed quality improvement:

10.1 Environmental Variability

Unpredictable weather patterns, soil heterogeneity, and climatic stresses can affect germination outcomes despite best practices, requiring adaptive management and resilient seed varieties.

10.2 Resource Limitations

Smallholder farmers often lack access to quality seeds, treatments, precision equipment, or irrigation infrastructure, limiting adoption of advanced practices.

10.3 Cost-Benefit Analysis

Economic evaluation is essential to ensure investments in seed treatments, technology, and management practices yield sufficient returns, especially in resource-constrained settings.

10.4 Knowledge and Training

Extension services, farmer education programs, and participatory research are critical for disseminating best practices and innovations.

10.5 Infrastructure Development

Seed storage facilities, quality control laboratories, and supply chains enhance seed quality preservation and availability.

10.6 Policy Support and Capacity Building

Government policies, subsidies, and capacity-building initiatives facilitate technology adoption and infrastructure development.

11. Integration of Agronomic Components for Enhanced Seed Performance

Integrating quality seed selection, effective seed treatments, optimized soil and environmental management, precise sowing, and vigilant post-sowing care creates a synergistic agronomic framework. This integration ensures seeds germinate rapidly and uniformly, developing into vigorous seedlings capable of withstanding biotic and abiotic stresses. Such a comprehensive approach maximizes resource use efficiency, crop establishment, and yield potential.

12. Contribution to Resilient Cropping Systems and Global Food Security

Improved seed quality and germination underpin resilient cropping systems by enhancing crop establishment, uniformity, and stress tolerance. These factors contribute to stable yields, resource conservation, and sustainable intensification of agriculture. Adoption of integrated agronomic practices and innovative technologies supports global food security by increasing productivity and resilience in the face of growing population pressures and climate change.

13. Conclusion

Agronomic practices to improve seed quality and germination are vital for uniform crop establishment, high productivity, and sustainable agriculture. Integrating quality seed selection, effective seed treatments, optimized soil and environmental management, precise sowing techniques, and vigilant post-sowing care creates favorable conditions for seed performance and crop establishment. Innovations in seed technology and precision agriculture complement these practices, enhancing resource use efficiency and resilience. Overcoming adoption challenges

through education, infrastructure, and accessible technologies will enable broader implementation, contributing to global food security and resilient cropping systems.

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Biochar as a Climate Mitigation Tool: Longevity, Stability, and Influence on Nitrous Oxide Emissions



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Introduction

Biochar, a carbon-rich material produced through the pyrolysis of organic biomass in oxygen-limited conditions, has garnered significant attention as a sustainable climate mitigation strategy. Its multifaceted benefits encompass long-term carbon sequestration, enhancement of soil fertility, and modulation of greenhouse gas (GHG) emissions, particularly nitrous oxide (N_2O), which is recognized for its high global warming potential. This comprehensive review delves into the scientific understanding of biochar's production, properties, persistence in soils, and its influence on N_2O emissions, elucidating the mechanisms involved, empirical evidence, challenges, and future research directions.

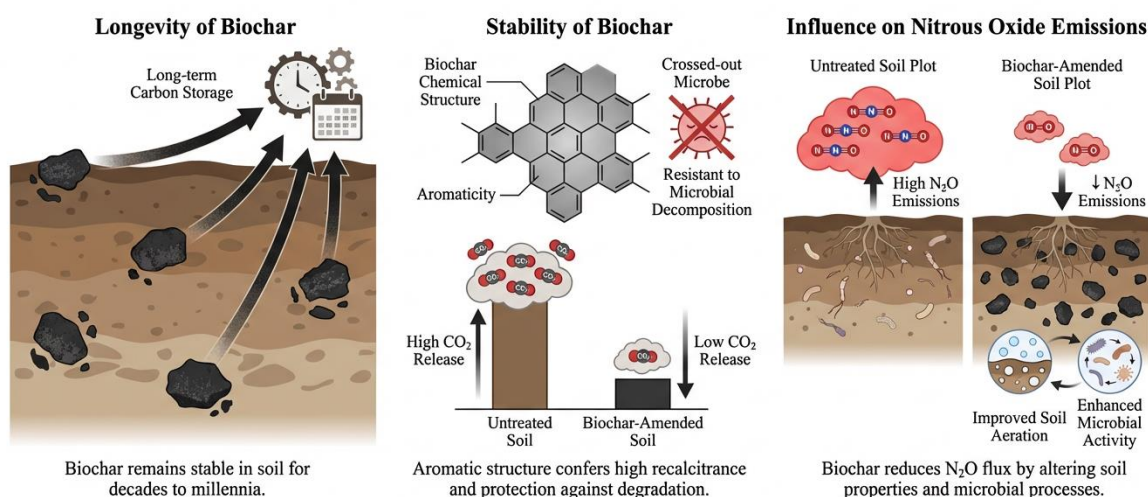


Figure 1: Biochar as a Climate Mitigation Tool: Longevity, Stability, and Influence on Nitrous Oxide Emissions

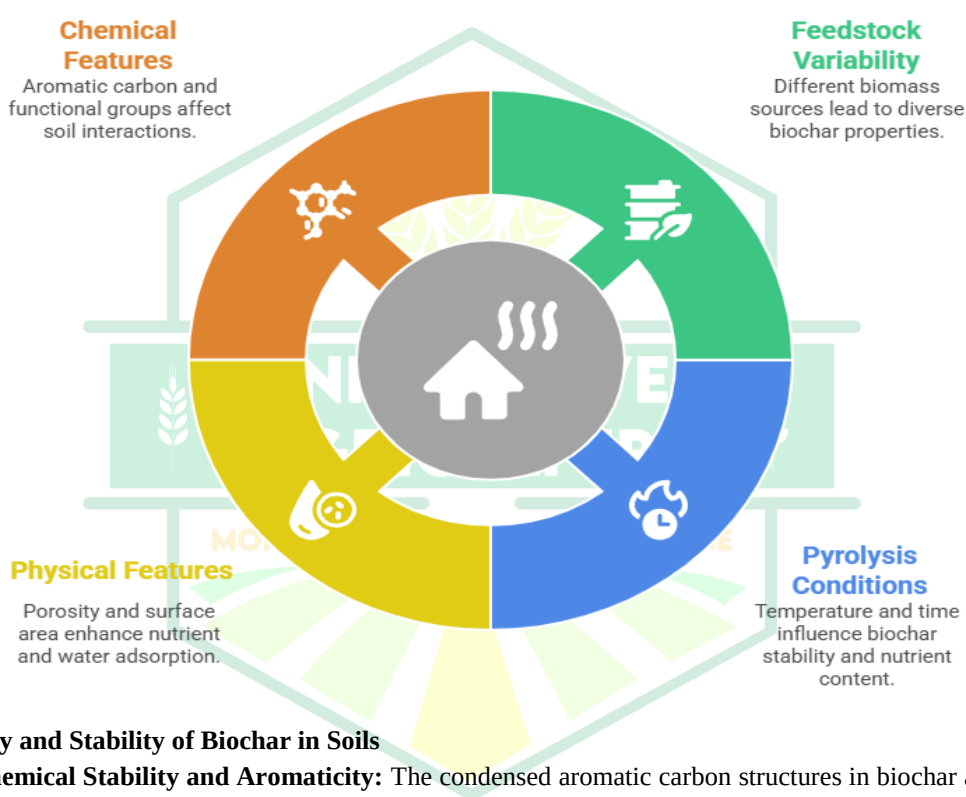
1. Biochar Production and Characteristics

- Feedstock Variability:** Biomass sources used for biochar production vary widely, including agricultural residues (e.g., corn stover, rice husks), forestry by-products (e.g., wood chips, sawdust), and animal manures. Each feedstock imparts distinct elemental compositions, nutrient profiles, and structural features to biochar. For instance, woody biomass typically yields biochars with higher carbon content and aromaticity, whereas manure-based biochars often contain higher nutrient concentrations but lower stability. The choice of feedstock not only influences the physicochemical properties of biochar but also affects its environmental interactions and efficacy in soil amendment. Furthermore, feedstock availability and sustainability are critical considerations for large-scale biochar production.
- Pyrolysis Conditions:** The temperature, heating rate, and residence time during pyrolysis are pivotal in shaping biochar properties. Low-temperature pyrolysis (300–400°C) tends to preserve more labile carbon and nutrients, resulting in biochars with higher cation exchange capacity but lower stability. Conversely, high-temperature pyrolysis (>600°C) enhances the formation of condensed aromatic structures, increasing chemical recalcitrance and longevity but often reducing nutrient availability. Slow pyrolysis favors the production of biochar with greater surface area and porosity compared to fast

pyrolysis. The optimization of pyrolysis parameters allows tailoring biochar characteristics for specific soil and environmental requirements, balancing nutrient retention and carbon stability.

3. **Physical and Chemical Features:** Biochar exhibits a porous matrix with a high surface area, facilitating adsorption of nutrients and water. Chemically, it is rich in aromatic carbon rings, resistant to microbial breakdown. The pH of biochar is commonly alkaline, which can influence soil acidity upon application. Mineral ash content varies and contributes to nutrient supply and interaction with soil minerals. The surface functional groups, such as carboxyl, hydroxyl, and phenolic groups, play a significant role in biochar's cation exchange capacity and its ability to interact with soil constituents and pollutants. These properties collectively determine biochar's behavior in soil environments, including nutrient cycling and microbial habitat provision.

Biochar Production and Characteristics



2. Longevity and Stability of Biochar in Soils

1. **Chemical Stability and Aromaticity:** The condensed aromatic carbon structures in biochar are highly resistant to microbial enzymatic degradation and chemical oxidation. This molecular configuration is a key determinant of biochar's recalcitrance. Analytical techniques such as nuclear magnetic resonance (NMR) spectroscopy have confirmed that higher aromaticity correlates with increased biochar stability. The chemical inertness of these structures slows biochar decomposition, enabling long-term carbon sequestration. However, the presence of labile carbon fractions in some biochars can lead to initial microbial mineralization, influencing short-term carbon dynamics.
2. **Physical Protection and Soil Interactions:** Beyond chemical recalcitrance, biochar's porous architecture offers physical protection to organic carbon by shielding it within micro- and nano-pores. Additionally, biochar particles interact with soil minerals, forming organo-mineral complexes that further stabilize carbon. These complexes reduce biochar's bioavailability and decomposition rates. The sorption of soil organic matter onto biochar surfaces can create a protective environment that limits microbial access and enzymatic degradation. Biochar's role in modifying soil aggregation also contributes to physical protection of sequestered carbon.

3. **Environmental Influences:** Soil properties such as texture, pH, moisture content, and microbial community structure significantly impact biochar degradation. For example, biochar tends to persist longer in acidic, sandy soils with low microbial activity compared to fertile, moist soils with high microbial biomass. Climatic factors, including temperature and precipitation patterns, also modulate biochar stability. Seasonal variations and land management practices can further influence biochar decomposition rates. Understanding these environmental interactions is crucial for predicting biochar's long-term carbon sequestration potential across diverse ecosystems.
4. **Estimated Persistence:** Empirical studies using radiocarbon dating and incubation experiments estimate biochar half-lives ranging from several decades to thousands of years. This wide range reflects variability in biochar types and environmental conditions. The long residence time underscores biochar's suitability as a durable carbon sink in terrestrial ecosystems. Modeling studies suggest that biochar's carbon sequestration potential could significantly contribute to global climate mitigation efforts if applied at scale, particularly in agricultural soils.

Table 1: Longevity and Stability of Biochar in Soil Systems

Parameter	Description	Key Mechanism	Reported Range / Values	Implication for Climate Mitigation
Mean Residence Time (MRT)	Duration biochar persists in soil	Aromatic C structure resists decomposition	100–1000+ years	Long-term carbon sequestration
Carbon Stability Fraction	Proportion of recalcitrant carbon	High degree of carbonization during pyrolysis	60–90% stable C	Reduces CO ₂ release
Pyrolysis Temperature Effect	Higher temperature increases stability	Formation of condensed aromatic rings	400–700°C optimal	Enhances persistence in soil
Decomposition Rate	Rate of biochar mineralization	Microbial resistance and chemical recalcitrance	<1–3% per year	Minimal carbon loss
Soil Interaction	Interaction with minerals and aggregates	Organo-mineral complex formation	Strong in clay soils	Further stabilization of SOC
Surface Oxidation Over Time	Aging increases functional groups	Oxidation enhances cation exchange capacity	Increases over years	Improves nutrient retention
Environmental Factors	Moisture, temperature, and soil type influence stability	Abiotic and biotic processes	Site-specific variability	Affects long-term sequestration efficiency

3. Mechanisms of Nitrous Oxide Emission Reduction

1. **Improved Soil Aeration and Moisture Dynamics:** Biochar's porous structure enhances soil aeration by increasing pore connectivity and water infiltration. Improved oxygen diffusion reduces anaerobic microsites where denitrification—a primary N₂O-producing process—occurs. Furthermore, biochar's water retention capacity buffers soil moisture fluctuations, mitigating conditions conducive to N₂O emissions. These physical changes create a more aerobic soil environment that favors complete denitrification to nitrogen gas (N₂) rather than partial reduction to N₂O.
2. **Soil pH Modulation:** Biochar often raises soil pH, shifting microbial community composition and enzymatic activities. Elevated pH tends to suppress the activity of nitrous oxide reductase inhibitors, promoting the reduction of N₂O to benign nitrogen gas (N₂). This pH effect can vary depending on initial soil acidity and biochar alkalinity. In acidic soils, biochar application can alleviate soil acidity, enhancing microbial processes that reduce N₂O emissions. However, excessive alkalinity may have adverse effects on certain soil biota, indicating the need for balanced application rates.
3. **Alteration of Microbial Communities:** Biochar influences the abundance and diversity of nitrifying and denitrifying microorganisms. By adsorbing substrates such as ammonium and nitrate, biochar alters nitrogen availability, potentially reducing substrate concentrations that fuel N₂O production.

Additionally, biochar may adsorb microbial signaling molecules, affecting gene expression related to nitrogen cycling. Studies employing molecular biology techniques, such as qPCR and metagenomics, have demonstrated shifts in microbial functional groups associated with nitrogen transformations following biochar amendment.

4. **Nutrient Retention and Adsorption:** The high surface area and cation exchange capacity of biochar enable it to adsorb ammonium (NH_4^+) and nitrate (NO_3^-) ions, decreasing their leaching and availability for microbial transformation into N_2O . This retention enhances nitrogen use efficiency and reduces nitrogen losses. By immobilizing nitrogen in soil, biochar reduces the substrate pool for nitrification and denitrification, thereby mitigating N_2O emissions. Additionally, nutrient retention improves plant uptake, further reducing excess nitrogen in the soil.
5. **Electron Shuttle and Redox Reactions:** Certain biochars contain redox-active functional groups that can facilitate electron transfer during denitrification, promoting the complete reduction of N_2O to N_2 . This electron shuttle effect is an emerging area of research with implications for biochar design. Electron shuttling may enhance microbial respiration efficiency and influence soil redox potential, thereby affecting nitrogen cycling dynamics. Engineering biochars with enhanced redox properties offers a promising avenue for targeted mitigation of N_2O emissions.

4. Empirical Evidence on Biochar's Impact on N_2O Emissions

1. **Range of Emission Reductions:** Reported reductions in N_2O emissions following biochar amendment vary widely, from negligible effects to decreases exceeding 90%. This variability stems from differences in biochar properties, soil types, crop systems, climatic conditions, and experimental methodologies. The heterogeneity of study designs, including differences in biochar application rates and measurement techniques, contributes to inconsistent findings.
2. **Influencing Factors:** Feedstock source and pyrolysis temperature affect biochar's chemical attributes and thus its efficacy in mitigating N_2O emissions. Application rates and methods (e.g., surface application versus incorporation) influence biochar-soil interactions. Soil nitrogen status is critical; biochar tends to be more effective in nitrogen-rich soils where denitrification is prevalent. Crop type and management practices also modulate the response of N_2O emissions to biochar.
3. **Meta-analytical Insights:** Syntheses of multiple studies generally support an overall trend of N_2O emission reduction with biochar use. However, they emphasize the importance of site-specific assessments and caution against broad generalizations. Meta-analyses highlight the need for standardized methodologies and reporting to enable robust cross-study comparisons.
4. **Transient Emission Dynamics:** Some studies document short-term increases in N_2O emissions immediately after biochar application, attributed to microbial disturbance, enhanced mineralization, or shifts in soil nitrogen pools. These transient effects highlight the need for careful timing and management practices, such as allowing biochar to age before application or combining it with other amendments to stabilize nitrogen pools.

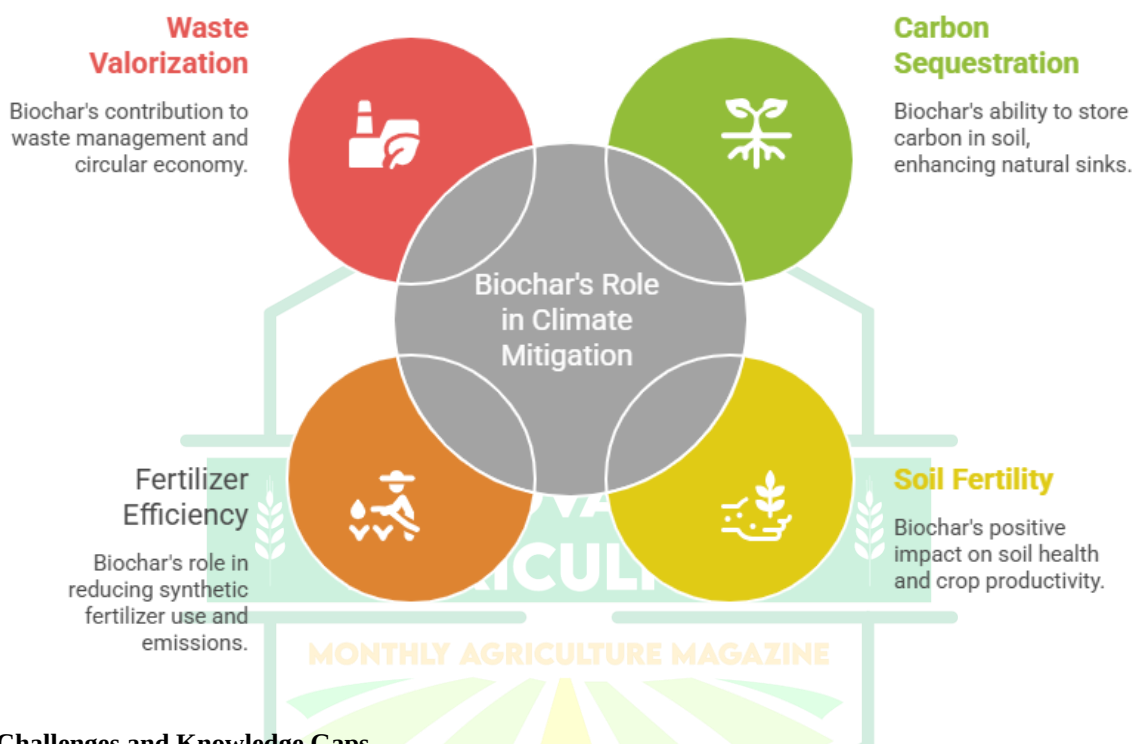
5. Biochar's Role in Integrated Climate Mitigation Strategies

1. **Carbon Sequestration Synergies:** Biochar complements natural carbon sinks such as forests and wetlands by providing a stable, anthropogenic carbon pool in agricultural soils. Its long-term persistence contributes to net negative emissions when integrated with other practices. Incorporating biochar into soil carbon management strategies can amplify mitigation outcomes while supporting ecosystem services.
2. **Soil Fertility and Productivity:** Beyond climate benefits, biochar enhances soil physical properties, nutrient availability, and microbial diversity, supporting sustainable crop production. Improved soil health can increase resilience to climate stressors such as drought and erosion. Enhanced nutrient cycling and water retention contribute to higher crop yields and reduced input requirements, promoting sustainable intensification.
3. **Fertilizer Use Efficiency:** By retaining nitrogen and improving nutrient cycling, biochar can reduce the dependence on synthetic fertilizers, lowering indirect N_2O emissions associated with fertilizer

manufacture and application. This reduction not only mitigates GHG emissions but also offers economic benefits to farmers through decreased fertilizer costs.

4. **Waste Valorization and Circular Economy:** Utilizing agricultural and forestry residues for biochar production diverts biomass from open burning or decomposition pathways that release GHGs. This valorization supports waste management and circular bioeconomy goals. Integrating biochar production with bioenergy generation can further enhance sustainability by creating renewable energy and sequestering carbon simultaneously.

Biochar's Climate Mitigation Framework



6. Challenges and Knowledge Gaps

1. **Standardization and Quality Control:** The lack of standardized production protocols and quality benchmarks complicates comparisons across studies and limits regulatory acceptance. Variability in biochar properties affects reproducibility and predictability of outcomes. Developing certification schemes and quality standards is essential for market development and policy support.
2. **Long-term Field Validation:** Most studies are short-term or conducted under controlled conditions. Long-term, multi-site field trials are essential to confirm biochar's persistence, effects on soil processes, and net climate benefits under real-world conditions. Such studies should encompass diverse agroecosystems and management practices to capture variability.
3. **Mechanistic Understanding:** The complex interactions among biochar, soil biota, and nitrogen cycling pathways require further elucidation. Advanced molecular and isotopic techniques can help unravel microbial mechanisms governing N_2O fluxes. Understanding the interplay between biochar properties and microbial ecology is critical for optimizing biochar design and application.
4. **Economic and Social Considerations:** Cost-effectiveness analyses, farmer perceptions, and policy frameworks influence biochar adoption. Incentives, education, and integration with existing agricultural practices are critical for scaling. Addressing logistical challenges, such as feedstock supply chains and pyrolysis infrastructure, is necessary to enable widespread implementation.

7. Future Directions

1. **Tailored Biochar Engineering:** Designing biochars with specific physical and chemical properties optimized for particular soil types, climates, and crop systems can maximize mitigation efficacy and agronomic benefits. Innovations in pyrolysis technology and feedstock blending can produce customized biochars targeting specific environmental challenges.
2. **Combined Soil Amendments:** Synergistic effects may be achieved by co-applying biochar with compost, fertilizers, or beneficial microbes, enhancing nutrient cycling and GHG mitigation. Integrated amendment strategies can improve soil health while mitigating emissions more effectively than single amendments.
3. **Monitoring and Modeling Advances:** Developing robust monitoring technologies and predictive models will improve understanding of biochar dynamics and support decision-making. Remote sensing, sensor networks, and process-based models can facilitate large-scale assessment of biochar impacts on soil carbon and GHG fluxes.
4. **Policy and Market Mechanisms:** Incorporating biochar into carbon credit schemes and climate policies can incentivize adoption. Clear guidelines and certification systems will facilitate market development. Collaborative efforts among researchers, policymakers, and stakeholders are essential to establish supportive frameworks and promote sustainable biochar deployment.

Conclusion

Biochar stands as a versatile and potent tool in the portfolio of climate change mitigation strategies. Its ability to sequester carbon stably in soils, improve soil health, and modulate nitrous oxide emissions offers multiple pathways to reduce agricultural greenhouse gas footprints. Realizing biochar's full potential requires addressing current knowledge gaps, standardizing production and application practices, and integrating biochar within holistic land management and policy frameworks. Continued interdisciplinary research and stakeholder engagement will be pivotal in harnessing biochar's benefits for sustainable and climate-resilient agriculture.

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Climate Change Impacts on Marine and Inland Fisheries



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Abstract

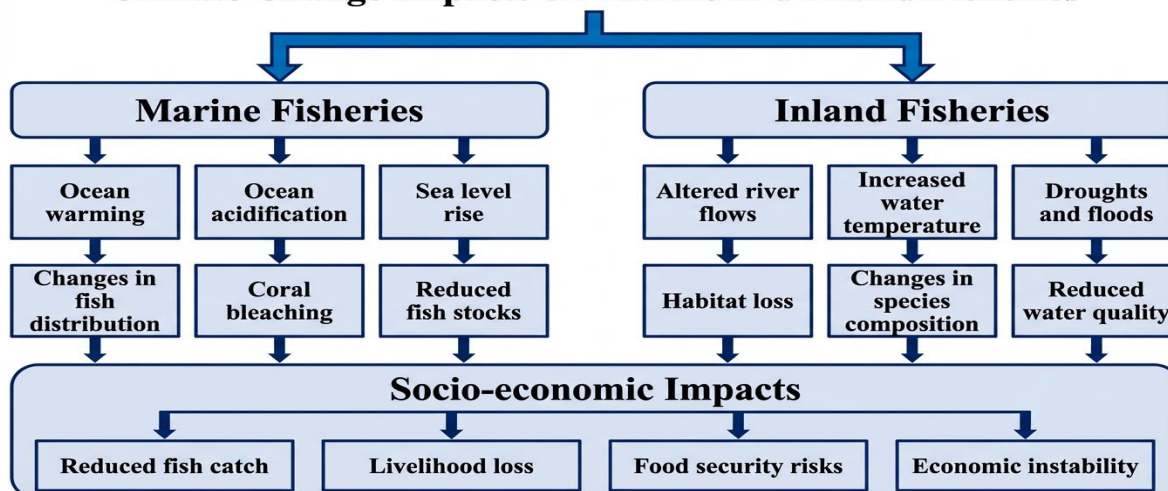
Climate change poses profound and multifaceted threats to marine and inland fisheries worldwide, affecting ecosystem dynamics, species distribution, productivity, and the socio-economic systems reliant on these resources. Rising global temperatures, ocean acidification, altered hydrological cycles, and increased frequency of extreme weather events disrupt aquatic habitats and fish populations, leading to shifts in species composition, declines in fish stocks, and challenges to fisheries management. This comprehensive review examines the ecological, economic, and social dimensions of climate change impacts on fisheries. It further explores adaptive management strategies essential for mitigating adverse effects, enhancing resilience, and ensuring the sustainability of fisheries amid ongoing climatic shifts.

Introduction

Fisheries, encompassing both marine and inland systems, represent a cornerstone of global food security, economic development, and biodiversity conservation. They provide vital protein sources for billions of people, support livelihoods for millions, and contribute significantly to national and international economies. However, climate change has emerged as a critical and complex driver of change within aquatic ecosystems, threatening the stability and productivity of fisheries worldwide. The alterations in temperature regimes, precipitation patterns, ocean chemistry, and the frequency of extreme weather events have cascading effects on fish physiology, behavior, habitat quality, and ecosystem interactions. These changes not only impact fish populations but also disrupt the socio-economic fabric of fishing communities, particularly those dependent on subsistence and small-scale fisheries.

This paper aims to provide an in-depth analysis of the impacts of climate change on marine and inland fisheries, emphasizing the ecological consequences, socio-economic implications, and potential adaptive responses. By synthesizing current knowledge, this review seeks to inform fisheries management and policy development to foster resilience and sustainability in the face of a rapidly changing climate.

Climate Change Impacts on Marine and Inland Fisheries



Impacts of Climate Change on Marine Fisheries

1. Temperature Rise and Species Distribution

Rising sea surface temperatures (SST) are among the most immediate and visible effects of climate change on marine ecosystems. Increased SST influences metabolic rates, growth, reproduction, and survival of marine organisms. Many fish species respond to warming by shifting their geographic ranges, typically moving poleward or to deeper, cooler waters to remain within their thermal tolerance limits. This redistribution disrupts traditional fishery grounds and alters community composition.

For example, commercially valuable species such as cod, haddock, and certain tuna species have exhibited poleward shifts, leading to changes in catch composition and availability for fisheries in temperate zones. These shifts can result in economic losses for communities reliant on species that are moving away, while potentially creating new opportunities in higher latitude regions. However, such range shifts can also lead to increased competition, altered predator-prey dynamics, and ecosystem imbalances.

Thermal stress also influences spawning timing and success, with many species experiencing mismatches between larval fish and plankton blooms, critical for early life stage survival. Moreover, changes in temperature can affect sex ratios in species with temperature-dependent sex determination, potentially impacting population dynamics.

2. Ocean Acidification

The ocean absorbs approximately 30% of anthropogenic CO₂ emissions, leading to a decrease in seawater pH, a process known as ocean acidification. This phenomenon poses significant challenges to marine life, particularly calcifying organisms such as corals, mollusks, and some plankton species, which form the structural basis of marine habitats and food webs.

Reduced calcification rates impair shell and skeleton formation, making these organisms more vulnerable to predation and environmental stress. The decline of coral reefs, often referred to as the "rainforests of the sea," diminishes critical nursery habitats for many fish species, thereby affecting recruitment and population sustainability.

Acidification also affects fish physiology, including sensory functions, behavior, and growth. Larval and juvenile stages are especially sensitive, with studies showing impaired olfactory cues and increased vulnerability to predators. These impacts cascade through food webs, potentially reducing fish biomass and altering community structures.

3. Changes in Ocean Circulation and Productivity

Climate change influences ocean circulation patterns, including major currents, upwelling systems, and thermohaline circulation. These changes affect nutrient distribution, primary productivity, and the overall energy flow within marine ecosystems.

Upwelling zones, which bring nutrient-rich waters to the surface, support some of the world's most productive fisheries. Alterations in the timing, intensity, or location of upwelling can reduce nutrient availability, leading to declines in phytoplankton biomass and subsequent reductions in fish productivity. Furthermore, stratification of the water column due to warming limits vertical mixing, restricting nutrient replenishment in surface waters. This can exacerbate nutrient limitation, decreasing primary production and impacting the entire food chain.

4. Extreme Weather Events

The increased frequency and intensity of extreme weather events such as hurricanes, cyclones, and marine heatwaves have direct and indirect effects on marine fisheries. Physical destruction of habitats, such as coral reefs and seagrass beds, results in loss of shelter and feeding grounds.

Marine heatwaves can cause mass mortality events, coral bleaching, and shifts in species distributions. These events also disrupt fishing operations, damage infrastructure like ports and processing facilities, and increase economic vulnerability.

Table 1: Major Climate Change Drivers and Their Effects on Fisheries

Climate Driver	Change Observed	Impact on Marine Fisheries	Impact on Inland Fisheries
Rising Temperature	Increased sea & water temperature	Species migration, coral bleaching	Altered fish metabolism, reduced growth
Ocean Acidification	Lower pH levels	Shellfish damage, reduced calcification	Minor direct effect, indirect food web impact
Sea Level Rise	Coastal inundation	Loss of breeding habitats (mangroves)	Floodplain alteration
Changing Rainfall	Irregular precipitation	Nutrient imbalance in coastal waters	Water level fluctuation in rivers/lakes
Extreme Events	Cyclones, floods	Habitat destruction, stock loss	Fish mortality, infrastructure damage

Impacts of Climate Change on Inland Fisheries

1. Hydrological Changes

Inland fisheries depend heavily on freshwater ecosystems such as rivers, lakes, reservoirs, and wetlands. Climate change alters hydrological cycles through changes in precipitation patterns, snowmelt timing, and evaporation rates.

Increased variability in rainfall can lead to more frequent droughts or floods, affecting water availability and quality. Reduced river flows and lowered lake levels can shrink habitats, reduce connectivity, and concentrate pollutants.

Altered flow regimes disrupt spawning cues for migratory fish species, impede juvenile dispersal, and increase mortality. Floodplain inundation, critical for breeding and feeding, may decline, reducing habitat complexity and productivity.

2. Temperature Effects on Freshwater Species

Freshwater fish are particularly sensitive to temperature changes due to their limited mobility and often narrow thermal tolerances. Elevated water temperatures can increase metabolic demands, reduce dissolved oxygen levels, and induce physiological stress.

Cold-water species such as trout and salmon are especially vulnerable, facing habitat contraction and local extinctions as suitable thermal refugia diminish. Warmer conditions may favor invasive or warm-water tolerant species, leading to altered community composition and potential loss of biodiversity.

Temperature increases also affect reproductive cycles, growth rates, and susceptibility to diseases and parasites, further threatening freshwater fish populations.

3. Habitat Degradation

Climate change exacerbates habitat degradation in freshwater systems through increased sedimentation, nutrient loading, and proliferation of invasive species.

Intense rainfall and runoff contribute to sediment deposition, smothering spawning grounds and reducing habitat complexity. Nutrient enrichment from agricultural runoff promotes eutrophication, leading to algal blooms, hypoxia, and fish kills.

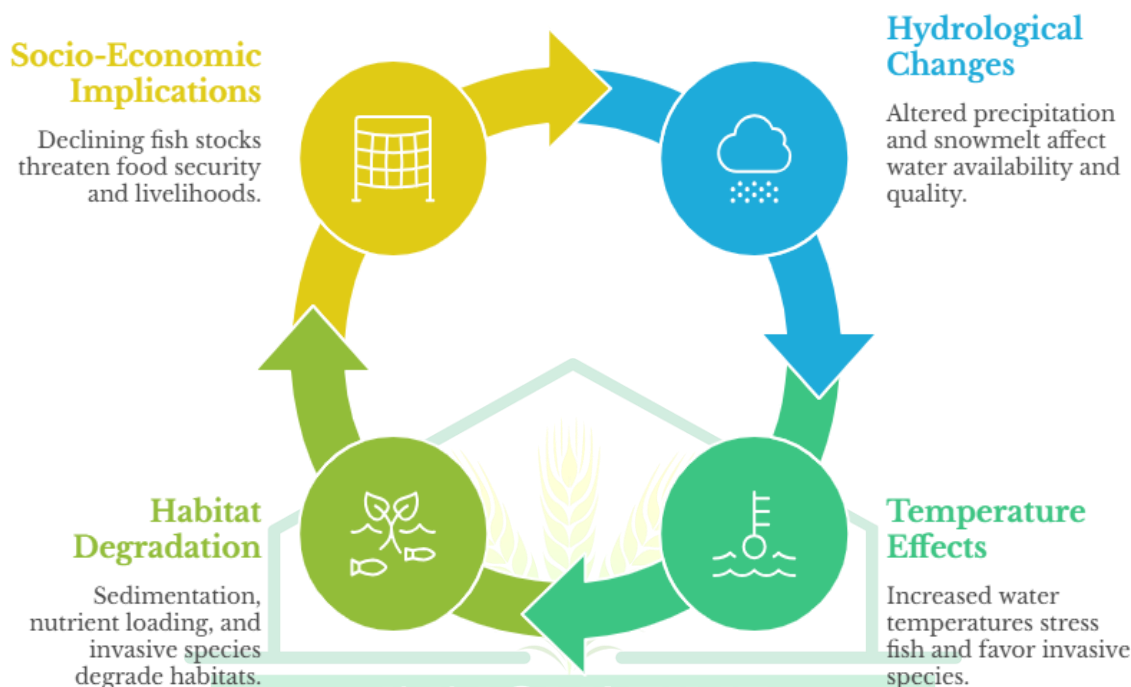
Warmer temperatures and altered flow regimes facilitate the spread of invasive species, which compete with native fish for resources and alter ecosystem dynamics.

4. Socio-Economic Implications

Inland fisheries are crucial for subsistence, nutrition, and income generation, particularly in developing regions. Climate-induced declines in fish stocks threaten food security and livelihoods, disproportionately impacting vulnerable and marginalized communities.

Reduced fish availability can increase malnutrition and poverty, necessitating shifts in livelihood strategies. The loss of cultural and recreational values associated with inland fisheries also affects community well-being.

Climate Change Impacts on Inland Fisheries Cycle



Emerging Threats and Interactions

- Invasive Species and Climate Change**
Climate change facilitates the spread and establishment of invasive aquatic species by altering habitat conditions and reducing the resilience of native species. Invasive species can outcompete native fish, alter food webs, and introduce diseases, compounding the impacts of climate change on fisheries.
- Pollution and Climate Stress Synergies**
Climate change interacts with pollution, such as nutrient runoff and chemical contaminants, exacerbating stress on aquatic ecosystems. Warmer temperatures can increase the toxicity of pollutants and reduce oxygen levels, further impacting fish health and productivity.
- Loss of Genetic Diversity**
Shifts in species distributions and population declines due to climate change can reduce genetic diversity, undermining the adaptive capacity of fish populations to future environmental changes.

Economic and Social Dimensions of Climate Change on Fisheries

- Impacts on Livelihoods and Food Security**
Fisheries provide employment and food for millions, especially in coastal and rural inland communities. Climate-induced changes in fish availability threaten these livelihoods, increasing vulnerability and food insecurity.
- Gender and Social Equity Considerations**
Women often play key roles in small-scale fisheries and fish processing. Climate impacts can disproportionately affect women's income and food access, highlighting the need for gender-sensitive adaptation strategies.
- Market and Trade Implications**
Changes in fish stocks influence supply chains, market prices, and international trade. Variability in catches may lead to economic instability for fishers and associated industries.

Policy and Governance Challenges

1. Integrating Climate Change into Fisheries Management

Current management frameworks often lack explicit incorporation of climate change projections and uncertainties. Integrating climate adaptation into fisheries policies is essential for effective governance.

2. Cross-Boundary and International Cooperation

Many fish stocks are transboundary, requiring coordinated management across jurisdictions. Climate-driven shifts in species distributions complicate governance and necessitate flexible, cooperative arrangements.

3. Funding and Capacity Building

Adequate resources and technical capacity are required to implement adaptive measures, especially in developing countries. International support and knowledge transfer are critical components.

Technological Innovations and Research Needs

1. Advances in Monitoring and Modeling

Improved remote sensing, autonomous underwater vehicles, and ecological modeling enhance understanding of climate impacts and support adaptive management.

2. Selective Breeding and Genetic Tools in Aquaculture

Developing climate-resilient fish strains through selective breeding and biotechnology can improve aquaculture sustainability under changing conditions.

3. Socio-Ecological Research

Interdisciplinary research integrating ecological, economic, and social data is vital to develop holistic adaptation strategies.

Adaptive Strategies and Management

1. Monitoring and Data Collection

Robust monitoring systems are essential to detect changes in fish populations, habitat conditions, and environmental variables. This data supports timely management decisions and adaptive responses.

2. Ecosystem-Based Fisheries Management (EBFM)

EBFM emphasizes the interconnectedness of species, habitats, and human activities. Incorporating climate variability and uncertainty into management plans enhances resilience and sustainability.

3. Climate-Resilient Aquaculture

Developing aquaculture systems tolerant to temperature fluctuations, disease, and water quality changes can supplement wild fisheries and reduce pressure on natural stocks. Diversification of species and production methods increases system flexibility.

4. Policy and Institutional Strengthening

Policies must support adaptive capacity through flexible regulations, resource allocation, and stakeholder participation. Cross-sectoral collaboration enhances coherence and effectiveness.

5. Community Engagement and Knowledge Sharing

Local knowledge and community involvement are vital for identifying vulnerabilities, co-developing solutions, and fostering stewardship. Capacity building and education empower communities to adapt effectively.

6. Ecosystem Restoration and Conservation

Protecting and restoring critical habitats such as mangroves, wetlands, and coral reefs enhances ecosystem resilience and supports fish populations under climate stress.

7. Diversification of Livelihoods

Encouraging alternative income sources reduces dependence on vulnerable fisheries and improves community resilience.

Conclusion

Climate change exerts profound impacts on marine and inland fisheries by altering environmental conditions, species dynamics, and ecosystem functions. These changes threaten fishery sustainability, food security, and economic stability globally. Addressing these challenges necessitates proactive, adaptive management strategies

that integrate ecological, social, and economic considerations. Enhancing resilience through monitoring, ecosystem-based management, climate-resilient aquaculture, supportive policies, technological innovation, and community engagement can mitigate adverse effects and secure the future of fisheries in a changing climate.

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Cost–Benefit and Water-Use Efficiency Analysis of Drip Irrigation in Water-Limited Regions



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1. Introduction

The largest single consumer of freshwater in the world is agriculture, which incurs about 70 per cent of total withdrawals. Water crisis, climate change, and increased water competition are increasingly threatening the sustainability of the traditional irrigation systems in areas where water is a limitation. These areas have arid and semi-arid climates, and the agricultural production and economic stability of such areas mostly depend on irrigation. As such, it is important to find solutions to enhance the water-use efficiency (WUE) as a means of securing food and environmental sustainability.

Micro-irrigation, drip irrigation, which has become a promising technology applied in the optimisation of water use in agriculture, is a micro-irrigation technique that delivers water at the plant root zone in small quantities in frequent intervals. Drip irrigation can also produce high yields, whereas compared to conventional surface irrigation practices (furrow or basin irrigation), which tend to have high water losses due to evaporation, runoff and deep percolation, the method can greatly lower water usage and also keep or even enhance harvest.

In this article, there is a detailed cost-benefit analysis and water-use efficiency of drip irrigation in water-restricted areas. It compares drip irrigation with the conventional irrigation methods, examines the economic aspects that affect its adoption and also assesses the effects on the environment.

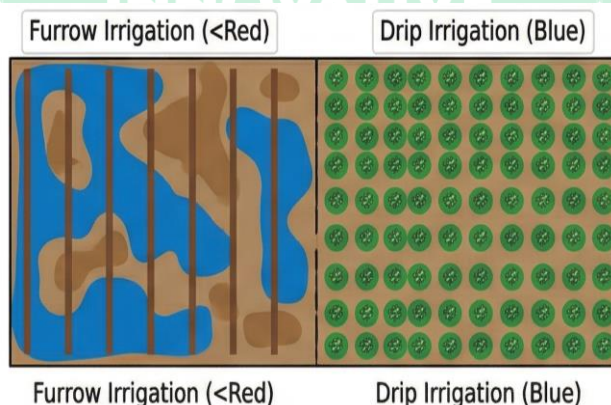


Figure 1. Water Application Uniformity Map

2. Water-Use Efficiency (WUE)

WUE is an index of the efficiency of water in yielding crops. It may be described in many different ways, though the common definition is the ratio of the crop yield to the sum of the water added or lost through evapotranspiration. High WUE implies that a larger crop is grown using less water, and this is very important in water-constrained regions.

Table 1. Comparison of Irrigation Efficiencies

Irrigation Method	Application Efficiency (%)	Water-Use Efficiency (kg/m ³)
Furrow	50-70	0.8-1.2
Basin	60-80	1.0-1.5
Sprinkler	70-85	1.2-1.8
Drip	85-95	1.5-2.5

3. Cost–Benefit Analysis

The economic viability of the use of drip irrigation is subject to numerous variables such as the initial cost of investment, the cost of operation and maintenance, improvement of crop yield and quality, and the cost of water. The transition of drip irrigation requires a cost-benefit analysis (CBA) that will evaluate the economic returns.

4. Initial Investment Costs

Drip irrigation systems are normally costly to install in the initial stages, such as the actual cost of emitters, tubing, filters, pumps, and control valves. Initial investment expenditure may highly differ with the design of the system, the extent of the irrigated land and also the type of crop to be grown.

5. Operating and Maintenance Costs

Although drip irrigation may save businesses on water and fertiliser expenditure, there are some recurrent expenses, including electricity or petrol to pump and filter, cleaning and maintenance of the system. To guarantee the best performance and life span of the drip system, maintenance should be done periodically.

5.1 Benefits

- Water Savings:** Drip irrigation is 30-70% less water use than conventional irrigation. This is an important advantage in water-intensive areas, where water is a valuable and scarce commodity.
- Increased Yields:** Drip irrigation may enhance crop yields by placing water and nutrients in the root zone, which makes the plants less stressed and maximises the nutrient uptake.
- Improved Crop Quality:** Drip irrigation can provide uniform water application, which results in enhanced crop quality, like better uniform ripening and increased sugar content.
- Reduced Labour Costs:** Drip irrigation has the potential to automate part of the labour-intensive operations of traditional irrigation, like the manual watering and the actual controlling of the weeds.
- Fertiliser Savings:** Drip fertigation will enable the application of fertilisers and other chemicals precisely; this will minimise the wastage of fertilisers and environmental pollution.

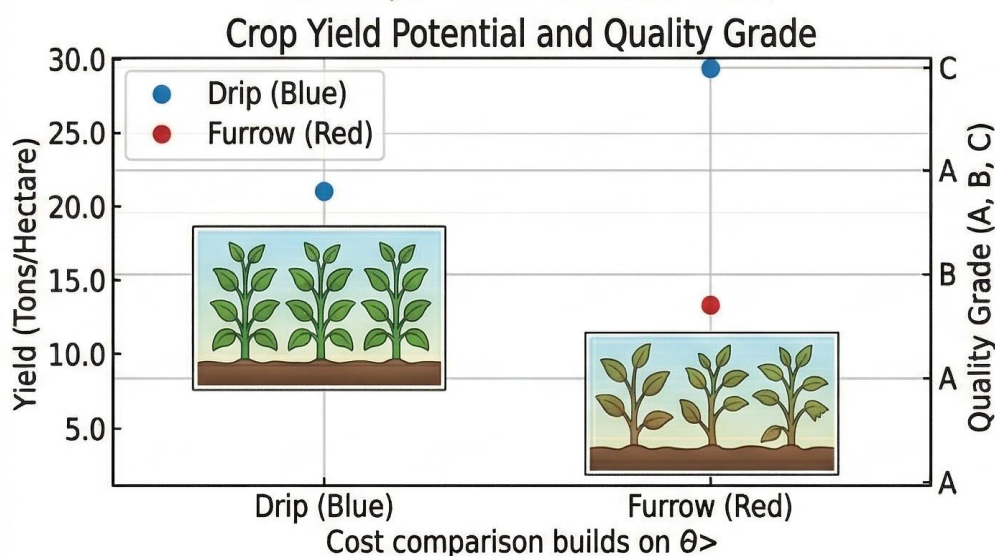


Figure 2. Crop Yield Potential and Quality Grade

6. Cost–Benefit Indicators

Several indicators apply to the economic feasibility of drip irrigation:

- Net Present Value (NPV):** This refers to the total of the present values of all cash flows (benefits less costs) of the project in the future. When NPV is positive, the project he is working on is profitable.
- Internal Rate of Return (IRR):** The discount rate at which the NPV of the project will be zero. The project is normally acceptable when the IRR is more than the cost of capital.
- Benefit-Cost Ratio (BCR):** This is the ratio between the total discounted benefits and the total discounted costs. A BCR that is more than one means that the gains exceed the expenditure.

- **Payback Period:** A project is said to pay back after a certain period of time when the cumulative net benefits of the project are equal to the initial investment. It is preferred to have a shorter payback period.

Table 2: Estimated Costs and Benefits of Drip Irrigation Adoption (per hectare)

Item	Traditional Irrigation (Furrow)	Drip Irrigation
Initial Investment (USD)	500	2500
Annual Operating & Maintenance (USD)	200	150
Water Cost (USD)	100	30
Fertiliser Cost (USD)	150	100
Labour Cost (USD)	200	100
Total Annual Operating Costs (USD)	650	380
Crop Yield (tons/hectare)	40	50
Crop Price (USD/ton)	100	100
Annual Crop Revenue (USD)	4000	5000
Net Annual Benefit (USD)	3350	4620

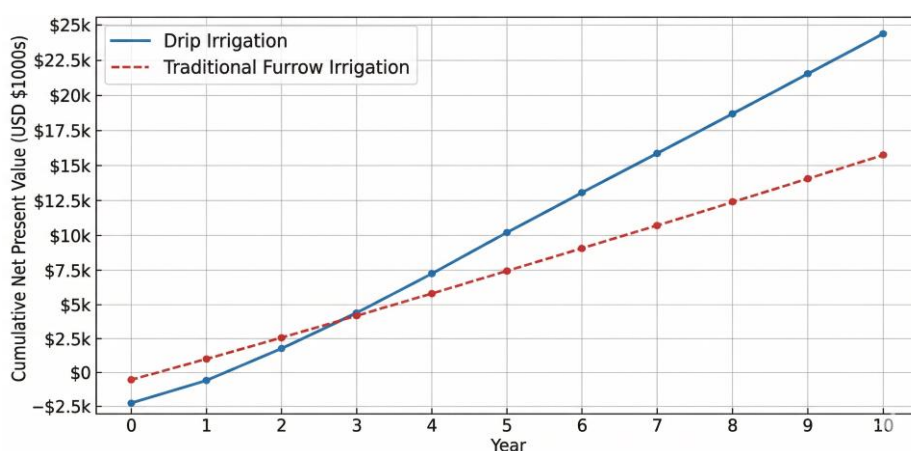


Figure 3. Comparison of Net Present Value for Different Irrigation Methods

7. Factors Influencing Drip Irrigation Adoption

In spite of the apparent benefits of drip irrigation, there are various challenges to this practice in areas with a lack of water. The adoption process depends on the following factors:

- High Initial Costs:** A drip irrigation system entails a lot of initial cost; hence, it may pose a big challenge to most farmers, particularly small-scale farmers who have restricted access to credit.
- Technical Knowledge and Skills:** Drip irrigation systems are to be properly installed, operated and maintained, and this may require technical knowledge and skills that some farmers do not have.
- Water Availability and Reliability:** Drip irrigation depends on the availability of water, which is sometimes hard to predict in areas with unreliable or insufficient water supply.
- Water Quality:** Low quality of water may cause clogging of emitters and filters, resulting in slower efficiency and life of the drip system.
- Market Access and Pricing:** Farmers need to have access to the market and the prices of their crops to recoup their investment and be profitable.
- Government Policies and Incentives:** The government policies and incentives should be used in support of the adoption of drip irrigation.

8. Environmental Impacts

Drip irrigation has several environmental benefits:

- Water Conservation:** Drip irrigation has the potential to save a lot of water, thus saving the limited water resources.
- Reduced Soil Erosion:** The accuracy of water application by the use of emitters reduces soil erosion as opposed to surface irrigation.

- c) **Reduced Nutrient Leaching:** Drip fertigation allows for targeted fertiliser application, minimising fertiliser leaching into groundwater.
- d) **Lower Greenhouse Gas Emissions:** Improved water and nutrient management can reduce emissions of greenhouse gases, such as nitrous oxide and methane.

Nevertheless, drip irrigation has certain possible negative impacts on the environment:

- a) **Energy Consumption:** Drip irrigation demands energy to pump water, and this may contribute to the emission of greenhouse gases in instances where fossil fuels are used.
- b) **Plastic Waste:** The disposal quality of certain drip irrigation elements may result in plastic waste.
- c) **Groundwater Depletion:** In other instances, more irrigation through drip irrigation use can result in more groundwater pumping, which intensifies the depletion of groundwater.

9. Conclusion

Drip irrigation is a very efficient and cost-effective method of water management in agriculture, especially in water-stressed areas. It contributes immensely to the water-use efficiency, water scarcity reduction, higher crop production, and better crop quality. Drip irrigation is a desirable method of sustainable agriculture, though the initial investment costs are relatively high, owing to the benefits of this solution in the long run not only to the economy but also to the environment. Nevertheless, it is important to take into consideration the factors that affect its use, including monetary limitations and technical abilities, to facilitate the widespread usage and implement it to the fullest potential. The supportive policies and interventions directed at allowing the farmers to switch to drip irrigation would be an important step towards providing water security and food in the areas that are experiencing water shortages.

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Determinants, Opportunities, and Challenges of Farmer Participation in Contract Farming Models



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1. Introduction

Many economies are largely agricultural-based, supplying livelihood to millions. Nonetheless, conventional agriculture is commonly associated with many problems, such as market and financial accessibility, as well as technology. Contract farming has emerged as a possible solution to such problems, providing farmers with a well-structured and secure avenue to reach markets and enhance their farming activities.

It is an article that takes a complex approach to the world of contract farming that explores the factors that drive the involvement of farmers, the potential it offers and the various challenges that can cripple its success. We will also include visual aids and guided information to make comprehending such concepts easier.

2. Determinants of Farmer Participation in Contract Farming

The internal and external factors have a variety of impacts on whether farmers will or will not join contract farming models. These determinants are important to understand to help in designing and implementing effective contract farming initiatives.

A. Internal Factors (Farmer characteristics)

1. **Education and Skills:** Higher education and technical skills of farmers make them more open to contract farming. They can better understand the terms and conditions of contracts and have higher chances of adapting to strict quality and safety requirements.
2. **Experience:** A farmer can be more attractive to the contracting firms due to experience in producing a particular crop or in the management of livestock. The companies can focus on the seasoned farmers who show stable production potentials.
3. **Resource Endowment:** Large landholders of farmers who have access to irrigation and the availability of vital farm equipment might be in a better position to meet the stipulations of the contract and make the necessary improvements.
4. **Risk Tolerance:** Risk-averse farmers might be more likely to engage in contract farming to enjoy assured prices and availability of technical support, which can help to reduce production risk and market risk.

B. External Factors (Market and institutional environment)

1. **Market Structure:** In markets with extreme price volatility or insufficient selection of buyers, contract farming may offer a solution of much-needed stability and a market entry point to the farmers.
2. **Contract Terms and Conditions:** To attract and maintain the participation of farmers, there must be fair and transparent contracts, such as transparent pricing, quality standards and dispute resolution mechanisms.
3. **Institutional Support:** Government policies, extension services, and financial institutions are very important in the facilitation of contract farming. Such support mechanisms are able to offer technical assistance, credit facilities and legal redress to both the farm and the firms.
4. **Relationship with Contracting Firm:** The most important is the mutual trust, communication, and respect between farmers and contracting firms. Good relationships create long-term relations and improve chances of following the contracts.

3. Opportunities Offered by Contract Farming Models

Contract farming can have great benefits to both the farmers and the contracting company when well applied.

1. **Guaranteed Market and Income:** The contracts provide a secure marketplace to the farmers, who may not be affected by the market dynamics and market risks. This guaranteed source of income will help in planning finances and investments better.

2. **Access to Inputs and Technology:** Contracting firms usually supply the farmers with quality seeds, fertilisers, pesticides and modern farming technologies. This may result in a greater production, higher quality of the product and a more efficient use of the resources.
3. **Technical Assistance and Extension Services:** Firms are often involved in providing technical assistance and extension services to help farmers adopt the best practices, quality requirements, and production issues.
4. **Improved Quality and Safety Standards:** Contract farming usually requires the incorporation of high levels of quality and safety. This has the potential of making the produce more marketable, and this will help in food safety and consumer confidence.
5. **Enhanced Bargaining Power:** Smallholder farmers with weak bargaining power could experience higher bargaining power when they collectively bargain as part of a contract farming arrangement.

Table 2. Determinants of Farmer Participation in Contract Farming

Factor	Description
Farmer Characteristics	
Education	Higher education leads to better understanding and adaptation.
Experience	Proven track record increases attractiveness to firms.
Resource Endowment	Access to land, water, and machinery facilitates compliance.
Risk Tolerance	Risk-averse farmers seek stability through contracts.
Market/Institutional Environment	
Market Structure	Contract farming provides stability in volatile markets.
Contract Terms	Fair, transparent, and legally binding agreements are crucial.
Institutional Support	Government and financial institutions play a facilitating role.
Firm Relationship	Trust, communication, and mutual respect build partnerships.

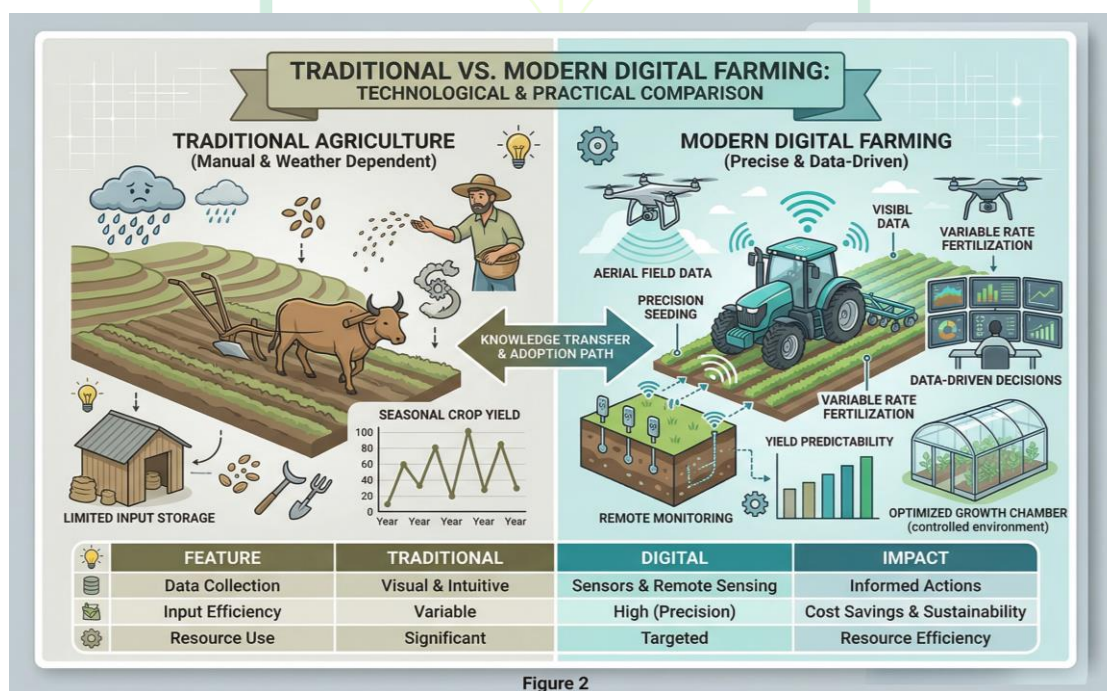


Figure 1. Traditional vs. Modern Digital Farming

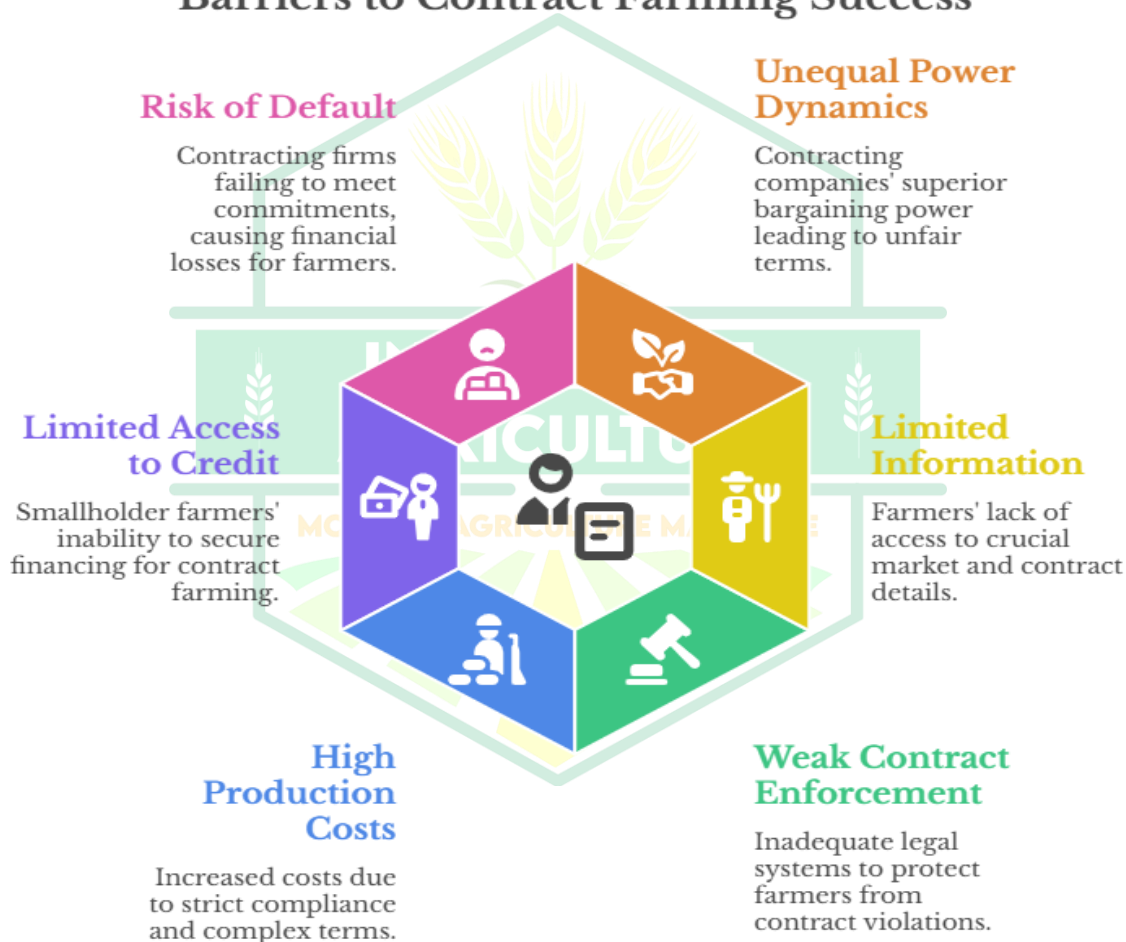
4. Challenges Inhibiting Farmer Participation and Success

Although the practice of contract farming may have some advantages, other factors show that this practice has several issues that may restrict its performance and influence.

1. **Unequal Power Dynamics:** Contracting companies tend to possess a greater bargaining power than single farmers, and this may result in unjust contract terms, price fixing, and exploitation.

2. **Limited Information and Transparency:** The farmers might be deprived of access to important information about market prices, costs of inputs and performance of the contract, which exposes them to exploitation.
3. **Weak Contract Enforcement:** The lack of appropriate legal systems and enforcement mechanisms can make it hard to have redress where a contract is violated by the contracting firm, in the case of farmers.
4. **High Production and Transaction Costs:** The cost of production and transaction can increase among farmers as a result of strict compliance with quality requirements, certification procedures, and complicated terms of the contracts.
5. **Limited Access to Credit and Finance:** Contract farming may not be inclusive of smallholder farmers due to their inability to obtain credit to invest in the inputs and technologies needed in the contract farming.
6. **Risk of Default by Contracting Firm:** Sometimes, the contracting firms can fail in their commitments, and farmers would end up having unsold produce and losing their money.

Barriers to Contract Farming Success



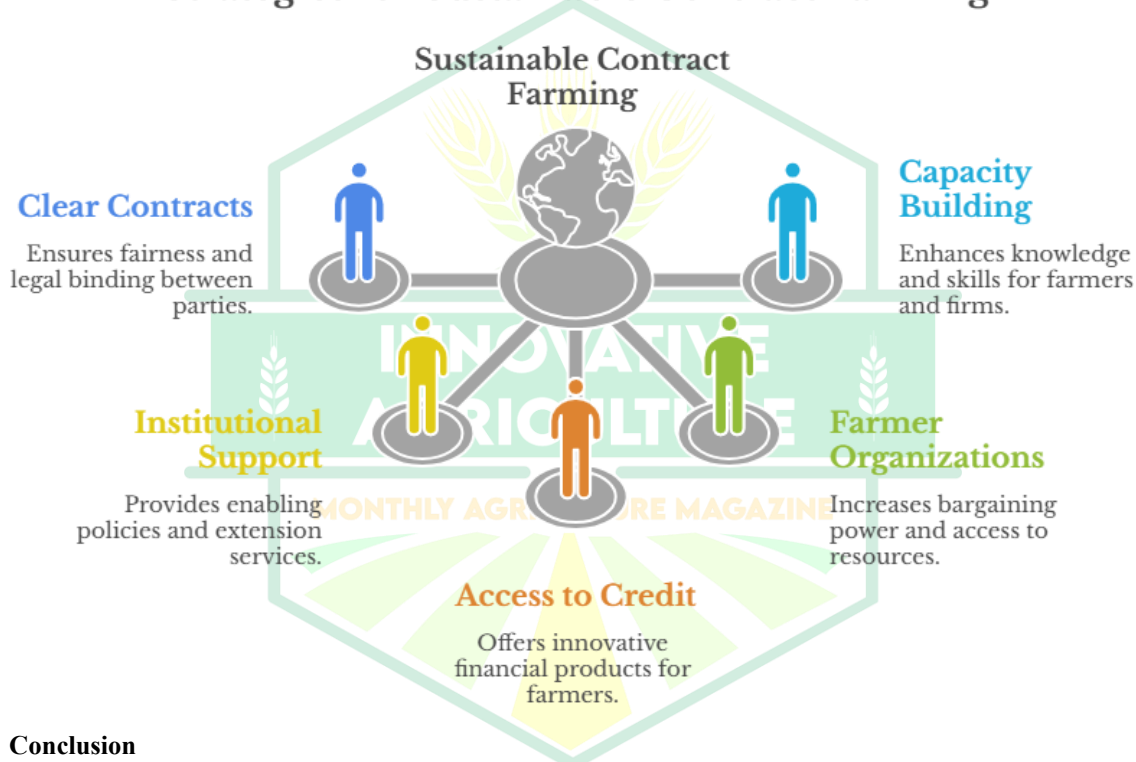
5. Strategies for Promoting Sustainable Contract Farming

To realise the benefits to the maximum and tackle the problems of contract farming, several strategies may be used:

1. **Developing Clear and Fair Contracts:** It is essential that the contracts between the farmers and the contracting firms are clear, fair and legally binding and that they strike a balance between the interests of the two parties.

2. **Strengthening Institutional and Policy Support:** Governments and other concerned institutions must ensure that they establish an enabling environment for contract farming by the provision of suitable policies, legal frameworks and extension services.
3. **Facilitating Access to Credit and Finance:** It is needed to innovate financial processes and custom-made loan products to be given to farmers who engage in contract farming.
4. **Promoting Farmer Organisations and Collective Bargaining:** The tendency to organise farmers into cooperatives or producer organisations can increase the bargaining power of the latter, lower the cost of transactions, and provide them with greater access to information and resources.
5. **Investing in Capacity Building and Training:** Provision of extensive training and capacity building to farmers and the contracting firms concerning knowledge of contract farming, technical expertise and risk management skills could enhance their knowledge of the subject matter.

Strategies for Sustainable Contract Farming



6. Conclusion

Contract farming is an opportunity that can be used to transform smallholder agriculture in that farmers are linked to markets, production practices are enhanced, and livelihoods are improved. Nevertheless, the implementation needs to be done carefully, taking into consideration the determinants affecting the participation of the farmers, understanding of the opportunities and challenges, and coming up with effective strategies that can support sustainable and equitable partnerships. Contract farming can play a significant role in agricultural development, poverty alleviation and food security by promoting collaboration, capacity building and enabling the institutional and policy environment.

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Efficient Water Management Techniques for Enhancing Pulse Production



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Introduction

Pulses are fundamental to global food security, contributing significantly to human nutrition, soil fertility through biological nitrogen fixation, and sustainable agricultural practices. Despite their importance, pulse production is often constrained by limited water availability and inefficient water use, particularly in semi-arid and arid regions where pulses are extensively cultivated. Efficient water management is imperative to optimize pulse yields, improve water use efficiency (WUE), and promote sustainable production systems. This comprehensive article expands upon key water management techniques tailored for pulse crops, integrating agronomic practices, technological innovations, and institutional frameworks to enhance productivity and conserve vital water resources.

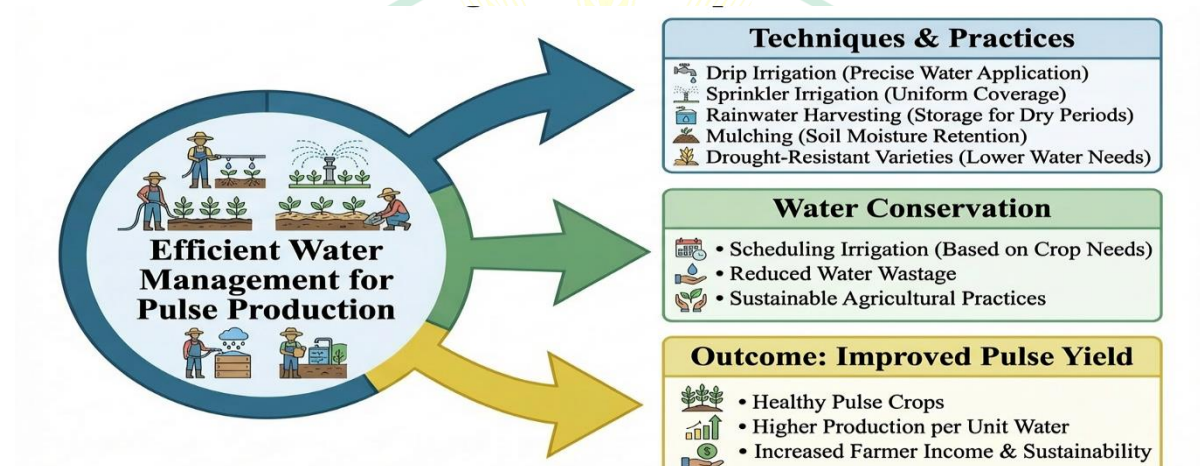


Figure 1: Efficient Water Management Techniques for Enhancing Pulse Production

1. Understanding Water Requirements of Pulse Crops

Pulse crops such as chickpea, lentil, pigeon pea, mung bean, and black gram have moderate water requirements compared to cereals but exhibit high sensitivity to water stress during critical growth stages. A nuanced understanding of these requirements is essential for designing effective water management strategies.

- Critical Growth Stages:** Flowering and pod filling represent the most water-sensitive phases, where moisture deficits can drastically reduce yield and seed quality. Water stress during vegetative growth affects biomass accumulation but has a relatively lesser impact on final yield.
- Water Use Efficiency (WUE):** Pulses inherently possess higher WUE due to their deep rooting systems and symbiotic nitrogen fixation; however, this potential is often compromised by suboptimal irrigation practices and environmental stresses.
- Soil-Plant-Atmosphere Continuum:** Water uptake by pulses depends on soil moisture availability, root health, and atmospheric demand (evapotranspiration). Integrated management considering these factors enhances irrigation efficiency and crop resilience.

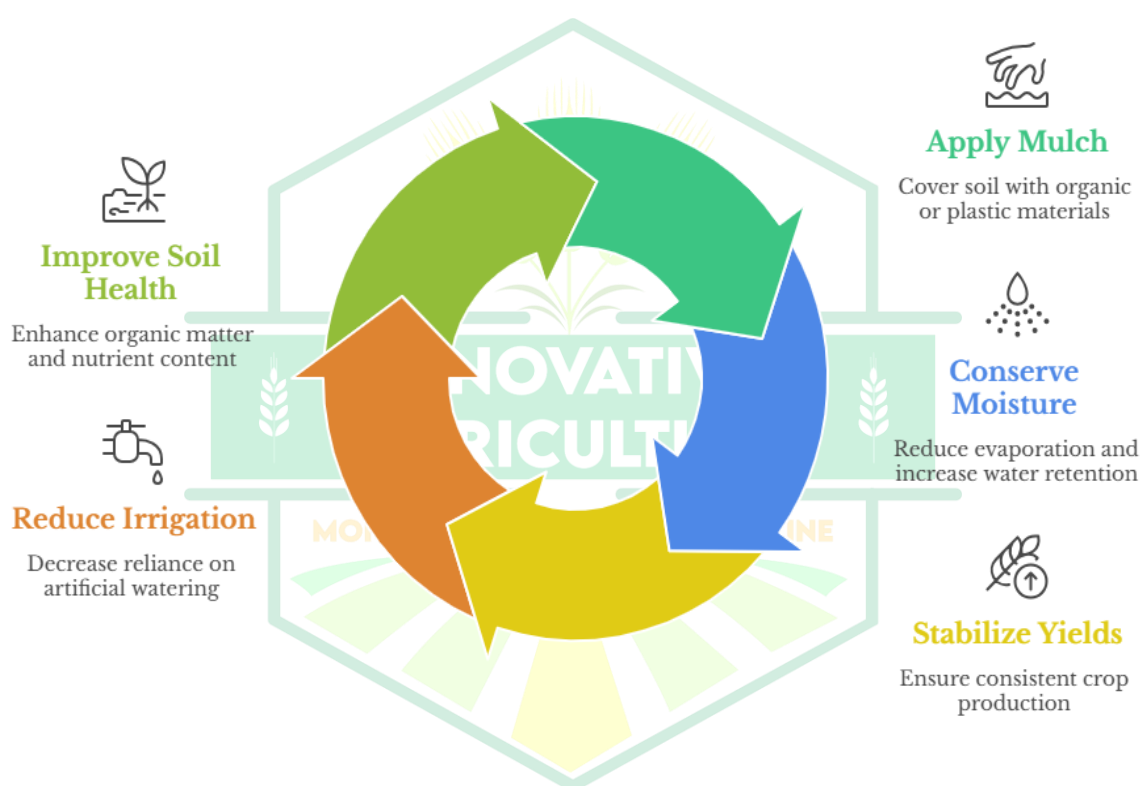
2. Soil Moisture Conservation Techniques

Preserving soil moisture is critical for pulse crops, particularly in rainfed systems where precipitation is erratic and often insufficient. Moisture conservation techniques improve water availability during dry spells, stabilizing yields and reducing irrigation dependency.

2.1 Mulching

- Organic Mulching:** Application of crop residues, straw, or green manures forms a protective layer that reduces evaporation losses by up to 30%, moderates soil temperature, suppresses weed growth, and improves soil organic matter content over time. Enhanced organic matter increases the soil's water holding capacity and nutrient availability, indirectly benefiting pulse growth.
- Plastic Mulching:** Polyethylene films effectively conserve moisture and can increase yields substantially. However, environmental concerns regarding plastic waste have prompted the development and adoption of biodegradable mulches and improved disposal methods.
- Innovations in Mulching:** Combining mulching with biochar application enhances soil moisture retention and nutrient dynamics, offering a sustainable approach to moisture conservation.

Soil Moisture Conservation Cycle



2.2 Conservation Tillage

- Reduced Tillage:** Minimizing soil disturbance preserves soil structure, organic carbon, and moisture retention capacity. Reduced tillage enhances infiltration rates, reduces runoff, and maintains soil porosity, fostering a favorable environment for pulse root development.
- Zero Tillage:** Direct sowing into undisturbed soil maintains surface residues and soil porosity, reducing evaporation and erosion. Zero tillage is especially beneficial in semi-arid zones where moisture conservation is paramount.
- Residue Retention:** Retaining crop residues on the soil surface post-harvest protects soil from sun and wind exposure, further reducing evaporation and enhancing moisture conservation.

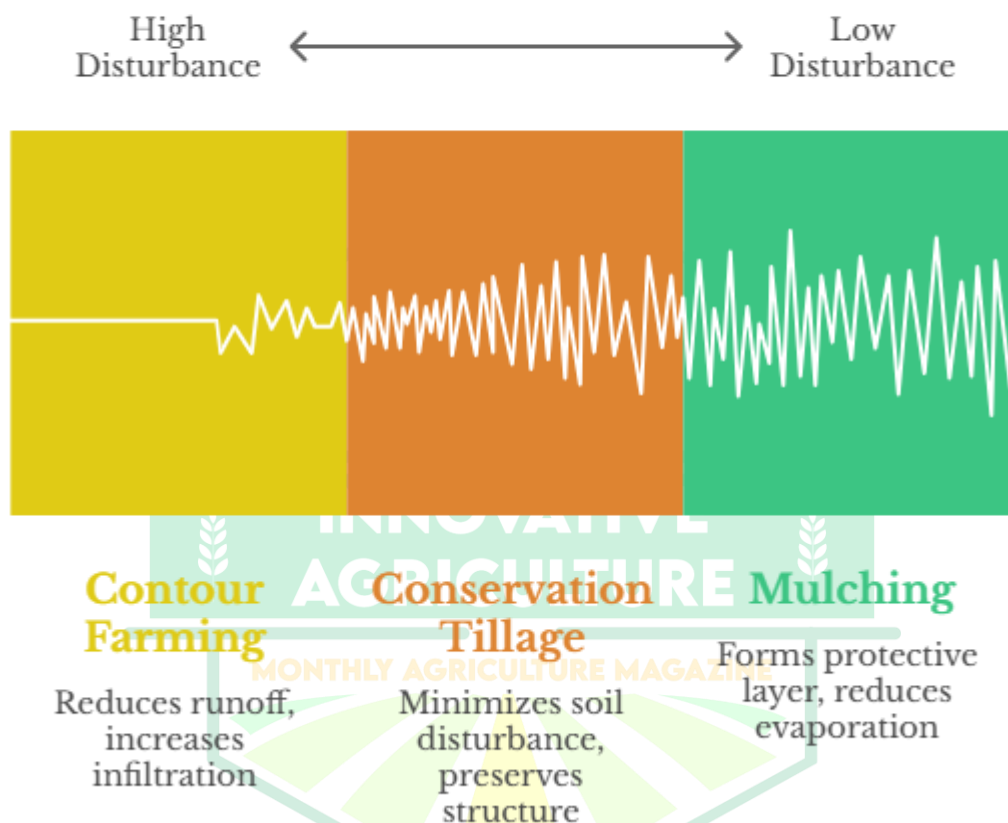
2.3 Contour Farming and Terracing

- On sloped terrain, contour plowing and terracing reduce runoff velocity, increase water infiltration, and prevent soil erosion, thereby conserving moisture critical for pulse crops.
- These practices also improve nutrient retention and reduce sediment loss, contributing to long-term soil health.

3. Efficient Irrigation Scheduling and Methods

Optimizing irrigation timing and delivery methods is essential to maximize water use efficiency and pulse yields, particularly in regions with limited or erratic rainfall.

Soil moisture conservation techniques ranked by soil disturbance.



3.1 Irrigation Scheduling

- Soil Moisture-Based Scheduling:** Utilization of tensiometers, capacitance probes, neutron moisture meters, and dielectric sensors enables irrigation only when soil moisture falls below crop-specific thresholds, preventing both over- and under-irrigation.
- Phenological Stage-Based Scheduling:** Prioritizing irrigation during critical stages such as flowering and pod filling maximizes yield response to water application, ensuring efficient use of limited water resources.
- Deficit Irrigation:** Applying water below full crop evapotranspiration during non-critical growth stages conserves water with minimal yield penalties, enhancing overall water productivity.
- Climate-Based Scheduling:** Incorporating weather forecasts, evapotranspiration data, and crop water stress indices allows dynamic adjustment of irrigation timing and volumes, optimizing water use under variable climatic conditions.

3.2 Irrigation Methods

- Drip Irrigation:** Delivers water directly to the root zone, minimizing evaporation and runoff losses. Drip systems are highly efficient, particularly for row-planted pulses, enabling precise water and nutrient

delivery (fertigation), which improves yield and reduces water consumption by up to 50% compared to surface irrigation.

- Sprinkler Irrigation:** Provides uniform water distribution, suitable for uneven terrain. Requires careful management to minimize evaporation and wind drift losses. Advances in low-pressure sprinklers and micro-sprinklers improve efficiency.
- Surface Irrigation:** Traditional furrow or basin irrigation methods are less efficient but can be improved through proper field leveling, furrow design, and timing to reduce water wastage.
- Automation and Sensor Integration:** Combining soil moisture sensors with automated irrigation controllers allows real-time irrigation decisions, reducing labor and optimizing water application.

Table 1: Efficient Water Management Techniques for Enhancing Pulse Productivity

Technique	Approach Type	Mechanism of Action	Impact on Yield/WUE (%)	Additional Benefits
Drip Irrigation	Micro-irrigation	Delivers water directly to root zone	20–50% yield increase, 30–60% water saving	Higher WUE
Sprinkler Irrigation	Controlled irrigation	Uniform water distribution	15–35% yield increase	Suitable for light soils
Irrigation Scheduling	Agronomic	Water application at critical stages	15–30% yield increase	Efficient resource use
Mulching (Organic/Plastic)	Soil management	Reduces evaporation loss	10–25% yield increase	Moisture conservation
Rainwater Harvesting	Water conservation	Stores excess rainwater	20–40% improved water availability	Reduces drought risk
Conservation Tillage	Agronomic	Improves soil moisture retention	10–20% yield increase	Soil health improvement
Use of Drought-Tolerant Varieties	Genetic	Efficient water use traits	15–30% yield stability	Climate resilience
Soil Moisture Sensors	Technological	Real-time irrigation decisions	10–25% water saving	Precision farming
Integrated Water Management (IWM)	System approach	Combines multiple techniques	25–60% productivity gain	Sustainable intensification
Alternate Furrow Irrigation	Water-saving method	Reduces water use without yield loss	15–30% water saving	Efficient irrigation

4. Rainwater Harvesting and Supplemental Irrigation

Augmenting water availability through rainwater capture is a sustainable strategy, particularly in rainfed pulse cultivation systems.

4.1 Farm Ponds and Check Dams

- Small-scale water storage structures capture runoff during rainy seasons, providing supplemental irrigation during dry spells, reducing reliance on erratic rainfall.
- Integration with groundwater recharge enhances water availability during critical crop stages.

4.2 Micro-Catchments and Contour Bunds

- Land shaping techniques that direct and retain runoff near root zones improve soil moisture availability and reduce erosion.
- These structures are cost-effective and adaptable to smallholder farms.

4.3 Roof Water Harvesting

- Collection of rainwater from farm buildings and other structures offers an additional water source for irrigation, enhancing water security.

4.4 Managed Aquifer Recharge

- Techniques such as recharge wells, percolation tanks, and infiltration basins store excess surface water underground, augmenting groundwater supplies for irrigation during dry periods.

5. Soil and Water Testing for Optimized Irrigation

Regular assessment of soil moisture and water quality informs precise irrigation and nutrient management strategies.

- a) **Soil Moisture Monitoring:** Employing gravimetric sampling, dielectric sensors, remote sensing, and IoT-enabled devices provides accurate data to schedule irrigation effectively.
- b) **Water Quality Testing:** Ensures irrigation water is free from excessive salinity, heavy metals, or contaminants that could harm pulse crops or degrade soil health.
- c) **Nutrient-Water Interaction:** Understanding how irrigation influences nutrient availability and uptake allows optimization of fertilizer application, preventing leaching and enhancing crop nutrition.

6. Use of Drought-Resistant and Water-Efficient Pulse Varieties

Genetic improvement and adoption of drought-tolerant pulse varieties reduce irrigation demand and enhance yield stability under water-limited conditions.

- a) Breeding programs focus on traits such as deep rooting, osmotic adjustment, stomatal regulation, and early maturity.
- b) Participatory varietal selection involving farmers ensures adaptability to local agro-ecological zones and farmer preferences, facilitating adoption.
- c) Integration of molecular breeding and genomics accelerates development of water-efficient varieties.

7. Crop Rotation and Intercropping for Water Efficiency

Diversified cropping systems improve water use efficiency and soil health, indirectly benefiting pulse production.

- a) **Crop Rotation:** Pulses rotated with cereals or other crops improve soil structure, moisture retention, and break pest and disease cycles, reducing input requirements.
- b) **Intercropping:** Growing pulses alongside compatible crops (e.g., maize, sorghum) reduces water competition and optimizes land and water productivity.
- c) These practices increase soil organic matter, enhance infiltration, and improve nutrient cycling, contributing to improved water availability.

8. Precision Agriculture Technologies

Technological advancements enable site-specific water management, improving efficiency and sustainability.

8.1 Remote Sensing and Geographic Information Systems (GIS)

- Satellite imagery, drones, and multispectral sensors monitor crop water status, soil moisture, and evapotranspiration at field scales, guiding precise irrigation decisions and early stress detection.

8.2 Soil Moisture Sensors and Internet of Things (IoT)

- Wireless sensor networks provide continuous, real-time soil moisture data, enabling dynamic irrigation scheduling and rapid response to water stress.

8.3 Automated Irrigation Systems

- Integration of data analytics, weather forecasts, and sensor inputs with irrigation hardware facilitates precise, timely water application, conserving resources and enhancing yields.

9. Improved Drainage and Waterlogging Management

Although water scarcity predominates, pulses are sensitive to waterlogging, which impairs root function, nitrogen fixation, and overall crop health.

- a) Proper field leveling, installation of drainage channels, and raised beds prevent water accumulation and improve aeration.
- b) Effective drainage mitigates risks of root diseases and nutrient deficiencies, supporting pulse productivity.

10. Farmer Training and Capacity Building

Knowledge dissemination and skill development are critical for the adoption of efficient water management practices.

- a) Training programs focus on water budgeting, irrigation scheduling, moisture conservation techniques, and climate variability adaptation.
- b) Farmer field schools, demonstrations, and participatory workshops promote hands-on learning and peer-to-peer knowledge exchange.
- c) Capacity building integrates water management with broader agronomic practices, pest management, and market linkages.

11. Institutional and Supply Chain Integration for Water Management

Linking water-efficient pulse production with institutional frameworks and market mechanisms enhances adoption and sustainability.

- a) **Farmer Producer Organizations (FPOs):** Facilitate collective investments in irrigation infrastructure, rainwater harvesting, and technology adoption, achieving economies of scale and improved bargaining power.
- b) **Access to Credit and Subsidies:** Financial support mechanisms enable farmers to acquire water-saving equipment, inputs, and adopt innovative practices.
- c) **Market Linkages:** Premium markets for sustainably produced pulses incentivize efficient water use and quality improvement, creating economic motivation for water conservation.
- d) **Policy Support:** Government programs promoting water conservation, subsidizing efficient irrigation technologies, and encouraging sustainable agricultural practices create enabling environments.

12. Sustainability and Environmental Considerations

Efficient water management in pulse production contributes to broader environmental sustainability and climate resilience.

- a) Reduces groundwater depletion, preserving aquifer health and long-term water availability.
- b) Minimizes soil degradation, salinization, and erosion, maintaining productive land.
- c) Supports biodiversity through sustainable land and water use practices.
- d) Aligns with climate-smart agriculture principles, enhancing resilience to climate variability, droughts, and extreme weather events.
- e) Promotes circular economy approaches such as water recycling, reuse, and integrated nutrient management.

Conclusion

Efficient water management techniques are indispensable for enhancing pulse production, conserving scarce water resources, and improving farmer livelihoods. By integrating soil moisture conservation, precision irrigation, rainwater harvesting, drought-tolerant varieties, and institutional support, pulse cultivation can achieve higher yields with optimized water use. Continued innovation, capacity building, and enabling policies are essential to mainstream these practices across diverse agro-ecological zones. Embedding water management within broader agribusiness frameworks—including marketing and supply chain integration—will strengthen the resilience, profitability, and sustainability of pulse production systems, positioning them to meet future challenges and opportunities effectively.

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Enhancing Millet Productivity under Climate-Induced Stress Conditions



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Abstract

Millets are climate-resilient cereal crops essential for food security in arid and semi-arid regions. However, climate-induced stresses such as drought, heat, soil salinity, and erratic rainfall increasingly threaten millet productivity. This review examines the multifaceted challenges posed by climate change to millet cultivation and explores integrated strategies to enhance millet productivity under stress conditions. Key approaches include improved agronomic practices, advanced breeding techniques, soil and water management innovations, and leveraging beneficial plant-microbe interactions. Socioeconomic and policy frameworks supporting millet cultivation are also discussed. Emphasizing a multidisciplinary approach, this review highlights the potential of millets to sustain agricultural productivity and nutrition security in the face of evolving climate challenges.

Introduction

Millets, encompassing species such as pearl millet, finger millet, foxtail millet, barnyard millet, and proso millet, are vital cereal crops cultivated predominantly in arid and semi-arid regions worldwide. Their inherent tolerance to drought, high temperatures, and poor soil fertility renders them indispensable for sustaining agriculture under harsh environmental conditions. As climate change intensifies, characterized by increased frequency of droughts, heat waves, erratic rainfall, and soil degradation, millet productivity faces mounting challenges. These stresses disrupt key physiological processes, including germination, photosynthesis, and reproductive development, leading to yield reductions.

The nutritional significance of millets further elevates their importance, as they provide essential micronutrients and dietary fiber crucial for human health, particularly in vulnerable populations. Despite their resilience, millets require targeted interventions to mitigate the adverse impacts of climate-induced stresses and to enhance productivity sustainably.

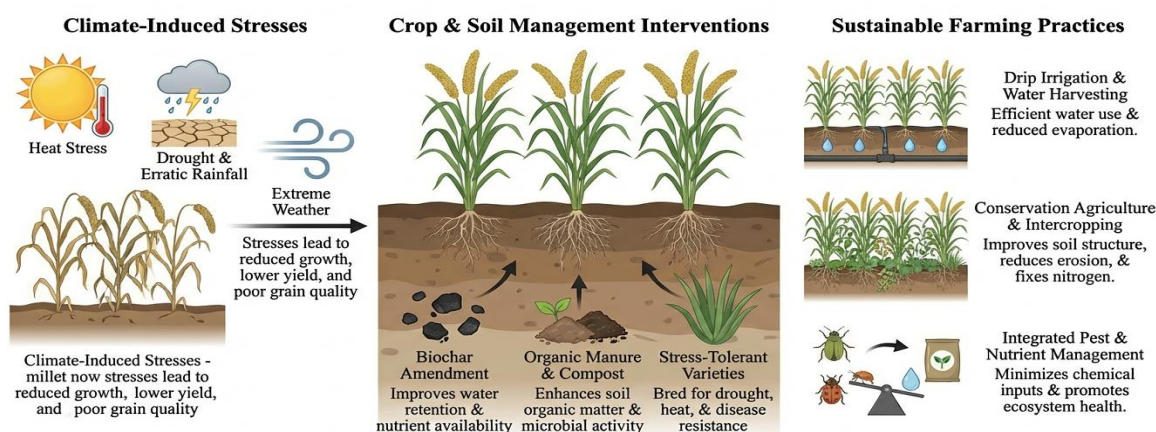
This comprehensive review synthesizes current knowledge on the effects of climate change on millet cultivation and evaluates strategies to improve millet performance under stress. It focuses on agronomic management, genetic improvement, soil and water conservation, and the role of beneficial microbial associations. Additionally, the review addresses socioeconomic and policy dimensions critical for the adoption and scaling of climate-resilient millet cultivation practices. By integrating these approaches, millets can contribute significantly to climate-smart agriculture and global food security.

1. Importance of Millets in Climate-Resilient Agriculture

1. Millets are a diverse group of small-seeded cereals including pearl millet, finger millet, foxtail millet, barnyard millet, and proso millet. Their inherent drought tolerance stems from physiological traits such as efficient stomatal regulation, deep rooting systems, and C₄ photosynthesis, enabling them to thrive in

arid and semi-arid environments. These characteristics make millets indispensable for sustaining agriculture in regions prone to water scarcity and erratic weather patterns intensified by climate change.

2. Nutritionally, millets are rich sources of essential micronutrients including calcium, iron, magnesium, and dietary fiber. This nutritional profile addresses micronutrient deficiencies prevalent in vulnerable populations, particularly in low-income regions facing climate-induced food security challenges. Millets also contain antioxidants and phytochemicals that contribute to human health, positioning them as valuable crops for both food and nutrition security.
3. Despite their resilience, millets are not immune to climate stressors. Yield limitations arise from heat waves, drought spells, and soil degradation, which can disrupt physiological processes such as photosynthesis, nutrient uptake, and reproductive development. To maintain and increase millet productivity, it is essential to integrate adaptive strategies that mitigate these climate-induced stresses.



Combined interventions improve resilience and significantly boost millet productivity despite climate challenges.

Figure 1: Enhancing Millet Productivity under Climate-Induced Stress Conditions

2. Climate-Induced Stress Factors Affecting Millet Productivity

1. **Drought Stress:** Drought impairs millet germination by limiting water availability required for seed imbibition and enzymatic activation. During vegetative and reproductive stages, water deficits reduce photosynthetic rates by causing stomatal closure, limiting CO₂ uptake. Drought also accelerates leaf senescence and reduces assimilate allocation to developing grains, culminating in lower grain weight and yield.
2. **Heat Stress:** Elevated temperatures, particularly during flowering, reduce pollen viability and fertilization success, leading to poor grain set. Heat stress accelerates phenological development, shortening the grain filling period and reducing carbohydrate accumulation in grains. High temperatures also increase respiration rates, depleting energy reserves critical for growth.
3. **Soil Salinity and Nutrient Deficiency:** Climate change-induced sea-level rise and erratic rainfall patterns contribute to soil salinization, which disrupts water uptake by creating osmotic stress and ion toxicity. Nutrient depletion, exacerbated by intensive cultivation and erosion, limits essential elements like nitrogen, phosphorus, and potassium, restricting millet growth and productivity.
4. **Erratic Rainfall and Flooding:** Unpredictable rainfall patterns cause alternating periods of drought and waterlogging. Waterlogging induces hypoxic soil conditions, impairing root respiration and nutrient uptake. Erratic rainfall also complicates sowing schedules and crop management, increasing vulnerability to stress.
5. **Pest and Disease Pressure:** Climate variability alters pest life cycles, distribution, and population dynamics, potentially increasing infestations. Warmer temperatures and humidity shifts can favor pathogen proliferation, leading to increased disease incidence and severity, which negatively impact millet yields.

Table 1: Climate-Induced Stress Factors Affecting Millet Productivity and Their Impacts

Stress Factor	Type of Stress	Physiological Impact on Millets	Yield Reduction (%)	Examples in Millets
Drought Stress	Abiotic	Reduced stomatal conductance, photosynthesis decline	20–60%	Common in Pearl Millet and Finger Millet
Heat Stress	Abiotic	Enzyme denaturation, reduced grain filling	15–50%	Affects Foxtail Millet during flowering
Salinity Stress	Abiotic	Ion toxicity, osmotic imbalance	10–40%	Observed in Barnyard Millet
Waterlogging	Abiotic	Root hypoxia, nutrient imbalance	15–35%	Sensitive stages in most millets
Nutrient Deficiency	Abiotic	Reduced chlorophyll and growth	10–30%	Nitrogen and zinc deficiency common
Erratic Rainfall	Abiotic	Flowering mismatch, poor grain set	20–45%	Rainfed millet systems
Pest & Disease Pressure	Biotic	Tissue damage, reduced biomass	10–25%	Blast disease in Finger Millet
High CO₂ Variability	Abiotic	Altered carbon metabolism	Variable	Impacts growth efficiency

3. Agronomic Practices to Enhance Millet Productivity under Stress

1. Drought-Resilient Crop Management:

- Conservation agriculture practices such as minimum tillage reduce soil disturbance, preserving soil structure and moisture. Mulching with crop residues reduces evaporation and moderates soil temperature. Residue retention enhances organic matter content, improving water holding capacity.
- Aligning sowing dates with forecasted rainfall ensures optimal soil moisture during critical growth phases, enhancing germination and establishment.
- Cultivating drought-tolerant millet varieties with deep and extensive root systems enhances water extraction from deeper soil layers, improving drought resilience.

2. Soil Fertility Management:

- Integrated nutrient management combines organic inputs like compost and manure with inorganic fertilizers to sustain soil fertility. Organic amendments improve soil structure, microbial activity, and nutrient retention, while fertilizers provide readily available nutrients.
- Application of biofertilizers such as nitrogen-fixing bacteria and phosphate-solubilizing microbes enhances nutrient availability and uptake, improving plant nutrition under stress.

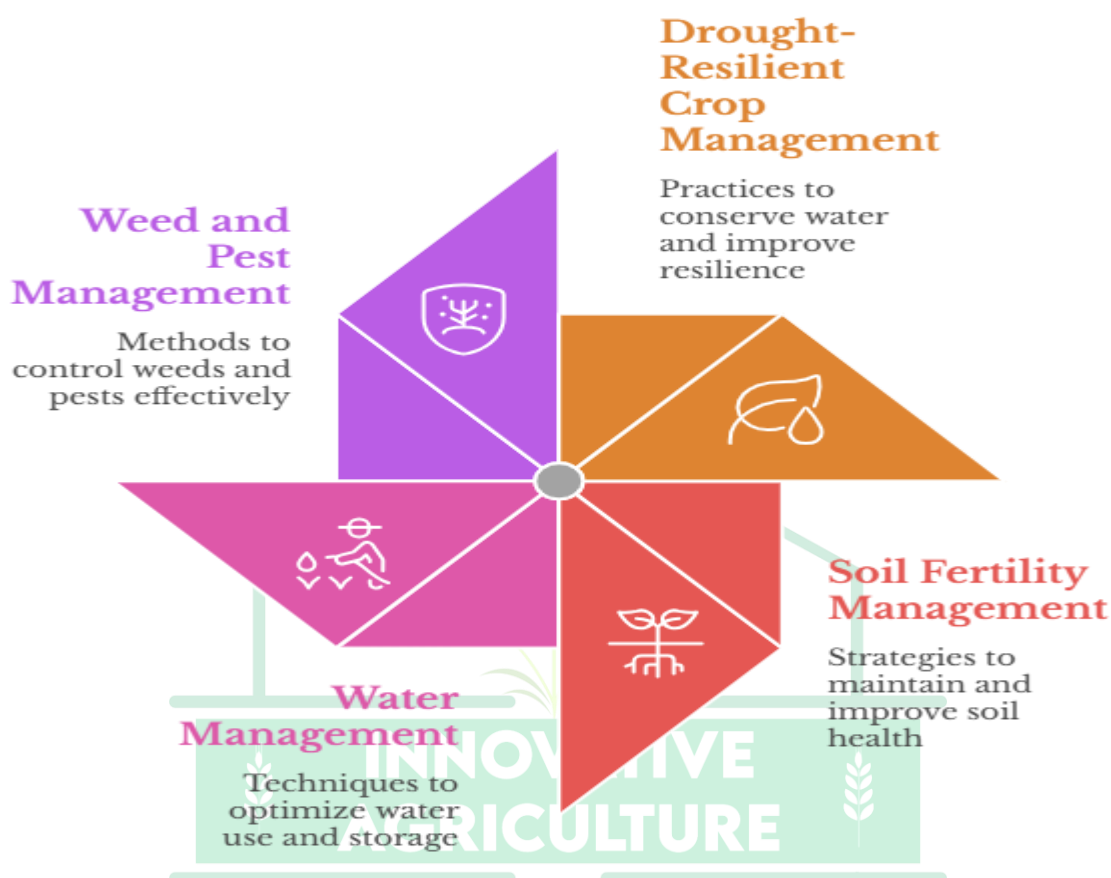
3. Water Management:

- Drip irrigation delivers water directly to the root zone, minimizing losses through evaporation and runoff, optimizing water use efficiency.
- Sprinkler irrigation simulates rainfall, enabling uniform water distribution and reducing waterlogging risks.
- Rainwater harvesting captures and stores precipitation for supplemental irrigation during dry spells, ensuring crop water supply.

4. Weed and Pest Management:

- Integrated Pest Management (IPM) employs resistant varieties, biological control agents (e.g., predators, parasitoids), and cultural practices such as crop rotation and intercropping to reduce pest populations.
- Timely weed control reduces competition for water, nutrients, and light, which is critical under resource-limited stress conditions.

Enhancing Millet Productivity



4. Breeding and Genetic Approaches for Stress Tolerance

1. **Conventional Breeding:**
 - a) Phenotypic selection focuses on traits like drought tolerance (e.g., stay-green phenotype), heat resistance, early maturity to escape terminal stresses, and efficient nutrient uptake.
 - b) Landraces and wild relatives harbor diverse genetic traits for stress tolerance, serving as valuable germplasm for breeding programs.
2. **Molecular Breeding and Marker-Assisted Selection (MAS):**
 - a) Identification of Quantitative Trait Loci (QTLs) linked to abiotic stress tolerance enables targeted introgression of favorable alleles into elite varieties.
 - b) MAS accelerates breeding cycles by selecting progenies carrying desired genes based on molecular markers rather than solely on phenotypic evaluation.
3. **Genomic and Biotechnological Advances:**
 - a) Genomic selection uses genome-wide markers to predict breeding values, enhancing selection accuracy for complex traits like drought tolerance.
 - b) Genome-wide Association Studies (GWAS) identify novel alleles associated with stress resilience.
 - c) Genetic engineering and CRISPR-Cas9 gene editing enable precise modification of stress-responsive genes to develop transgenic millets with enhanced tolerance.
4. **Phenotyping Platforms:**
 - a) High-throughput phenotyping employs remote sensing, imaging, and sensor technologies to measure physiological and morphological traits related to stress responses, enabling rapid screening of large breeding populations.

5. Soil and Water Management Innovations

1. Soil Moisture Conservation:

- Application of biochar improves soil porosity, water retention, and nutrient holding capacity, enhancing plant available water under drought.
- Contour bunding and terracing reduce runoff on slopes, promoting water infiltration and reducing soil erosion.

2. Salinity Management:

- Gypsum application displaces sodium ions in sodic soils, improving soil structure and permeability.
- Organic amendments increase microbial activity and soil organic matter, mitigating salinity effects.
- Cultivation of salt-tolerant millet varieties allows production in saline-prone areas.

3. Water Use Efficiency:

- Irrigation scheduling based on soil moisture sensors and crop water requirements prevents over- or under-irrigation.
- Deficit irrigation applies water below full crop evapotranspiration demand during less sensitive growth stages to conserve water without major yield loss.

6. Role of Plant-Microbe Interactions

1. Rhizosphere Microbiome:

- Arbuscular Mycorrhizal Fungi (AMF) form symbiotic associations with millet roots, enhancing phosphorus uptake and improving drought tolerance by increasing water absorption.
- Plant Growth-Promoting Rhizobacteria (PGPR) produce phytohormones, solubilize nutrients, and induce systemic resistance, supporting growth under stress.

2. Bioinoculants:

- Commercial formulations of beneficial microbes applied as seed coatings or soil amendments improve nutrient uptake, stimulate root growth, and enhance stress tolerance.
- Biostimulants containing microbial metabolites modulate plant hormonal balance and antioxidant systems, mitigating oxidative damage caused by abiotic stress.

3. Microbial Mediated Stress Alleviation:

- Microbes produce osmoprotectants like proline and glycine betaine that help maintain cell turgor during drought.
- ACC deaminase-producing bacteria lower ethylene levels in plants, reducing stress-induced growth inhibition.
- Microbial antioxidants scavenge reactive oxygen species, protecting plants from oxidative stress.

7. Climate-Smart Agricultural Practices

1. Diversified Cropping Systems:

- Intercropping millets with legumes enhances nitrogen availability through biological nitrogen fixation, improves soil structure, and reduces pest incidence, contributing to system resilience.
- Crop diversification spreads risk and stabilizes income under variable climate conditions.

2. Agroforestry Integration:

- Trees provide shade and windbreaks, moderating microclimate extremes.
- Leaf litter and root exudates improve soil organic matter and nutrient cycling.
- Agroforestry systems enhance biodiversity and carbon sequestration.

3. Precision Agriculture:

- Remote sensing and GIS technologies monitor crop health, soil moisture, and nutrient status, enabling site-specific management.
- Decision support tools optimize input use, reducing waste and environmental impact.

4. Climate Forecasting and Advisory Services:

- Access to accurate weather forecasts guides planting, irrigation, and pest management decisions.
- Early warning systems enable proactive stress management.

8. Socioeconomic and Policy Dimensions

1. Farmer Awareness and Capacity Building:

- a) Training programs on climate-resilient practices empower farmers to adopt improved technologies.
- b) Farmer field schools and participatory research enhance knowledge exchange and innovation uptake.

2. Access to Inputs and Credit:

- a) Subsidized provision of quality seeds, fertilizers, and irrigation infrastructure reduces barriers to adoption.
- b) Microcredit schemes enable smallholders to invest in climate-smart technologies.

3. Market Linkages and Value Addition:

- a) Developing processing units and value chains increases millet marketability and profitability.
- b) Branding and certification of millet products can create niche markets, incentivizing production.

4. Policy Support:

- a) National and regional policies promoting millet research, seed systems, and climate-smart agriculture facilitate scaling.
- b) Incentives for sustainable practices encourage farmer participation.

9. Future Research Directions

1. Breeding millet varieties with combined tolerance to multiple stresses such as drought, heat, and salinity to address complex climate challenges.
2. Investigating root system architecture and physiological traits to enhance water and nutrient acquisition efficiency under stress.
3. Employing omics technologies (transcriptomics, proteomics, metabolomics) to elucidate molecular mechanisms underlying stress responses and identify novel targets for improvement.
4. Conducting long-term, multi-location field trials to assess the cumulative impact of climate-smart practices on productivity and ecosystem services.
5. Socioeconomic research to identify adoption barriers and design tailored interventions for diverse farming communities.

Conclusion

Enhancing millet productivity under climate-induced stress demands an integrated approach combining improved agronomic management, advanced breeding technologies, innovative soil and water practices, and supportive policies. Leveraging millets' inherent resilience, coupled with scientific and technological advancements, can secure millet-based food systems against the backdrop of climate variability. Empowering farmers through capacity building and ensuring access to resources will be critical for widespread adoption of climate-resilient millet cultivation.

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Epidemiology & Disease Forecasting Models for Foliar Fungal Pathogens



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1. Introduction:

Farmers are in a constant fight against a great number of pests and diseases, and one of the most difficult and harmful ones is the foliar fungal pathogen. These agents of disease invade plant leaves, interfere with photosynthesis, lowering plant health, and eventually causing severe losses in yield. The economic and environmental consequences of these diseases are enormous, requiring proper management strategies. Conventionally, disease management was very dependent on calendar-based applications of fungicides, which, in most cases, are not very efficient and may cause resistance to pathogens and environmental issues. The disease forecasting models provide a more sustainable and focused method in the sense that it predicts the time and the severity of the disease outbreaks so that farmers can make more informed decisions as to when and where to implement control mechanisms.

2. Epidemiology of Foliar Fungal Pathogens:

The most basic idea of developing the foliar fungal pathogens is epidemiology, the study of factors that determine the occurrence and distribution of diseases in populations. These pathogens have complicated life cycles, and they interact with their hosts and with the environment. Their spread and effects are based on several important epidemiological principles:

2.1 Disease Triangle:

A triadic concept in plant pathology is the disease triangle, which depicts how three elements, which include a vulnerable host plant, a virulent pathogen, and an appropriate environment, interact to cause disease. The lack or decline of any of these components is able to prevent or reduce disease.

- a) **Susceptible Host:** Crops are highly different in terms of their susceptibility to various fungi. Susceptibility depends on factors such as the variety of plants, stages of development and nutritional status. Tolerant or resistant varieties play a very important role in integrated disease management (IDM) strategies.
- b) **Virulent Pathogen:** Both the presence and an abundance of viable pathogen inoculum are critical in the onset of disease. Pathogens are of different virulence (capability to produce disease) and aggressiveness (rate of disease progression). Sources of inoculum may be the infected plant debris, infected weeds, soil and spores carried by water or wind.
- c) **Favourable Environment:** The environmental conditions are crucial at all stages of the disease cycle. Humidity is sometimes a major necessity, which eases the germination of spores and infection. The important environmental variables are:
 - o **Temperature:** Fungi possess growth, sporulation, germination, and infection ranges of temperature. The optimal temperatures differ with the species of pathogen.
 - o **Leaf Wetness Duration (LWD):** The duration of time spent with the wet leaves (e.g. after rain, dew or irrigation) is an important consideration to many foliar pathogens. Long-term LWD is the essential moisture for spore germination and infection.
 - o **Relative Humidity (RH):** High relative humidity may also favour sporulation and germination, as well as lead to wetness of the leaves.
 - o **Wind:** Wind prevents the short-range distribution of fungal spores, which helps in the propagation of diseases.
 - o **Rainfall:** Rainfall diffuses not only the moisture needed to cause the infection but also helps in the short-distance movement of spores by splashing.

Table 3. Environmental Factors Favouring Key Foliar Fungal Pathogens

Pathogen	Disease	Host Crop	Optimal Temperature (°C)	Optimal Wetness (hours)	Leaf Duration	High Humidity Favouring	Relative
<i>Blumeria graminis</i> f. sp. <i>tritici</i>	Powdery Mildew	Wheat, Barley	15-22	No (prefers low LWD, high RH)		Yes	
<i>Puccinia triticina</i>	Wheat Leaf Rust	Wheat	15-25	>6		Yes	
<i>Septoria tritici</i>	Septoria Tritici Blotch	Wheat	15-25	>12		Yes	
<i>Alternaria solani</i>	Early Blight	Tomato, Potato	24-29	>8		Yes	
<i>Cercospora beticola</i>	Cercospora Leaf Spot	Sugar Beet	25-30	>15		Yes	
<i>Plasmopara viticola</i>	Downy Mildew	Grape	18-24	>4		Yes	

2.2 Disease Cycle:

The disease cycle is a sequence of disease events resulting in disease development and spreading. It usually deals with the following steps:

- Inoculation:** Dispersal of spores (inoculum) to the surface of a susceptible host plant.
- Germination:** Under favourable environmental conditions (e.g., specific temperature and moisture), the spore germinates, producing a germ tube.
- Infection:** The germ tube or specialised structures (e.g., appressoria) penetrate the host tissue through natural openings (e.g., stomata) or wounds.
- Colonisation (Incubation Period):** The fungus settles down in the host tissue and draws nutrients, which leads to the development of symptoms. The time interval between infection and the appearance of symptoms is termed the incubation period.
- Reproduction (Sporulation):** Spores (secondary inoculum) develop on the tissue that has been infected by the fungus.
- Dispersal:** The spores that have been generated are spread to the adjacent plants, and the new infection cycles begin.

2.3 Polycyclic and Monocyclic Diseases:

Foliar fungal diseases may be classified according to the penetration cycles that are undertaken during one growing season.

- Polycyclic Diseases:** The diseases go through numerous cycles of infection in a season. Primary infections start as a result of the initial inoculum and then give rise to secondary inoculum, causing disease spread at a very high rate and causing devastating epidemics. These may be wheat leaf rust and early blight.
- Monocyclic Diseases:** These diseases are only capable of one infection cycle every season. First inoculum leads to infections, and the second inoculum is not produced, or it does not play a significant role in within-season infection. Some of them are loose smut and certain soil-borne diseases. Foliar fungal pathogens are usually polycyclic in nature and thus very dynamic, and can cause epidemics quickly.

2.4 Rate of Disease Progress:

The rate of disease propagation in a population of plants depends on many factors, among which are the virulence of a pathogen, the predisposition of a host, environmental friendliness, and the density of initial inoculum. This rate may be measured with the help of epidemiological models, which usually can be described with logistic or exponential growth patterns.

3. Disease Forecasting Models:

Disease forecasting models are mathematical and computational models that use epidemiological and environmental data to forecast the possibility, the time, and the degree of future disease outbreaks. The final objective is to have timely information to aid in making decisions that can be used in managing the diseases, mainly the optimisation of fungicide application.

3.1 Types of Forecasting Models:

Forecasting models can be classified based on their underlying approach:

- Empirical (Statistical) Models:** These models are based on the past information to establish correlations among the environmental factors (e.g., temperature, LWD) and the recorded progression or prevalence of a disease. Such methods as regression analysis are usually applied to form predictive equations. Empirical models are comparatively easy to construct but very sensitive to the quality and representativeness of the historical data to be used. They may not be good at working in new or harsh conditions.
- Mechanistic (Process-Based) Models:** The models attempt to model the biological and ecological processes that constitute the process of disease. They integrate general understanding of the biology of pathogens, host vulnerability and environmental factors at every step (infection, latent period, sporulation, dispersal). Mechanistic models are more complicated and demand specific data in terms of biological parameters, but provide a better insight and apply to other environments.
- Hybrid Models:** Hybrid models combine features of both the empirical and the mechanistic model and can use empirical relationships to model some of the elements, but take on a mechanistic insight on other elements.

Table 4. Types of Foliar Fungal Pathogen Forecasting Models and Their Characteristics

Model Type	Description	Data Requirements	Strengths	Weaknesses	Examples
Empirical (Statistical)	Uses historical data to find relationships between environmental variables and disease.	Historical weather & disease data, specific parameters	Simpler to develop, computationally efficient	Limited generalizability, might not capture complex biological interactions.	TOMCAST (Early Blight), NEWA models
Mechanistic (Process-Based)	Simulates biological processes based on understanding of pathogen biology & ecology.	Biological parameters, detailed weather data	Greater understanding and potential for better extrapolation provide insight.	More complex to develop, requires detailed data, and higher computational needs	EIPRE (Wheat diseases), G-WHEAT (Wheat)
Hybrid	Combines elements of empirical and mechanistic models.	Combination of historical & biological data	Leverages strengths of both approaches, balances complexity & performance	Can be challenging to integrate different model components seamlessly	Some components of disease forecasting systems

3.2 Key Components of a Forecasting Model:

- Weather Data:** Timely and accurate weather data is of the essence to any disease forecasting model. Temperature, rain, relative humidity, and solar radiation are important parameters. Potential sources could be on-field weather stations, regional networks and satellite data.
- Biological Parameters:** The information regarding the biology of the pathogen is essential to mechanistic models. This involves parameters like the best temperature to use in order to germinate the spores, duration of the latent period and the rate of spore production. These parameters are frequently established using a controlled laboratory or greenhouse experiment.
- Host Characteristics:** Models may incorporate information about the host crop, such as its growth stage, variety resistance level, and canopy architecture.
- Modelling Approach:** The modelling strategy (e.g. regression, differential equations, rule-based systems, machine learning) is determined by the available data, the complexity of the disease system, and the purpose of use.

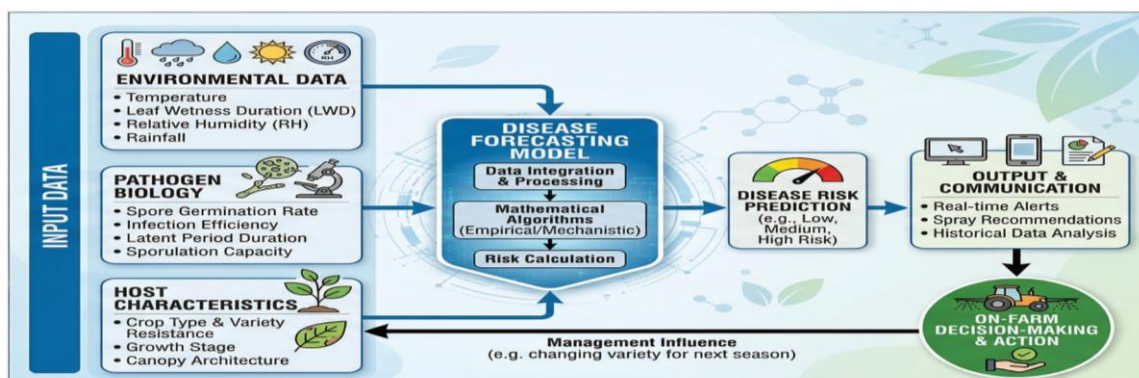


Figure 4. Conceptual Framework of a Disease Forecasting Model

4. Application of Forecasting Models:

Forecasting models are deployed on different systems and platforms:

- Regional Systems:** The regional disease forecasting systems are frequently conducted by government agencies and research institutions. Such systems receive weather information via networks of stations, models and send alerts or advisories on diseases to farmers via websites, newsletters or mobile applications.
- On-Farm Systems:** Some are incorporated into on-farm weather stations or on-farm crop management software. These enable farmers to come up with location-specific predictions depending on the exact weather conditions in their farms.
- Decision Support Systems (DSS):** More elaborate DSS take into account additional models besides other variables, such as stage of crop growth, variety resistance, and economic factors. Such systems offer particular suggestions on the timeline of fungicides, the kind of fungicides to use, and the application rate.

5. Benefits of Disease Forecasting Models:

- Optimised Fungicide Applications:** The major advantage is that the unnecessary sprays of fungicides are minimised. This results in a reduction of cost incurred by farmers and minimisation of the chances of the development of resistance against pathogens.
- Improved Disease Management:** Forecasting models can also allow farmers to take proactive measures to control the disease by alerting farmers early enough before the disease reaches critical stages.
- Reduced Environmental Impact:** The less use of fungicides will entail less chemical burden in the environment, which will minimise the risks to non-target organisms and ecosystems.
- Enhanced Yield and Quality:** The diseases are controlled in time and in an efficient manner to safeguard the crop yields and preserve the product's quality.
- Decision Making Support:** Models are useful to give significant information to aid intricate choices on the manner of managing the disease to avoid depending on the past and or the hunch.

Unveiling the Multifaceted Benefits of Disease Forecasting Models



6. Challenges and Limitations:

- Data Availability and Quality:** Weather data is an important constraint, particularly in areas with low infrastructure. Detailed biological data of certain pathogen strains and hosts whose varieties may be difficult to access can also be a difficulty.
- Model Complexity:** Before creating an appropriate mechanistic model, it is important to have a profound knowledge of complex biological systems. This requires a huge investment in research and skills.
- Generalizability:** Models developed in one region or for a specific crop variety might not perform optimally in different environmental conditions or with different pathogen strains.
- Economic Viability:** On-farm forecasting systems are expensive to implement for small-scale farmers.
- Adoption Rates:** Farmers may be unwilling to use new technologies because they are either not aware of them, or they are complex, or they lack trust in the reliability of the model.
- Uncertainty:** There is a level of uncertainty in all the forecasting models, and predictions are not certain.

7. Conclusion:

The issue of foliar fungal pathogens remains a major challenge to agriculture in the world, and the management of these pathogens is paramount. The predictive modelling of diseases is a promising and long-term mechanism for predicting disease outbreaks and management decisions. By allowing them to use environmental information and understanding of the biology of pathogens, these models have the capability to decrease the unnecessary use of fungicides, enhance the effectiveness of disease control, and help to make agricultural activity more sustainable.

Regardless of the difficulties in the availability of data and the complexity of models, the further development of sensor technology, remote sensing, as well as machine learning and genomics, is bound to increase the accuracy and usefulness of these models. Forecasting models should be incorporated into the IDM frameworks and encouraged for farmers in order to maximise their effects. With the effective use of these tools, the agricultural industry can take a more active and evidence-based stance in dealing with the foliar fungal issues, crop protection, food security, and environmental sustainability in the coming years.

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Emerging Soil Contaminants: Risk Assessment and Sustainable Remediation Approaches



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1. Introduction

Emerging soil contaminants (ESCs) represent a complex and evolving class of pollutants that pose significant challenges to environmental health, agricultural productivity, and human safety. These contaminants differ from traditional soil pollutants such as heavy metals and legacy pesticides by their novel chemical structures, sources, and behavior in soil ecosystems. ESCs include pharmaceuticals, personal care products (PPCPs), microplastics, engineered nanomaterials (ENMs), per- and polyfluoroalkyl substances (PFAS), endocrine-disrupting chemicals (EDCs), and other industrial chemicals. Their persistence, potential for bioaccumulation, and interactions with soil biota necessitate advanced risk assessment methodologies and the development of sustainable remediation technologies tailored to mitigate their impacts effectively.

This comprehensive review synthesizes current knowledge on ESCs, focusing on their nature, sources, environmental fate, risk assessment frameworks, analytical techniques, and sustainable remediation approaches. It integrates multidisciplinary insights from soil science, environmental toxicology, chemistry, and engineering to provide a holistic understanding essential for managing ESCs in soil environments.

Emerging Soil Contaminants: Risk Assessment and Sustainable Remediation Approaches

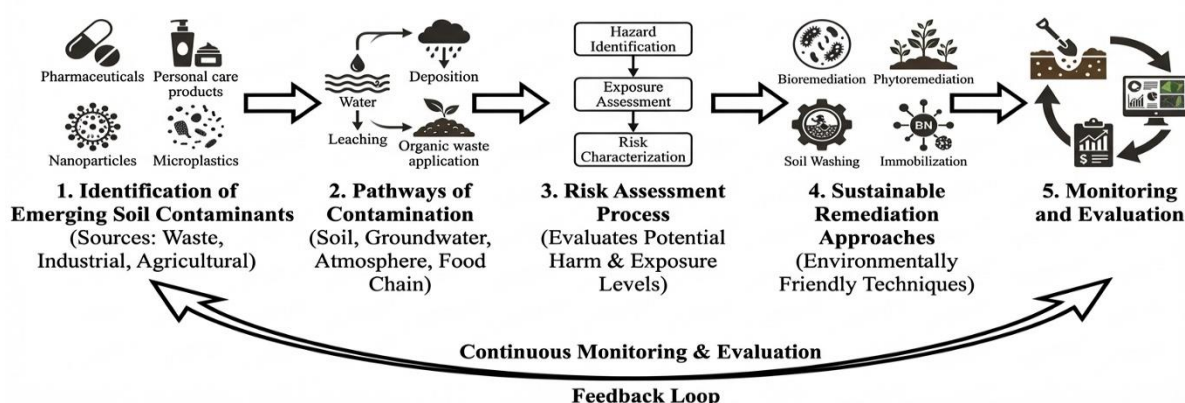


Figure 1: Conceptual Framework of Emerging Soil Contaminants

2. Nature and Sources of Emerging Soil Contaminants

2.1 Definition and Classification

ESCs are defined as contaminants newly detected in soils or those gaining recognition for their environmental and health risks. Unlike well-characterized pollutants, ESCs often lack standardized monitoring protocols and regulatory frameworks. Key categories include:

1. **Pharmaceuticals and Personal Care Products (PPCPs):** These encompass a wide range of biologically active compounds such as antibiotics, hormones, analgesics, disinfectants, and cosmetic ingredients. They enter soils primarily through land application of biosolids, wastewater irrigation, and manure from treated animals.
2. **Microplastics and Nanoplastics:** Microplastics are plastic particles less than 5 mm in size, originating from litter, tire wear, and degradation of larger plastics. Nanoplastics, smaller than 100 nm, may arise from further breakdown and pose distinct environmental behaviors due to their size.
3. **Engineered Nanomaterials (ENMs):** ENMs include nanoparticles intentionally manufactured for applications in agriculture (e.g., nano-fertilizers, nano-pesticides), industry, and medicine. Their unique physicochemical properties influence their environmental mobility, reactivity, and toxicity.
4. **Per- and Polyfluoroalkyl Substances (PFAS):** PFAS are synthetic fluorinated compounds widely used for their hydrophobic and lipophobic properties in firefighting foams, textiles, and coatings. Their chemical stability results in high persistence and bioaccumulation.
5. **Endocrine Disrupting Chemicals (EDCs):** EDCs interfere with hormonal systems and include certain pesticides, plasticizers, and industrial chemicals capable of causing reproductive and developmental effects.
6. **Other Industrial Chemicals:** This group includes flame retardants, plasticizers such as phthalates, and novel flame retardants emerging from industrial processes.

Table 1: Classification and Characteristics of Emerging Soil Contaminants (ESCs)

Category	Examples	Key Properties	Environmental Concern
PPCPs	Antibiotics, hormones, cosmetics	Biologically active, water-soluble	Antibiotic resistance, toxicity
Microplastics/Nanoplastics	Plastic fragments (<5 mm, <100 nm)	Persistent, high surface area	Soil structure alteration, toxin carriers
ENMs	Nano-fertilizers, nanoparticles	High reactivity, mobility	Unknown long-term toxicity
PFAS	Fluorinated compounds	अत्यधिक persistent, bioaccumulative	Groundwater contamination
EDCs	Plasticizers, pesticides	Hormone-disrupting	Reproductive toxicity
Industrial Chemicals	Flame retardants, phthalates	Stable, toxic	Long-term soil contamination

2.2 Sources and Pathways to Soil

1. **Agricultural Practices:** Application of animal manure, biosolids, and reclaimed wastewater introduces PPCPs, antibiotics, and microplastics into agricultural soils. The increasing use of nanomaterials in fertilizers and pesticides also contributes to direct soil contamination.
2. **Industrial Discharges:** Effluents from manufacturing, waste disposal, and accidental spills release PFAS, heavy metals, and synthetic organic chemicals into the environment.
3. **Urban Runoff and Atmospheric Deposition:** Contaminants from urban areas are transported via stormwater runoff and atmospheric deposition to peri-urban and rural soils.
4. **Landfills and Waste Dumps:** Leachate infiltration from waste sites introduces complex contaminant mixtures, including microplastics and nanomaterials, into surrounding soils.
5. **Wastewater Treatment Residuals:** Biosolids and sludge applied to land as fertilizers contain a mixture of ESCs, often at varying concentrations.

3. Environmental Fate and Behavior of Emerging Soil Contaminants

3.1 Transport Mechanisms

1. **Adsorption and Desorption:** ESCs interact with soil organic matter, clay minerals, and metal oxides. These interactions influence their mobility, bioavailability, and potential for leaching.
2. **Leaching:** Water percolation transports soluble ESCs through soil profiles, potentially contaminating groundwater. Soil texture, organic content, and contaminant solubility govern leaching rates.
3. **Volatilization:** Certain organic ESCs may volatilize under specific temperature and moisture conditions, although this is generally limited for most ESCs.

4. **Runoff and Erosion:** Surface transport during precipitation events can carry ESCs to adjacent water bodies, contributing to off-site contamination.

3.2 Degradation Processes

1. **Biodegradation:** Microbial communities in soil can metabolize some ESCs, with rates dependent on contaminant structure, bioavailability, and environmental conditions.
2. **Photodegradation:** Limited to surface-exposed contaminants, photodegradation can transform ESCs under sunlight exposure.
3. **Chemical Transformation:** ESCs may undergo hydrolysis, oxidation-reduction, and other abiotic reactions altering their chemical forms and toxicity.
4. **Persistence:** Many ESCs, notably PFAS and certain nanomaterials, are highly resistant to degradation, leading to long-term environmental persistence.

3.3 Bioavailability and Bioaccumulation

1. **Bioavailability:** The extent to which ESCs are available for uptake by soil organisms and plants depends on their binding to soil components, aging processes, and microbial activity.
2. **Bioaccumulation:** ESCs can accumulate in soil fauna and plants, potentially transferring through food webs and posing risks to higher trophic levels, including humans.

4. Risk Assessment of Emerging Soil Contaminants

4.1 Hazard Identification

1. Characterization of acute and chronic toxic effects on soil microorganisms, invertebrates, plants, and humans.
2. Identification of specific toxicological endpoints such as endocrine disruption, genotoxicity, carcinogenicity, and reproductive toxicity.

4.2 Exposure Assessment

1. Quantification of ESC concentrations in soil, pore water, plants, and soil biota.
2. Evaluation of exposure pathways including direct ingestion of soil, dermal contact, inhalation of contaminated dust, and dietary intake through crops.

4.3 Dose-Response Assessment

1. Establishment of relationships between ESC concentrations and observed adverse biological effects.
2. Consideration of sub-lethal, chronic, and mixture effects to capture realistic exposure scenarios.

4.4 Risk Characterization

1. Integration of hazard and exposure data to estimate ecological and human health risks.
2. Use of probabilistic models and uncertainty analysis to address data gaps and variability.

4.5 Challenges in ESC Risk Assessment

1. Lack of standardized analytical methods and reference materials for many ESCs.
2. Complexity arising from contaminant mixtures and potential synergistic or antagonistic interactions.
3. Insufficient ecotoxicological data, particularly for novel nanomaterials and microplastics.
4. Difficulty in quantifying bioavailability and exposure accurately.

5. Analytical Techniques for Detection and Quantification

5.1 Sampling Strategies

1. Designing representative soil sampling plans accounting for spatial variability.
2. Ensuring sample integrity by avoiding contamination and minimizing degradation during collection, transport, and storage.

5.2 Extraction and Sample Preparation

1. Employing solvent extraction, solid-phase extraction, and microwave-assisted extraction optimized for different ESC classes.
2. Tailoring protocols to maximize recovery and minimize matrix interferences.

5.3 Instrumental Analysis

1. **Chromatographic Techniques:** Gas chromatography (GC) and liquid chromatography (LC) coupled with mass spectrometry (MS) enable sensitive and selective detection of organic ESCs such as PPCPs and PFAS.
2. **Spectroscopic Methods:** Inductively coupled plasma mass spectrometry (ICP-MS) facilitates quantification of metal-based nanomaterials and heavy metals.
3. **Microscopy and Spectroscopy:** Electron microscopy (SEM, TEM) and spectroscopic techniques characterize nanomaterial morphology, size distribution, and chemical composition.
4. **Emerging Techniques:** Biosensors and immunoassays offer rapid, cost-effective screening for specific ESCs.

6. Sustainable Remediation Approaches

6.1 Principles of Sustainable Remediation

1. Minimizing secondary pollution and environmental disturbance.
2. Maximizing resource recovery, reuse, and soil restoration.
3. Enhancing soil ecosystem services and health.
4. Ensuring cost-effectiveness and social acceptability.

6.2 Physical Remediation Techniques

1. **Soil Washing and Flushing:** Application of solvents or surfactants to desorb contaminants from soil particles. Challenges include incomplete removal of ESCs and generation of secondary waste streams requiring treatment.
2. **Thermal Treatment:** Heating soils to volatilize or thermally decompose contaminants. While effective, this method is energy-intensive and may alter soil physicochemical properties adversely.
3. **Soil Replacement and Capping:** Excavation and replacement of contaminated soil or covering with clean material to isolate contaminants. Effective but expensive and disruptive to soil ecosystems.

6.3 Chemical Remediation Techniques

1. **Chemical Oxidation/Reduction:** Use of oxidants (e.g., permanganate, Fenton's reagent) or reductants to degrade organic ESCs. Process control is critical to prevent formation of harmful byproducts.
2. **Stabilization and Immobilization:** Addition of amendments such as biochar, clay minerals, or phosphates to bind ESCs, reducing their bioavailability and mobility. Particularly suited for metal contaminants.

6.4 Biological Remediation Techniques

1. **Bioremediation:** Exploiting indigenous or introduced microbial populations to biodegrade ESCs. Techniques include biostimulation (nutrient addition) and bioaugmentation (microbial inoculation). Effective for biodegradable organic ESCs such as PPCPs.
2. **Phytoremediation:** Utilizing plants and associated rhizosphere microorganisms to uptake, degrade, or stabilize contaminants. Suitable for metals, organics, and some nanomaterials. Selection of hyperaccumulator species and understanding plant-microbe interactions are critical.
3. **Vermiremediation:** Employing earthworms and other soil fauna to enhance contaminant degradation and improve soil structure and microbial activity.

6.5 Advanced and Emerging Remediation Technologies

1. **Nanoremediation:** Application of reactive nanoparticles (e.g., zero-valent iron, titanium dioxide) to degrade ESCs through redox reactions or photocatalysis. Promising but requires assessment of nanoparticle fate, transport, and ecotoxicity.
2. **Electrokinetic Remediation:** Application of electric fields to mobilize and extract charged contaminants, effective in fine-textured soils and for ionic ESCs.
3. **Constructed Wetlands and Bioreactors:** Engineered ecosystems combining physical, chemical, and biological processes to treat contaminated runoff and leachates.
4. **Integrated Remediation Systems:** Combining multiple remediation approaches tailored to site-specific ESC mixtures and soil characteristics to maximize efficacy.

Remediation techniques ranked by invasiveness and environmental impact.



7. Monitoring and Long-Term Management

1. Establishing comprehensive monitoring programs to evaluate remediation effectiveness and ESC fate over time.
2. Utilizing bioindicators, molecular biomarkers, and advanced analytical methods to assess ecological recovery and residual risks.
3. Implementing adaptive management strategies that incorporate emerging scientific data and technological advances.

8. Regulatory and Policy Perspectives

1. Recognition of existing regulatory gaps concerning ESCs in soil environments.
2. Development and harmonization of guidelines and risk-based frameworks for ESC monitoring and management.
3. Promotion of sustainable remediation through policy incentives, standards, and best practice dissemination.
4. Engagement of stakeholders, including farmers, industry, policymakers, and the public, to raise awareness and foster collaborative management.

9. Case Studies and Practical Applications

1. Successful bioremediation of antibiotic-contaminated agricultural soils using specialized microbial consortia with demonstrated reduction in contaminant levels and toxicity.
2. Phytoremediation projects targeting PFAS-contaminated soils employing deep-rooted plants and rhizosphere engineering to stabilize and uptake contaminants.
3. Nanoremediation trials focusing on pesticide degradation in agricultural soils using zero-valent iron nanoparticles, showing enhanced degradation rates.
4. Integrated remediation efforts in urban landfill-impacted soils combining soil washing, bioremediation, and phytoremediation to address complex contaminant mixtures.

10. Conclusion

Emerging soil contaminants present multifaceted challenges that require integrated, multidisciplinary approaches for effective risk assessment and remediation. Sustainable remediation strategies that combine physical, chemical, and biological techniques, tailored to site-specific conditions and contaminant profiles, offer effective solutions while preserving soil health and ecosystem services. Advances in analytical technologies, risk modeling, and remediation methods, supported by robust regulatory frameworks and stakeholder collaboration, are essential to managing ESCs and safeguarding soil resources for current and future generations.

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Fish Disease Management and Health Monitoring in Aquaculture Systems



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1. Introduction

As the aquaculture sector has grown faster, the risk of disease outbreaks has also increased. Stress and pathogen transmission (bacteria, viruses, parasites, fungi) could be enhanced by intensive conditions of culture (high fish densities, closed water systems and controlled feeding regimes). These pathogens may lead to high levels of mortality, low growth rates and poor quality of the products, resulting in high losses of revenue. Proper management of the disease takes a multi-faceted approach involving preventative care, early diagnosis and effective treatment. Moreover, effective health surveillance initiatives are essential in the prediction of possible outbreaks, as well as assessing the effectiveness of control measures. The article deals with key elements of a proactive fish health management program.

Fish Disease Management and Health Monitoring in Aquaculture Systems

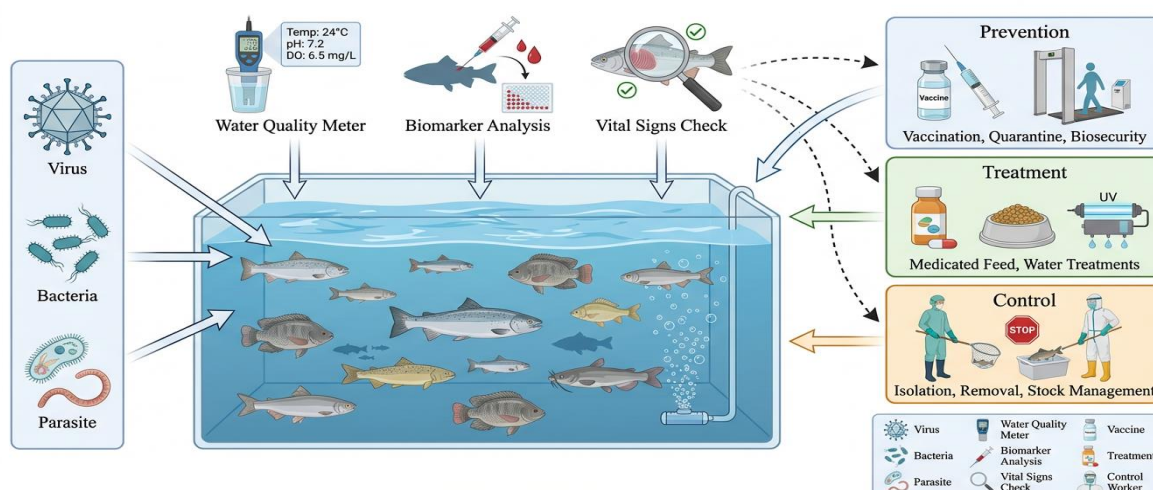


Figure 1: Fish Disease Management and Health Monitoring in Aquaculture Systems

2. Principles of Disease Management

The traditional epidemiological triad, the host, the pathogen and the environment, forms the basis of the main principle of fish disease management.

- **Host Factors:** Ages, life stage, nutritional conditions, overall health, strain, species, and genetics are susceptible factors to disease.
- **Pathogen Factors:** The virulence, dose and persistence of the pathogen are crucial.
- **Environmental Factors:** Water quality parameters (e.g., temperature, dissolved oxygen, pH, ammonia), stocking density, handling stress, and the presence of other environmental stressors significantly affect fish health and disease susceptibility.

Effective disease management entails manipulation of these aspects in order to reduce the chances of disease. Such a reactive method, with which we merely react to the situation after an outbreak has happened, is not always sufficient, and therefore not cost-effective. Preventive strategy is much more proactive.

2.1 Preventive Measures

The foundation of sustainable management of aquaculture diseases consists of prevention. It is the most economical method of containing the disease, as well as to avoid its intrusion into the system in the first place.

2.1.1 Biosecurity Protocols

Biosecurity is defined as the steps put in place in order to ensure that there is no introduction, spread and persistence of infectious agents in an aquaculture plant. Strong biosecurity measures are needed, and they usually involve:

- Quarantine:** It is always necessary to have a strict quarantine period with the introduction of new stock. Fish ought to be isolated, observed to detect any form of illness, and even treated for pathogens and later incorporated into the primary culture system.
- Sanitisation:** It is essential to have stringent measures regarding disinfection of equipment (nets, tanks, pumps, vehicles), infrastructure in the facility, and the staff. It is usually used with iodine-based disinfectants, chlorine solutions and ultraviolet (UV) radiation.
- Controlled Access:** It is significant to restrict access to the facility and strictly regulate the movement throughout the various parts of the farm. There is a need to observe strict hygiene protocols by visitors and staff.
- Vector Control:** The measures required to control any possible vectors of the disease, such as wild fish, birds, insects, and other water sources that may have been contaminated, are essential.

Table 1: Key Components of an Aquaculture Biosecurity Plan

Biosecurity Component	Rationale	Example Actions
Site Selection & Design	Minimise environmental stressors and pathogen exposure.	Choose locations with good water quality, adequate distance from other farms, and design systems for easy cleaning.
Water Quality Management	Reduce environmental stress and inhibit pathogen growth.	Regular monitoring, effective filtration, proper stocking density, and appropriate feeding practices.
Seed Stock Management	Ensure only healthy fish enter the system.	Use certified disease-free broodstock and fingerlings from reputable sources. Implement quarantine protocols.
Equipment & Facility Sanitisation	Eliminate pathogens on surfaces and equipment.	Implement strictly enforced cleaning and disinfection procedures for all shared equipment and surfaces.
Vector Control	Prevent the introduction of pathogens by other organisms.	Install netting, fencing, and control measures for pests and potential disease-carrying organisms.
Personnel Hygiene	Reduce the risk of pathogen transfer by workers.	Implement procedures for hand washing, changing clothes, and cleaning footwear upon entering and exiting culture areas.
Feed Management	Minimise potential contamination and optimise fish health.	Use high-quality, pathogen-free feed. Store feed properly and monitor for mould or spoilage.
Waste Management	Properly dispose of dead fish and effluent.	Implement protocols for removing and disposing of mortalities and managing farm waste according to regulations.

2.1.2 Health Monitoring and Surveillance

A health survey should be carried out regularly and systematically to identify the initial signs of a disease outbreak. This includes:

- Routine Observations:** The trained staff are supposed to monitor a fish regularly, i.e., to notice a symptom of behaviour (e.g., loss of appetite, swimming lethargy), physical appearance (e.g., skin lesions, gill discolouration, fin rot), or high mortality rates.
- Pathogen Screening:** Regular screening of healthy or at-risk fish populations for specific pathogens (e.g., viruses, bacteria) is crucial for identifying asymptomatic carriers and initiating early interventions.
- Water Quality Monitoring:** The most important aspect is maintaining the optimum water quality. Constant observation of such parameters as temperature, dissolved oxygen, pH, ammonia, nitrite, and carbon dioxide gives vital information to avoid stressful conditions in the environment and to see the environment with its favourable conditions for pathogens.

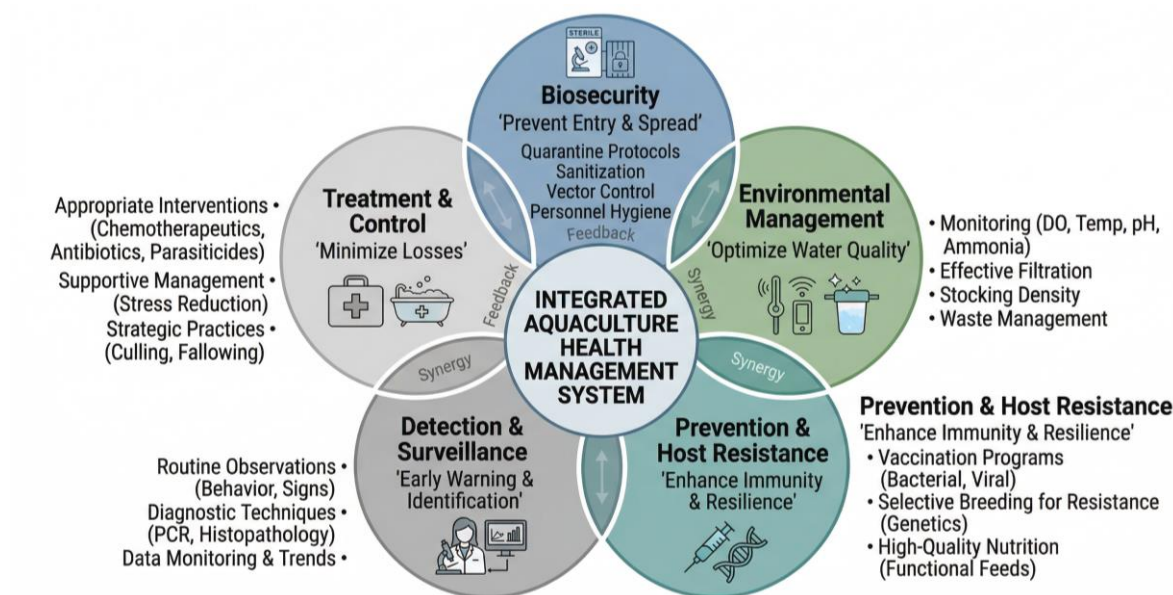


Figure 2. Integrated Aquaculture Health Management System

2.1.3 Vaccination Programs

Vaccines have potent potential in improving the selective immune reaction of fish and minimising the occurrence and intensity of illness. There are bacterial and viral vaccines with different efficacies, depending on the species and the particular pathogen and method of delivery.

- **Vaccination Methods:** Fish can be immunised by means of immersion (dip), feeding (feed additives), or injecting (manual or automated). The most common technique is injection, which is usually the most effective yet demanding and the most expensive.
- **Vaccine Development:** Current research efforts are in the development of newer and more effective vaccines, such as DNA vaccines and oral delivery systems, with the hope of having broad-spectrum protection and ease of administration.

2.2 Diagnostics and Disease Identification

Early and proper diagnosis is essential in commencing the proper treatment or management intervention. Standard diagnostic practices are important in order to provide reliability and consistency among laboratories.

Table 2: Common Diagnostic Techniques in Fish Health

Diagnostic Technique	Type	Application
Histopathology	Microscopic Examination	Analysis of tissue structure to detect lesions, cellular changes, and the presence of intracellular pathogens.
Microbiology	Culture & Sensitivity	Isolation and identification of bacterial pathogens from infected tissues. Determining antibiotic sensitivity is critical for guiding treatment.
Virology	Cell Culture & Molecular Techniques	Detection and identification of viruses, often using cell lines and Polymerase Chain Reaction (PCR) based assays (e.g., real-time qPCR).
Parasitology	Wet Mounts & Microscopic Exam	Identification and quantification of external and internal parasites (protozoa, helminths, crustaceans).
Molecular Techniques	PCR, Real-time qPCR	Highly sensitive and specific methods for the rapid detection and quantification of pathogen nucleic acids (DNA/RNA).
Immunological Techniques	ELISA, Western Blot	Detection of specific antibodies or antigens related to a pathogen, useful for diagnosing past or present infections.

2.2.1 Advanced Molecular Diagnostics

Diagnosis of fish diseases has been revolutionised by the use of molecular tools, especially PCR and real-time qPCR. These methods offer:

- High Sensitivity and Specificity:** The low levels of pathogens can be detected early, even before the clinical minimal manifestation.
- Rapid Turnaround Times:** With the help of quick results, it is possible to make a quick managerial decision, and the results are often provided within a few hours.
- Quantification:** qPCR is a method of real-time quantification of pathogen load, which gives an idea of the severity of an infection.

The current trends are concentrating on portable and multiplex diagnostic platforms to perform diagnostic tests rapidly and in the field.

2.3 Treatment and Control Strategies

Once a disease outbreak takes place, the pathogen needs to be contained as soon as possible to ensure as few losses as possible. The choices of treatment applied in aquaculture are usually fewer than those in terrestrial agriculture, so their application has to be taken into consideration.

2.3.1 Chemotherapeutics

Practice of chemotherapeutics (use of chemicals) to treat diseases in fish includes:

- Antibiotics:** These play a vital role in the treatment of bacterial infections. Nevertheless, the development of antibiotic resistance is one of the primary issues, and their use must be reasonable and with no deviations (when it is necessary). Sensitivity analysis is necessary to guarantee effectiveness.
- Parasiticides:** These are used to treat both external and internal parasites (e.g. bathing sea lice with formalin, protozoa with formalin). Another problem in parasitic control is the development of resistance.
- Disinfectants/Antiseptics:** This is applied to the topical treatment of wounds or external infections or used as an agent of general farm hygiene.

Regulatory Framework: The use of chemotherapeutics in aquaculture is strictly regulated in many regions to protect consumer health and the environment. Withdrawal periods must be carefully adhered to.

2.3.2 Environmental Management

The management of a disease outbreak is usually started with the most important part of optimizing the environmental conditions. Key strategies include:

- Improving Water Quality:** While stress can be reduced by increasing the amount of dissolved oxygen, pH optimisation, and reducing the concentrations of ammonia and nitrite, to increase fish resilience.
- Reducing Stocking Density:** The reduction of the pathogen transmission and competition for resources can be achieved through the decrease in the level of concentration of fish.
- Stress Reduction:** Minimising handling, avoiding transport, and maintaining stable water parameters are crucial for supporting recovery.

3. Health Monitoring and Disease Surveillance

The extensive health surveillance and monitoring initiatives are important to:

- Early Detection:** This is where the potential disease outbreak is established before the organisation incurs huge losses.
- Efficacy Assessment:** Evaluating the effectiveness of prevention and treatment strategies.
- Risk Assessment:** The discovery of the emerging pathogens and their possible effect.

3.1 Data Management and Analysis

Effective health monitoring depends on effective data collection, data management, and data analysis. Systems must be created to monitor:

- Deaths (unit and time-based, and possibly cause-specific)
- Performance parameters growth
- Feed rates and food conversion ratios (FCR)
- Water quality data
- Health findings and diagnostic findings.

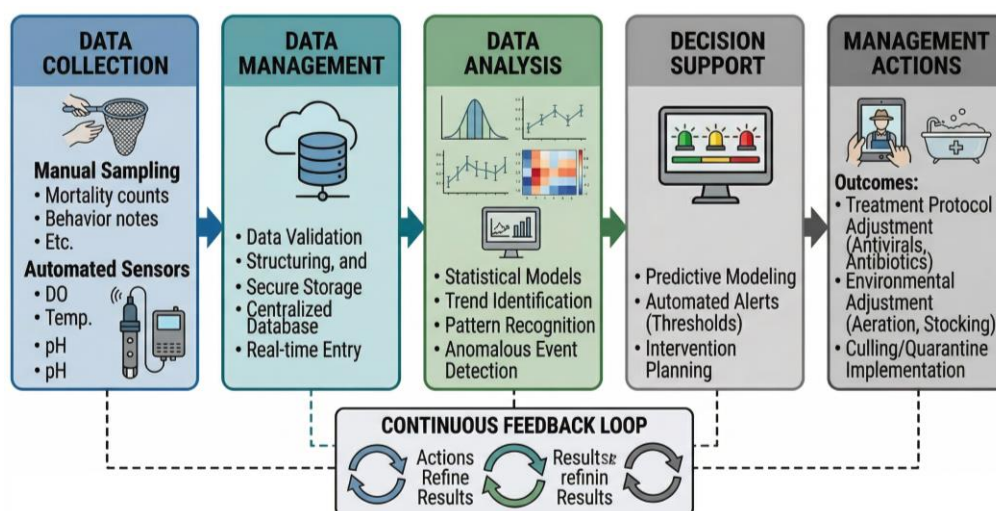


Figure 3. Workflow for Fish Health Monitoring and Disease Surveillance

4. The Role of Nutrition in Fish Health

Healthy eating is essential to the good functioning of the immune system and an increase in disease resistance. Nutritional deficiencies may predispose to pathogen infection, whereas a particular functional ingredient may enhance immune activity.

- Macronutrients:** Optimal levels of protein, lipids, and carbohydrates are essential for growth and metabolic function, including the maintenance of mucosal barriers and immune responses.
- Micronutrients:** Vitamins (e.g., Vitamin C, Vitamin E) and minerals (e.g., zinc, selenium) are critical for antioxidant function and immune system regulation.
- Functional Feeds:** Feeds that are fortified with certain compounds like immunostimulants, probiotics, prebiotics and essential fatty acids are intended to increase disease resistance.

5. Environmental Influences on Fish Health

Among the factors that may influence fish health and disease dynamics strongly are environmental factors:

- Temperature:** This is very critical in influencing both fish and pathogen metabolism. Sudden fluctuation in temperatures may cause stress and weaken the immune system. The proliferation of most pathogens can be encouraged by high temperatures.
- Dissolved Oxygen (DO):** Weak DO levels constitute one of the main stressors in the aquaculture mean resulting in depressed appetites, retarded growth, and vulnerability to diseases.
- pH:** Radical pH levels (both acidic and alkaline) may irritate gills and mucosal surfaces, which allow pathogens.
- Ammonia and Nitrite:** Toxic nitrogenous wastes may intensively affect the gill, kidney, and other organs, inhibit the immune system, and predispose to diseases.

The most important factor is ensuring that the water quality remains at and exceeds optimal levels, and this occurs by the use of good filtration, circulation, aeration, and the need to change the water on a regular basis (where necessary).

6. Emerging Diseases and Global Challenges

The aquaculture industry is continually threatened by the development of new diseases, usually with the help of:

- Global Trade:** Fish, eggs and equipment that are moved across international borders have the potential of exposing new pathogens to new geographical areas.
- Climate Change:** There is an increase in the water temperature, alterations in the precipitation cycle, and an increase in the number of extremes of weather, which can change the virulence of the pathogen, the distribution of the vectors, and the stress of the environment.
- Intensification:** The further increase in the intensity of production systems raises the threat of diseases.

To combat these new menaces, international collaboration, uniform diagnostic and regulatory measures, and further studies on preventative and curative measures are necessary.

7. Conclusion

Management of fish diseases and health monitoring should be incorporated into the overall sustainable and profitable aquaculture systems. It is based on a multi-faceted approach that places an emphasis on preventative strategies, such as strong biosecurity, effective vaccination programs, and genetic enhancement. The timely and prompt diagnostics, as well as the proper treatment and control plans, are essential in the event of disease outbreaks. Moreover, proactive health surveillance performed on a consistent and organised basis with the help of data management and analysis is essential to the early warning and assessment of management effectiveness. The interaction of fish health, nutrition and environmental environments and the regulatory systems highlights the multi-faceted nature of this important discipline. Further research, innovation, and international cooperation are essential to handle the new challenges and achieve the long-term sustainability of the aquaculture sector.

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Fish Nutrition and Feed Innovations in Modern Aquaculture



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1. Introduction

Aquaculture has been the most rapidly expanding food-producing industry in the world, which is critical in the provision of protein needs of a projected population of 9.7 billion as we head towards 2050. But there is a serious problem with the intensification of fish farming: nutritional efficiency. The feed costs in intensive aquaculture comprise about 50-70 per cent of the total costs of operation. As a result, the shift towards the conventional farm-made diet, to the nutritionally balanced, extruded diet, and the continued search for sustainable ingredient sources are what the contemporary aquatic science borders on.

2. Fundamentals of Fish Nutrition

Fish, unlike terrestrial livestock, have specific metabolic needs depending on the aquatic habitat. They are ectothermic, i.e. their metabolism depends on water temperature and have high protein demand both as sources of energy and protein growth.

2.1 Protein and Amino Acids

The costliest and most crucial ingredient of fish food is protein. It contains the essential amino acids (EAAs) that are required in tissue construction and enzymatic activities. The ten essential amino acids needed by most finfish include: arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine.

2.2 Lipids and Essential Fatty Acids

Many living beings depend on lipids as the major source of energy, leaving protein to grow. More to the point, fish (in particular, marine species) demand long-chain polyunsaturated fatty acids (LC-PUFAs) like Eicosapentaenoic acid (EPA) and Docosahexaenoic acid (DHA), which are essential in membrane fluidity and immunity.

2.3 Carbohydrates and Energy Utilisation

Although carnivorous fish species can metabolise low amounts of glucose, herbivorous and omnivorous species, such as Tilapia and Carp, can oxidise increased amounts of starch in their diet. In modern processing of feeds (extrusion), the starch is gelatinised so that it is easier to digest.

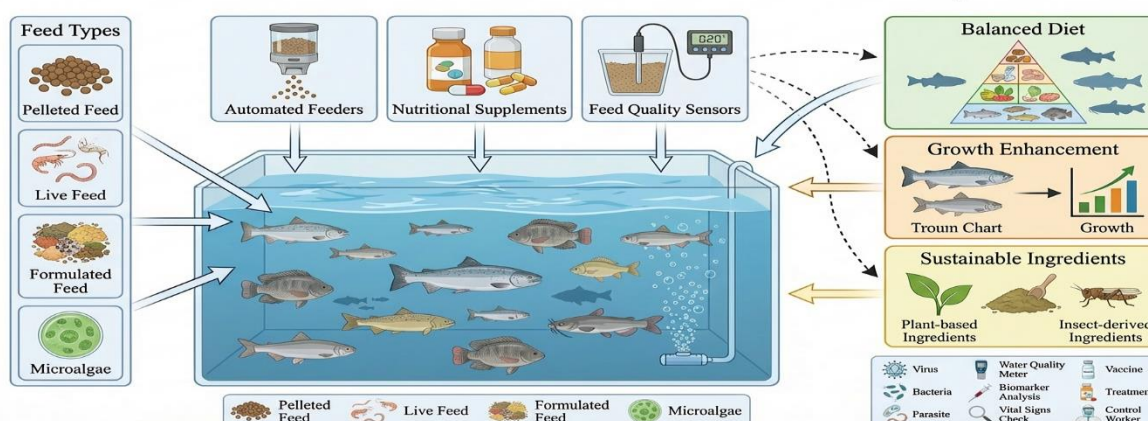


Figure 5. Fish Nutrition and Feed Innovations

3. The Shift Toward Alternative Ingredients

Historically, the gold standard of the aquaculture feed was Fishmeal (FM) and Fish Oil (FO), with these products being ideal in terms of amino acid balance and palatability. Nevertheless, serious stagnation in the wild-capture

fisheries and increased costs have relegated the industry to the so-called FIFO (Fish-In: Fish-Out) reduction approach.

3.1 Plant-Based Proteins

The most ubiquitous alternative is soybean meal; however, it has anti-nutritional factors (ANFs) such as phytates and protease inhibitors. New developments entail the application of Soy Protein Concentrates (SPC) and fermented plant products to enhance bioavailability.

3.2 Insect Meal

Black Soldier Fly (BSF) larvae (*Hermetia illucens*) and Mealworms (*Tenebrio molitor*) have made inroads. Organic waste has the potential to be reared into insects and transform low-quality by-products into high-quality protein (40-60%) and lipids.

3.3 Single-Cell Proteins (SCP)

It is possible to engineer microalgae, bacteria and yeast in bioreactors, which are bio-factories. Proteins derived from bacteria, e.g., contain a high protein content and can be cultivated on methane or CO₂ as a carbon source, therefore, decoupling the production of feed sources from arable land.

Table 5. Comparison of Conventional and Alternative Protein Sources

Ingredient	Protein Content (%)	Lipid Content (%)	Key Advantages	Major Constraints
Fishmeal	65–72	8–12	High palatability, ideal EAA profile	High cost, ecological sustainability
Soybean Meal	44–48	1–2	Low cost, steady supply	Anti-nutritional factors, low Methionine
Insect Meal (BSF)	40–55	15–35	High palatability, circular economy	Scalability, high chitin content
Microalgae	30–60	10–25	Rich in EPA/DHA	High production cost
Bacterial SCP	60–80	5–10	Small land footprint	Consumer acceptance, nucleic acid levels

4. Innovations in Feed Additives and Functional Feeds

The trend in modern aquaculture is no longer the use of aquaculture as a means of survival nutrition but as a means of functional nutrition, i.e. dietary practices aimed at promoting health, stress resistance and environmental sustainability.

4.1 Prebiotics, Probiotics, and Postbiotics

- **Probiotics:** Live beneficial bacteria (e.g., *Bacillus*, *Lactobacillus*) that improve gut microbiota and outcompete pathogens.
- **Prebiotics:** Non-digestible fibres (e.g., MOS, FOS) that selectively stimulate the growth of beneficial gut microbes.
- **Postbiotics:** Non-living micro-organisms and /or their constituents that provide a health benefit to the host.

4.2 Enzymes and Phytase

Feed contains exogenous enzymes such as proteins and carbohydrases, which are introduced to digest complex molecules that the fish cannot digest. Specifically, phytase is very important; it liberates the phosphorus that is trapped in plant phytates, so that less phosphorus is released to the water, hence eutrophication is prevented.

5. Precision Nutrition and Feed Manufacturing

As important as the chemical composition of the feed is its physical properties.

5.1 Extrusion Technology

In the modern twin-screw extruders, it is possible to have a high level of control over the buoyancy (floating or sinking) of the pellets, their durability, and resistance to water. This will preserve the feed till the time it is fed on, thus reducing nutrient erosion and water contamination.

5.2 Micro-encapsulation

In the case of a larval fish, which has an underdeveloped digestive tract, micro-encapsulation prevents the loss of sensitive nutrients (vitamins, enzymes) and guarantees their entrance to the hindgut (absorption). Nanotechnology

in nutrition: Nanotechnology involves using small particles to produce various products, including nanotextiles, nano-reductive nanoparticles, nanoproducts, and nanoparticle devices.

5.3 Nanotechnology in Nutrition

Nanotechnology is the application of small particles to create different products, such as nanotextiles, nanoproducts, nanoparticle devices and nano-reductive nanoparticles. Absorption rates have been improved by the use of nano-minerals (e.g., Nano-Selenium, Nano-Zinc) because they have a high surface-area-to-volume ratio. This gives the opportunity to lower the inclusion levels and attain superior growth performance and immune response.

6. Sustainability and Environmental Impact

It is no longer only about growth when feeding fish, but also the Feed Conversion Ratio (FCR). When the FCR is lower, the feed needed to raise 1 kg of fish is also lower, and this is directly proportional to the environmental footprint.

Table 6. Average FCR of Major Aquaculture Species

Species	System Type	Typical FCR	Feed Innovation Opportunity
Atlantic Salmon	Intensive Cage	1.1–1.3	High-energy, low-FM diets
Nile Tilapia	Semi-intensive Pond	1.4–1.7	Utilisation of biofloc and plant protein
Pangasius	Intensive Pond	1.5–1.8	Improvement of byproduct utilization
Shrimp (<i>L. vannamei</i>)	Intensive Raceway	1.2–1.6	Water-stable pellets, attractants

6.1 Mitigation of Nitrogen and Phosphorus Discharge

The ammonia and phosphate in the water are caused by overfeeding or the quality of the feed. Low pollution feeds have innovations that use highly digestible feeds and the use of precise amino acid ratios (ideal protein concept) to minimise metabolic nitrogen excretion.

7. Challenges and Future Directions

The obstacles are still numerous, although a technological breakthrough has taken place:

1. **Cost of Alternatives:** Insect meal and SCP are potential products, but at this time, they are not able to compete with the price of soybean meal.
2. **Palatability:** Fishmeal contains the so-called attractants, which are not present in many alternative proteins; thus, the intake of these proteins is ensured by the use of synthetic stimulants.
3. **Regulatory Frameworks:** International trade is complicated by the variation in the standards of the use of processed animal proteins (PAPs) and genetically modified (GM) crops in the countries.

8. Conclusion

Change in fish nutrition is oscillating towards dependence on marine-based foods with a more diversified collection of sustainable options, which is technology-based. The aquaculture sector can make sure its sustainability in the long term by incorporating precision production, functionality additives, and the concept of the circular economy. The research in the future should still be on the approach, which is referred to as the Omics, which is that of nutrigenomics and proteomics, to discover how certain nutrients can affect gene expression in fish and eventually create personalised diets that help to improve the welfare and productivity of the fish.

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Impact of Agricultural Intensification on Soil Ecological Networks and Food Webs



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1. Introduction

Agricultural intensification involves the increased use of synthetic fertilizers, pesticides, mechanization, monoculture cropping, and irrigation to boost crop yields and meet global food demand. While successful in enhancing productivity, these practices have significant adverse effects on soil ecological networks and food webs, which are critical for maintaining soil health, nutrient cycling, organic matter decomposition, and ecosystem resilience. Soil organisms ranging from microorganisms to macrofauna form complex, interdependent networks that regulate these essential soil processes. Disruptions to these networks threaten the sustainability of agricultural systems by impairing soil functionality, reducing biodiversity, and weakening ecosystem services. Understanding these impacts and their mechanisms is vital for developing sustainable agricultural practices that safeguard soil ecosystems and promote long-term productivity.

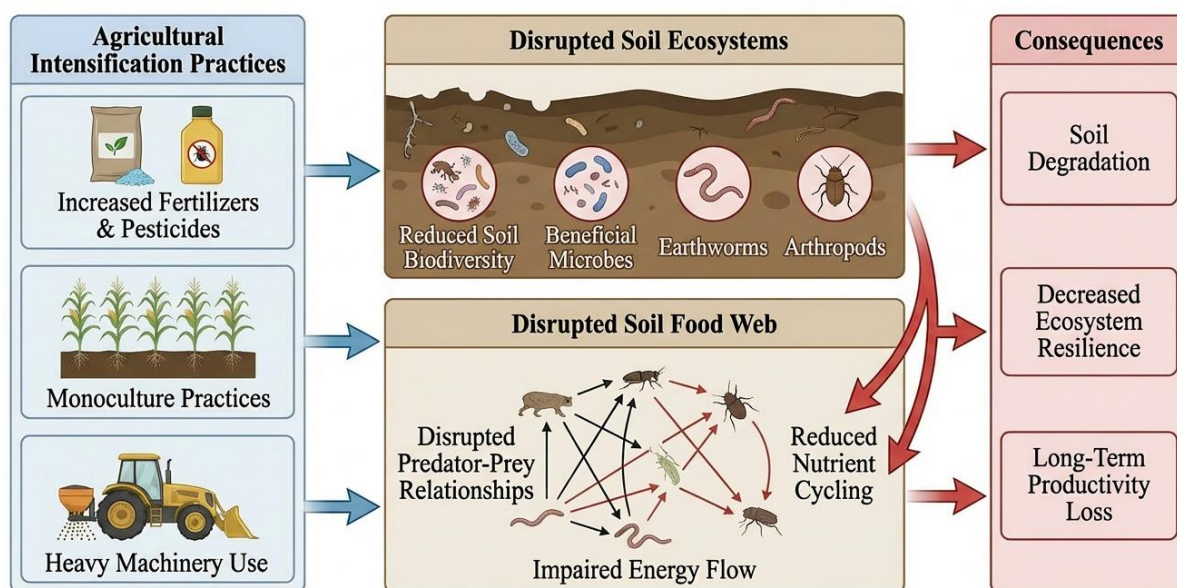


Figure 1: Impact of Agricultural Intensification on Soil Ecological Networks and Food Webs

2. Soil Ecological Networks and Food Webs: Concepts and Importance

2.1 Definition and Structural Components

Soil ecological networks consist of the complex interactions among diverse soil organisms, including bacteria, archaea, fungi, protozoa, nematodes, microarthropods, earthworms, and larger fauna. These networks facilitate the decomposition of organic matter, mineralization of nutrients, soil aggregation, and suppression of soil-borne diseases. Soil food webs describe the trophic interactions and energy flows among these organisms, from primary decomposers (microorganisms) through microbivores, predators, and omnivores. The structure of these networks, characterized by species richness, trophic diversity, and interaction strength, underpins ecosystem stability and resilience by providing functional redundancy and buffering capacity against disturbances.

2.2 Functional Roles in Soil Ecosystems

- Microbial Communities:** Microorganisms, including bacteria and fungi, are the primary drivers of organic matter decomposition and nutrient cycling. They transform complex organic compounds into

mineral forms accessible to plants and form symbiotic relationships such as mycorrhizae, which enhance nutrient uptake.

- b) **Mesofauna and Macrofauna:** Soil fauna such as nematodes, collembolans, mites, and earthworms regulate microbial populations through predation, aid in organic matter fragmentation, and contribute to soil structure formation by creating pores and aggregating particles.
- c) **Trophic Interactions:** The interactions among different trophic levels maintain population control, facilitate energy transfer, and increase ecosystem resilience. Functional redundancy within trophic levels ensures that the loss of some species does not compromise overall ecosystem functioning.

2.3 Soil Food Web Complexity and Ecosystem Stability

The complexity of soil food webs, including the number of species and the diversity of trophic interactions, is directly linked to ecosystem stability. High complexity allows for multiple pathways of energy flow and nutrient cycling, making the system more resilient to perturbations such as drought, pest outbreaks, or chemical disturbances. Functional redundancy ensures that key processes continue even if some species decline.

3. Agricultural Intensification: Practices and Soil Impacts

3.1 Characteristics of Agricultural Intensification

Agricultural intensification is typified by:

- a) **Increased Chemical Inputs:** The application of synthetic fertilizers supplies essential nutrients to crops but can alter soil chemistry and microbial communities. Pesticides (herbicides, insecticides, fungicides) are used to control pests and diseases but may also affect non-target soil organisms.
- b) **Monoculture Cropping Systems:** The practice of growing a single crop species over large areas reduces plant diversity and homogenizes the soil environment.
- c) **Tillage and Mechanization:** Frequent tillage disturbs soil structure, while heavy machinery compacts soil, affecting habitat quality for soil organisms.
- d) **Irrigation Expansion:** Increased water application modifies soil moisture regimes, impacting microbial activity and nutrient dynamics.

3.2 Direct and Indirect Effects on Soil Biota

- a) **Chemical Toxicity:** Agrochemicals can be toxic to soil organisms, reducing their abundance and diversity. Pesticides may cause mortality or sub-lethal effects such as impaired reproduction or behavior.
- b) **Habitat Homogenization:** Monocultures reduce habitat heterogeneity, limiting microhabitats and ecological niches necessary for diverse soil communities.
- c) **Physical Disruption:** Tillage and compaction physically disturb soil aggregates and microhabitats, directly damaging soil fauna and altering microbial habitats.
- d) **Altered Resource Availability:** Changes in organic matter inputs and soil chemistry affect the quantity and quality of substrates available to soil biota, influencing community composition and function.

4. Effects on Soil Biodiversity and Community Composition

4.1 Decline in Species Richness and Abundance

Intensive agricultural practices often lead to significant reductions in soil biodiversity. Pesticides and fertilizers may directly reduce populations of bacteria, fungi, nematodes, and soil fauna through toxicity. Habitat homogenization due to monocultures further restricts available niches, leading to the loss of specialist and sensitive species. Empirical studies document declines in earthworm biomass, collembolan diversity, and microbial richness in intensively managed soils compared to natural or less disturbed systems.

4.2 Shifts in Microbial and Faunal Community Composition

- a) **Microbial Shifts:** Fertilizer-induced nutrient enrichment favors fast-growing, copiotrophic bacteria that thrive in nutrient-rich environments, often at the expense of oligotrophic taxa adapted to low-nutrient conditions. This shift can disrupt nutrient cycling processes.
- b) **Mycorrhizal Decline:** Excess phosphorus fertilization suppresses arbuscular mycorrhizal fungi, which are critical for plant nutrient uptake and soil structure maintenance.
- c) **Faunal Changes:** Declines in keystone fauna such as earthworms and predatory nematodes reduce soil aeration, organic matter decomposition, and natural pest control.

4.3 Loss of Functional Diversity and Keystone Species

Functional diversity, the range of different functional roles played by soil organisms, is essential for ecosystem processes. Loss of keystone species—organisms that have disproportionate effects on ecosystem function—leads

to impaired soil aggregation, nutrient cycling, and pest regulation. Reduced functional redundancy increases ecosystem vulnerability to disturbances.

Table 1: Impact of Agricultural Intensification on Soil Biota and Food Web Structure

Component	Key Organisms	Role in Soil Ecosystem	Effect of Intensification	Ecological Impact
Microorganisms	Bacteria, fungi	Decomposition, nutrient cycling	Reduced diversity, dominance shift	Slower nutrient cycling
Microfauna	Nematodes, protozoa	Microbial regulation	Decline in trophic diversity	Imbalanced food web
Mesofauna	Mites, collembola	Organic matter breakdown	Reduced population (pesticides)	Lower decomposition rate
Macrofauna	Earthworms, insects	Soil structure formation	Decline due to tillage	Poor aggregation
Predators	Beetles, spiders	Control prey populations	Reduced due to chemicals	Weak trophic regulation

5. Disruption of Soil Food Web Structure and Function

5.1 Simplification and Reduced Trophic Complexity

Agricultural intensification simplifies soil food webs by reducing species diversity and trophic interactions. This simplification diminishes network connectivity and functional redundancy, weakening ecosystem stability and resilience. Simplified food webs have fewer pathways for energy flow and nutrient cycling, making them more susceptible to environmental stresses.

5.2 Altered Energy Flow and Nutrient Cycling

Changes in decomposer and consumer communities affect the rate and pathways of organic matter decomposition and nutrient mineralization. For example, a shift from fungal- to bacterial-dominated decomposition can accelerate nitrogen mineralization but increase nitrogen losses via leaching or gaseous emissions. Disrupted predator-prey relationships may lead to pest outbreaks and reduced suppression of soil pathogens.

5.3 Impairment of Soil Ecosystem Services

The cumulative effects of biodiversity loss and food web simplification lead to declines in critical ecosystem services such as soil aggregation (which affects water retention and aeration), nutrient retention, disease suppression, and carbon sequestration. These impairments reduce soil fertility and productivity, increasing reliance on chemical inputs and undermining long-term sustainability.

Table 2: Functional Consequences of Soil Food Web Disruption

Soil Function	Healthy Soil System	Intensified System	Long-Term Impact
Nutrient Cycling	Efficient and balanced	Disrupted	Reduced fertility
Soil Structure	Stable aggregates	Weak structure	Increased erosion
Carbon Sequestration	High SOC storage	Low SOC	Climate impact
Disease Suppression	Strong biological control	Weak	Increased pests/diseases
Productivity	Sustainable yield	Short-term increase	Long-term decline

6. Mechanisms Underlying Soil Food Web Alterations

6.1 Chemical Inputs

- Fertilizers:** High fertilizer inputs alter soil nutrient ratios and pH, favoring certain microbial groups (e.g., bacteria) over others (e.g., fungi), which can disrupt nutrient cycling balance.
- Pesticides:** Herbicides, insecticides, and fungicides can cause direct mortality or sub-lethal effects on soil fauna, altering population dynamics and trophic interactions.
- Herbicides and Fungicides:** These may affect microbial communities and disrupt symbiotic relationships, further cascading through the food web.

6.2 Physical Disturbances

- Tillage:** Repeated plowing breaks soil aggregates, disrupts fungal hyphal networks, and destroys earthworm burrows, fragmenting habitats.

b) **Soil Compaction:** Machinery compacts soil, reducing pore space, limiting oxygen diffusion and water infiltration, which are critical for microbial and faunal activity.

c) **Mechanical Damage:** Heavy equipment physically damages soil organisms and their microhabitats.

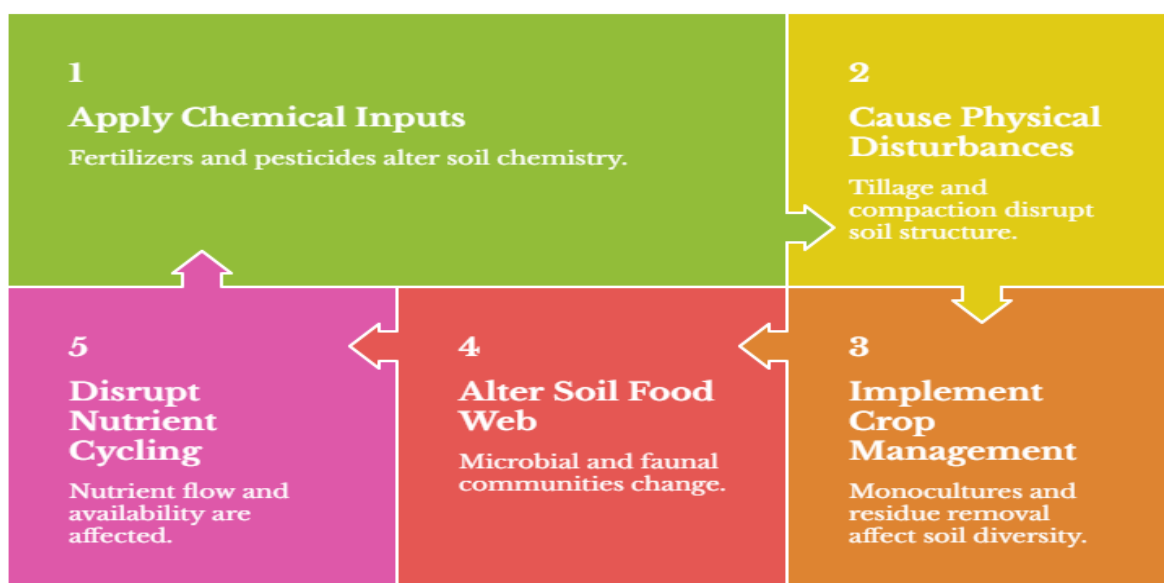
6.3 Crop Management Practices

a) **Monocultures:** Reduced plant diversity limits the diversity of root exudates, which serve as substrates for soil microbes, reducing microbial diversity.

b) **Residue Removal:** Burning or removing crop residues reduces organic matter inputs, limiting energy sources for decomposers.

c) **Irrigation:** Alters soil moisture regimes, impacting microbial respiration and nutrient cycling.

Cycle of Soil Food Web Alterations



7. Consequences for Soil Health and Agricultural Sustainability

7.1 Decreased Soil Fertility and Nutrient Imbalances

Disrupted microbial and faunal communities reduce nutrient mineralization efficiency and alter nutrient cycling pathways, leading to nutrient imbalances and decreased soil fertility. This often results in increased fertilizer use to sustain yields, perpetuating dependency and environmental degradation.

7.2 Increased Pest and Disease Incidence

Simplified soil food webs weaken natural pest regulation by reducing populations of predators and parasites. This leads to increased soil-borne diseases and pest outbreaks, often resulting in higher pesticide use.

7.3 Reduced Soil Carbon Sequestration and Increased Greenhouse Gas Emissions

Altered microbial community structure impairs soil organic matter stabilization, reducing carbon storage capacity. Enhanced mineralization rates can increase emissions of CO₂ and nitrous oxide, contributing to climate change.

8. Strategies for Mitigating Negative Impacts

8.1 Conservation Agriculture Practices

- a) **Reduced or No-Tillage:** Minimizes soil disturbance, preserving soil structure and microbial networks.
- b) **Cover Cropping:** Maintains continuous organic inputs and habitat heterogeneity.
- c) **Crop Rotation:** Enhances resource diversity and disrupts pest cycles.

8.2 Integrated Pest and Nutrient Management

- a) **Minimize Chemical Inputs:** Use targeted application to reduce pesticide and fertilizer overuse.
- b) **Biological Control:** Employ natural enemies for pest suppression.
- c) **Precision Nutrient Management:** Optimize fertilizer timing and rates to avoid excess.

8.3 Organic Amendments and Biochar Application

- a) **Compost and Manure:** Increase soil organic matter and provide substrates for microbial growth.
- b) **Biochar:** Improves soil physical properties, provides habitat for microbes, and buffers pH.

8.4 Agroecological Diversification

- a) **Intercropping and Agroforestry:** Increase above- and belowground biodiversity.
- b) **Habitat Management:** Create refuges and corridors for soil organisms.

9. Research and Monitoring Needs

9.1 Long-Term Ecological Studies

Conduct longitudinal studies to quantify temporal changes in soil biodiversity and food web structure under different intensification regimes to understand resilience and recovery.

9.2 Development of Bioindicators and Molecular Tools

Use metagenomics, stable isotope probing, and other molecular techniques to rapidly assess soil biodiversity and functional potential.

9.3 Integration into Precision Agriculture

Incorporate soil ecological data into decision-support systems to enable adaptive management that maintains soil biodiversity.

9.4 Cross-Disciplinary Research

Link soil biodiversity metrics with ecosystem functions and crop productivity to develop holistic management recommendations.

10. Policy Implications and Sustainable Land Management

- a) **Policy Support:** Encourage reduced chemical inputs and conservation agriculture through incentives and regulations.
- b) **Extension Services:** Educate farmers on the importance of soil biodiversity and sustainable practices.
- c) **Certification Schemes:** Integrate soil health indicators into sustainability standards.
- d) **Stakeholder Engagement:** Foster collaboration among farmers, scientists, policymakers, and industry.

11. Conclusion

Agricultural intensification profoundly impacts soil ecological networks and food webs, often resulting in biodiversity loss, simplified trophic structures, and impaired ecosystem services essential for sustainable agriculture. Mitigation requires adopting management practices that conserve or restore soil biodiversity, maintain trophic complexity, and promote ecosystem resilience. Integrating ecological knowledge into agricultural policies and practices is essential to balance productivity goals with environmental stewardship, ensuring long-term soil health and agricultural sustainability.

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Impact of Farmer Producer Organizations (FPOs) on Market Access, Bargaining Power, and Income Enhancement



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Introduction

Farmer Producer Organizations (FPOs) have emerged as a pivotal institutional innovation aimed at empowering small and marginal farmers by enabling collective action. In agrarian economies characterized by fragmented landholdings, low individual bargaining power, and limited market participation, FPOs serve as aggregators that enhance farmers' ability to access markets, negotiate better terms, and increase incomes. This comprehensive analysis explores the multifaceted impact of FPOs on market access, bargaining power, and income enhancement, situating these effects within contemporary marketing strategies and supply chain integration frameworks. By fostering collective strength, improving information flow, and facilitating value addition, FPOs contribute significantly to rural development and agribusiness competitiveness.

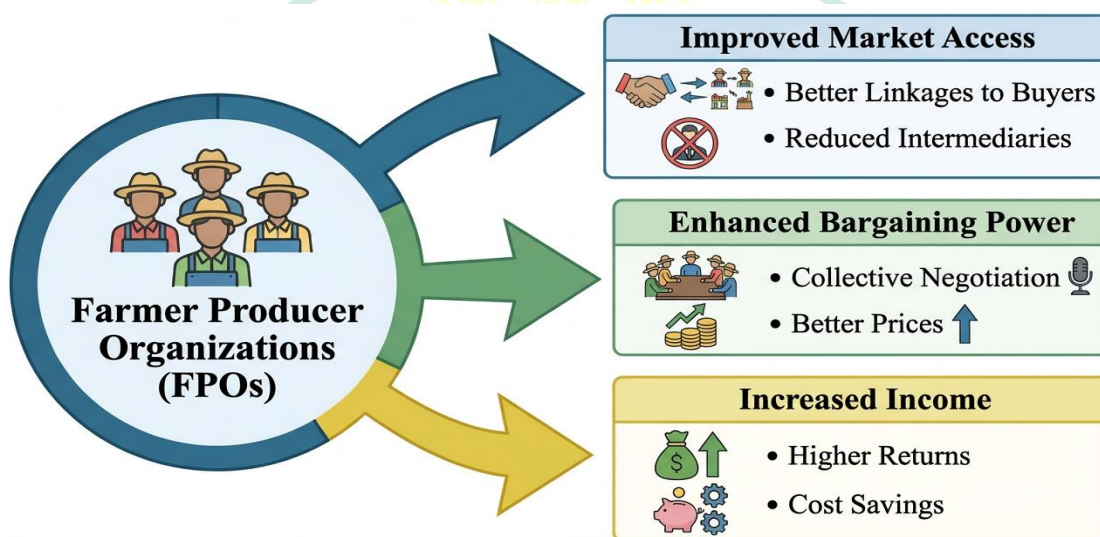


Figure 1: Farmer Producer Organizations (FPOs)

1. Impact of FPOs on Market Access

1.1 Collective Market Linkages

FPOs aggregate produce from numerous smallholder farmers, creating volumes that are attractive to large-scale buyers such as wholesalers, retailers, processors, and exporters. This aggregation overcomes the supply constraints faced by individual farmers who often struggle to meet the quantity and quality requirements of institutional buyers. By pooling resources, FPOs enable farmers to participate in formal markets that were previously inaccessible.

The collective marketing approach reduces dependence on fragmented and often exploitative local intermediaries, thereby improving price realization and market reach. Moreover, FPOs facilitate direct linkages with modern retail chains, agro-processing firms, and export markets, which demand consistent supply and quality assurance. These linkages often come with contractual agreements that provide farmers with assured markets and minimize uncertainties.

1.2 Digital Platforms and E-commerce Integration

FPOs increasingly leverage digital marketing tools and e-commerce platforms to expand their market reach beyond local geographies. Online marketplaces and mobile applications allow FPOs to showcase products, engage with end consumers, and conduct transactions with minimal intermediaries. This digital transformation aligns with the broader trend of digital marketing and e-commerce in agribusiness, enhancing transparency and efficiency.

Social media platforms such as Facebook, Instagram, and WhatsApp serve as channels for product promotion, storytelling, and customer engagement. Some FPOs have developed dedicated websites and mobile apps to facilitate order placements, payments, and customer feedback. This integration enables them to tap into urban and international markets, increasing demand and improving price competitiveness.

1.3 Improved Market Information and Transparency

Access to timely and accurate market information is a critical enabler of effective market participation. FPOs act as conduits for disseminating real-time data on prices, demand trends, quality standards, and consumer preferences to their members. This information flow reduces asymmetry, empowering farmers to make informed production and marketing decisions.

Technological tools such as SMS alerts, mobile apps, and cloud-based platforms facilitate rapid communication. By integrating market intelligence into their operations, FPOs align supply with demand, reducing post-harvest losses and inventory mismatches. This transparency also builds trust with buyers, who gain confidence in the reliability and quality of the supply.

1.4 Access to Institutional and Export Markets

FPOs enhance farmers' access to institutional buyers such as government procurement agencies, schools, hospitals, and corporate buyers who require large volumes and consistent quality. By meeting volume and quality thresholds, FPOs open avenues for stable and lucrative contracts.

In addition, FPOs facilitate entry into export markets by aggregating produce that meets international quality and safety standards. They support compliance with certifications like GlobalGAP and organic labels, enabling farmers to benefit from premium pricing and diversified revenue streams.

Table 1: Impact of FPOs on Market Access and Bargaining Power

Parameter	Without FPOs	With FPOs	Mechanism of Improvement	Quantitative Impact (%)
Market Access	Limited to local traders	Access to multiple markets (mandis, digital platforms like eNAM (National Agriculture Market))	Collective aggregation and digital linkage	30–60% increase
Price Realization	Lower due to intermediaries	Higher due to direct sales	Elimination of middlemen	15–40% increase
Bargaining Power	Weak individual negotiation	Strong collective negotiation	Bulk selling and volume advantage	20–50% improvement
Market Information Access	Limited and delayed	Real-time price and demand information	ICT-enabled systems	25–45% better decisions
Transaction Costs	High (transport, logistics)	Reduced through shared services	Economies of scale	10–30% reduction
Quality Standardization	Inconsistent quality	Standard grading and sorting	Collective processing	Improved market acceptance

2. Impact of FPOs on Bargaining Power

2.1 Collective Negotiation and Price Realization

FPOs enhance farmers' bargaining power by consolidating their produce and representing them as a unified entity in negotiations with buyers and input suppliers. This collective strength enables better price discovery, improved contract terms, and reduced transaction costs.

Through contract farming and forward agreements, FPOs secure assured markets and pricing mechanisms that shield farmers from price volatility and exploitative practices. These arrangements often include quality

specifications, delivery schedules, and payment terms, providing financial predictability and reducing market risks.

Collective bargaining also extends to input procurement, where FPOs negotiate bulk purchases of seeds, fertilizers, and machinery at discounted rates, lowering production costs for members.

2.2 Strengthening Institutional Linkages

FPOs serve as platforms to build stronger relationships with key stakeholders such as financial institutions, government agencies, agribusiness firms, and NGOs. These partnerships facilitate access to credit, subsidies, capacity-building programs, and technology, which collectively enhance farmers' negotiation capabilities.

By fostering trust-based, long-term relationships, FPOs embody relationship marketing principles, improving their collective influence and enabling more effective advocacy on behalf of members. These linkages often result in preferential terms, technical assistance, and policy support that benefit the collective.

2.3 Empowerment through Capacity Building

Bargaining power is also strengthened by improving farmers' knowledge and skills. FPOs organize training sessions on negotiation tactics, quality standards, contract management, and legal rights. This capacity building equips farmers with the confidence and competence to engage effectively with buyers and suppliers.

Educational programs on market dynamics, pricing mechanisms, and consumer trends enable farmers to make strategic decisions and avoid exploitative arrangements. The collective identity of FPOs also fosters solidarity, encouraging members to uphold quality standards and contractual obligations.

2.4 Advocacy and Policy Influence

FPOs, through collective representation, can influence agricultural policies, market regulations, and subsidy programs. By voicing farmers' concerns and demands to policymakers, they contribute to creating a more favorable business environment. Enhanced bargaining power at the policy level can lead to improved infrastructure, access to credit, and support schemes that benefit members.

3. Impact of FPOs on Income Enhancement

3.1 Economies of Scale and Cost Efficiency

One of the most tangible benefits of FPOs is the realization of economies of scale in input procurement, production, and marketing. Bulk purchasing of seeds, fertilizers, machinery, and other inputs reduces costs for individual members. Shared infrastructure such as storage facilities, processing units, and transportation further lowers operational expenses.

By optimizing resource utilization and reducing wastage, FPOs increase net income for farmers. Supply chain integration within FPOs streamlines logistics, reduces delays, and ensures better quality control, directly impacting profitability.

3.2 Value Addition and Product Diversification

FPOs often invest in value addition activities including processing, grading, packaging, and branding. These activities enable farmers to capture higher margins by moving beyond raw commodity sales to processed or differentiated products.

Collective decision-making and pooled resources facilitate diversification into high-value crops, organic produce, and specialty products that cater to niche markets. Certification and branding efforts, aligned with sustainable and ethical marketing practices, attract premium prices and loyal consumer segments.

Examples include FPOs establishing small-scale processing units for milling, drying, or packaging, which increase shelf life and market appeal. Branding initiatives highlight quality, origin, and sustainability credentials, differentiating products in competitive markets.

3.3 Access to Finance and Risk Mitigation

FPOs improve members' access to formal credit and insurance products by acting as credible entities for financial institutions. Enhanced financial inclusion enables investments in productivity-enhancing technologies and mitigates risks related to crop failure or market fluctuations.

Financial stability supports income growth by enabling farmers to plan production cycles, adopt quality standards, and invest in value addition without liquidity constraints. Group-based lending models and collateral-free loans facilitated through FPOs reduce financial barriers.

3.4 Capacity Building and Knowledge Sharing

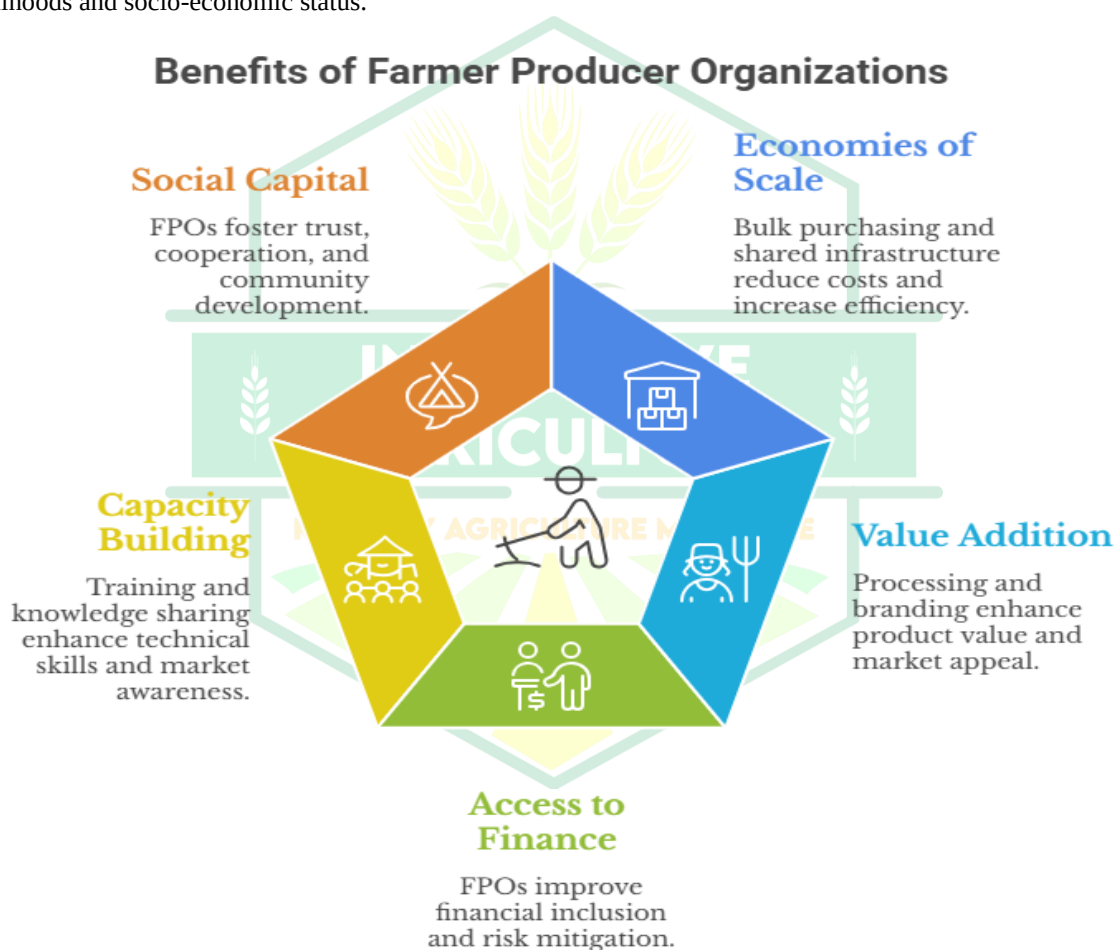
Regular training and extension services provided through FPOs enhance farmers' technical skills, financial literacy, and market awareness. Improved agronomic practices increase yields and product quality, while better understanding of market dynamics supports strategic decision-making.

Peer learning within FPOs fosters innovation diffusion and adoption of best practices, contributing to sustained income growth and resilience. Knowledge sharing on post-harvest management, sustainable farming, and climate adaptation further strengthens economic outcomes.

3.5 Social Capital and Empowerment

Beyond economic benefits, FPOs build social capital by fostering trust, cooperation, and collective identity among members. This social cohesion enhances access to resources, reduces transaction costs, and promotes community development.

Women and marginalized groups often gain greater participation and voice through FPOs, contributing to inclusive growth and poverty reduction. Empowerment through collective action translates into improved livelihoods and socio-economic status.



4. Synergistic Role of FPOs in Marketing and Supply Chain Integration

FPOs exemplify the integration of contemporary marketing strategies with supply chain coordination. Digital marketing tools enable direct engagement with consumers, facilitating brand building and demand generation for FPO products. Simultaneously, supply chain integration ensures quality control, traceability, and efficient logistics, fulfilling market expectations.

This synergy enhances operational efficiency, reduces costs, and strengthens competitive positioning. For example, blockchain-enabled traceability systems adopted by some FPOs substantiate sustainability claims, enhancing consumer trust and enabling premium pricing.

Collaborative planning within FPOs aligns production with market demand, optimizing resource allocation and minimizing waste. Integrated logistics support timely delivery, preserving product quality and customer satisfaction.

Furthermore, FPOs leverage integrated marketing communications (IMC) to coordinate messaging across digital platforms, retail outlets, and community engagement, reinforcing brand consistency and consumer loyalty.

5. Challenges and Future Prospects

Despite their transformative potential, FPOs face several challenges:

- Managerial Capacity:** Limited professional management skills hinder effective governance, strategic planning, and operational efficiency. Strengthening leadership and administrative capabilities is critical.
- Access to Finance:** Insufficient collateral and credit history restrict access to formal financial services. Innovative financing models and policy support are needed.
- Technological Adoption:** Digital infrastructure gaps and low digital literacy impede the use of advanced marketing and supply chain technologies. Training and infrastructure development are essential.
- Regulatory Environment:** Complex registration procedures and compliance requirements pose barriers to formalization and scaling. Simplified processes and supportive policies can facilitate growth.
- Market Competition:** Fierce competition from established agribusiness firms and fluctuating market conditions challenge sustainability. Continuous innovation and differentiation are required.

Future prospects for FPOs involve:

- Leveraging artificial intelligence and big data analytics for enhanced market intelligence, demand forecasting, and personalized marketing.
- Expanding e-commerce platforms and digital payment systems to streamline transactions and widen market reach.
- Adopting blockchain and IoT for transparent, secure, and efficient supply chain management.
- Emphasizing sustainability and circular economy principles to differentiate products and meet evolving consumer expectations.
- Strengthening policy support, capacity building, and multi-stakeholder partnerships to build institutional robustness.

Conclusion

Farmer Producer Organizations significantly enhance market access, bargaining power, and income for small and marginal farmers by aggregating production, fostering collective negotiation, and integrating marketing with supply chain operations. Through economies of scale, value addition, capacity building, and strategic partnerships, FPOs transform fragmented agrarian markets into cohesive and competitive value chains. Addressing existing challenges through innovation, policy support, and skill development will be critical to unlocking their full potential in driving inclusive and sustainable agribusiness growth.

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Impact of Minimum Support Price (MSP) Policies on Farm Income, Market Stability, and Production Decisions



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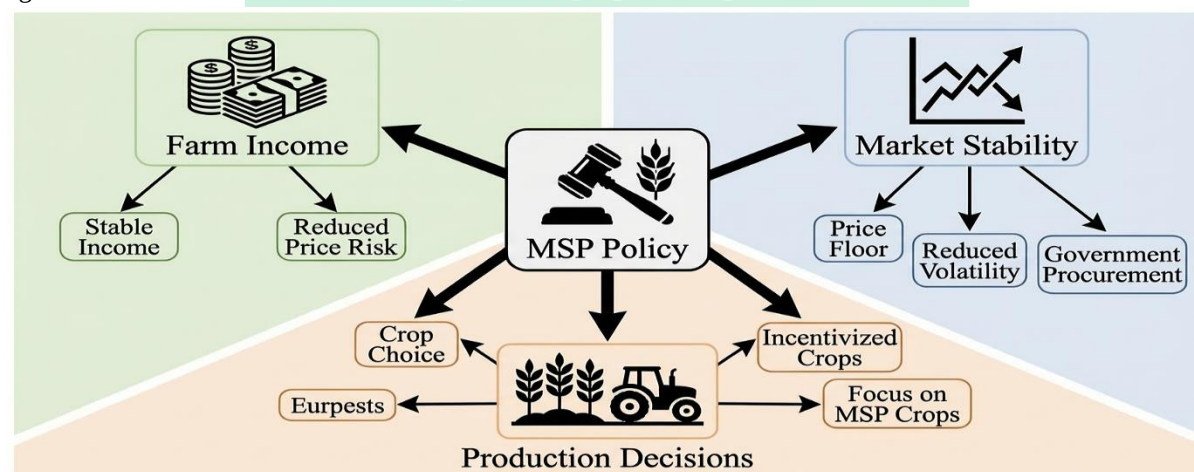
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1. Introduction

Agricultural markets are volatile in nature, and they are characterised by high prices that vary as a result of the supply and demand forces, weather conditions, and international trade conditions. Such variations have the potential to seriously affect the income of farms, and this has become a major challenge to food security and agricultural development. Governments around the world have responded by introducing some form of price support, such as Minimum Support Prices (MSPs), in order to reduce the negative impacts of price volatility and provide a stable farmer income.

MSPs are predetermined minimum prices where governments are willing to buy the agricultural commodity of farmers, which in essence guarantees a floor price on their commodity. These policies are geared towards ensuring that farmers are safeguarded against sudden price decline, especially in times of bumper harvest and also ensure that all is safe against market surprises. Although the main aim of MSPs is to facilitate the income of the farms, the impact of MSPs is not limited to direct income assistance, but also to the production choices, market dynamics, and food security.

This paper critically analyses the effects of MSP policies in determining the income, stability in the market of the farms and their production decisions. It discusses how MSPs affect these important variables and the different variables that define their effectiveness. Empirical evidence and theoretical frameworks have been used to back up the analysis, and they give a holistic picture of the complex relationships between MSP policies and agricultural outcomes.



MSP Policy: Government price floor.

Farm Income: Financial well-being of farmers.

Market Stability: Reduced price fluctuations.

Production Decisions: Choices on what to grow.

Figure 1: Impact of Minimum Support Price (MSP) Policies on Farm Income, Market Stability, and Production Decisions

2. Impact on Farm Income

The immediate effect of the MSP policies is on farm incomes. MSPs ensure that farmers do not run the risk of collapsing prices, especially when production is high, by ensuring that the commodity is sold at a minimum price. This guarantees the farmers an adequate payback on their investments and gives the farmers a stable source of income.

2.1 Price Support and Income Stability

The policies created by the MSP are effective in ensuring that the farmers are not subjected to risks in terms of price; this has the effect of stabilising their earnings and, at the same time, making them less susceptible to the changes in the market. In case the market prices are below the MSP, the government steps in and buys the produce at that price, making sure it does not incur losses for the farmers. Small and marginal farmers are more prone to price shocks, and therefore, this price support mechanism is of great importance to them.

2.2 Impact on Income Levels

Besides stabilisation of income, MSPs may result in an increase in the total income of the farms. This is done when the MSP is higher than the market-clearing price, and farmers receive a better price on their produce. This income increase is dependent on the level of the MSP as compared to the cost of production and the market prices.

Table 7. Impact of MSP on Farm Income

Region	Crop	Year	Farm Income Change (%)	Source
India	Wheat	2018	+15%	Deshpande et al., 2019
China	Rice	2017	+10%	Li et al., 2018
Brazil	Soybeans	2016	+8%	Moraes et al., 2017

2.3 Limitations and Challenges

MSPs have the potential to boost farm incomes, but they do not work well due to several reasons. First, it is common to find that coverage of MSPs is only on a few crops, and the rest of the farmers will be at risk of market failure. Secondly, procurement under MSPs is usually centralised in specific areas, resulting in disparities in income support regionally. Thirdly, MSP policies may be difficult to implement, and it is sometimes impossible to overcome logistical bottlenecks and administration inefficiency that may deny farmers the full benefits.

3. Impact on Market Stability

The MSP policies are important in stabilising agricultural markets by stabilising prices and providing a predictable environment to the farmers and consumers.

3.1 Price Stabilisation

MSPs serve as a minimum price, since the price cannot drop to absurd levels. This minimises price volatility in the agricultural market and makes the market more stable. The stability in prices is crucial to the farmers because they are able to make informed choices in planting and make plans.

3.2 Reduced Market Uncertainty

MSPs eliminate the uncertainty in the market by giving the consumers and producers a minimum price. The farmers are able to be more confident in the amount they are able to produce, and consumers will not be subjected to price surges. This stability encourages investment within the agricultural sector and helps the economy to grow in general.

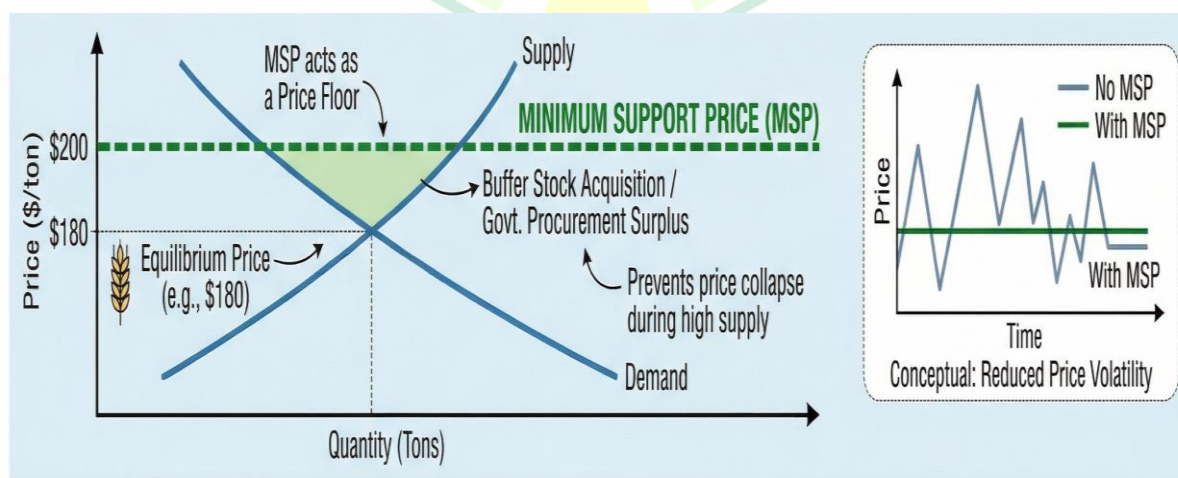


Figure 2: The Effect of MSP on Price Stability (WHEAT MARKET)

3.3 Impact on Private Trade

Nevertheless, MSPs also have a tendency to drive out the existence of private trade, with the government turning out to be a major consumer in the market. This will be able to restrain competition and market efficiencies. The amount of this shift is based on the amount of the MSP and the capacity of the government to purchase.

4. Impact on Production Decisions

The policy of MSP has the potential to greatly impact the production choices made by farmers, which shapes the composition and amount of the agricultural production.

4.1 Incentive Effects

MSP gives farmers a strong motivation to produce crops that are favoured by the policy. At an optimal level of the MSP, the farmers will be motivated to allocate more resources to these crops, including land and capital. This has the capacity to raise the production of MSP-supported commodities.

4.2 Crop Diversification

The tendency of MSPs towards specialising in fewer crops may lead to the lack of crop diversification because farmers are less interested in producing crops not covered by the policy. This may adversely impact the health of soil, biodiversity and general sustainability of agriculture.

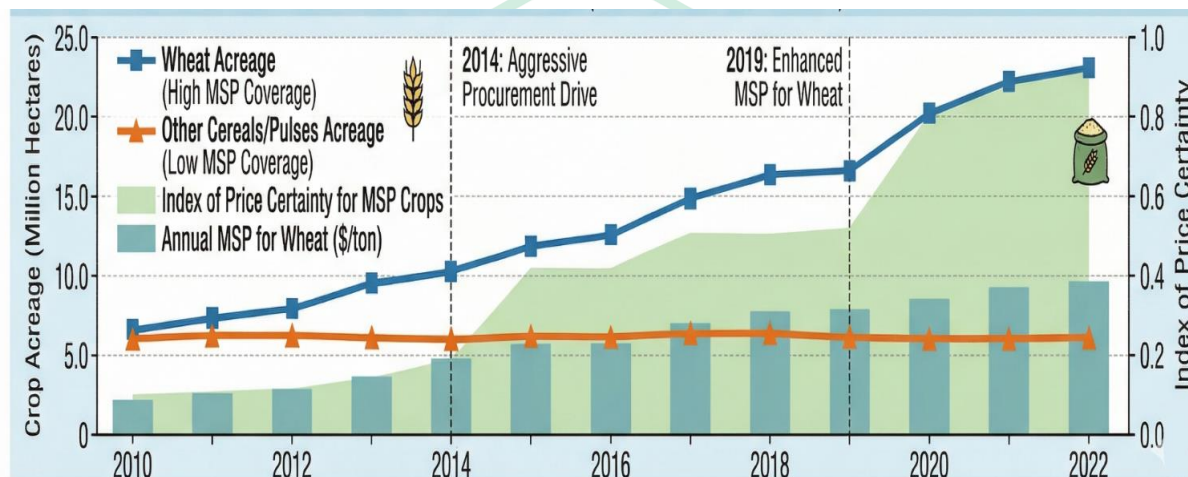


Figure 3. Impact of MSP on Crop Acreage

4.3 Adoption of New Technologies

Another way in which MSPs would affect the use of new agricultural technologies is through their capacity to do so. MSPs can also stimulate farmers to invest in new technological inputs, including better seeds and fertilisers, and new farming practices, by making sure that their income does not decline due to price risk and that their income stays constant. This may result in a boost in productivity and efficiency of the agricultural sector.

5. Conclusions

The effects of MSP policies on the farm income, market stability and production decisions are significant. They can be effective in supporting the farm incomes, especially the small and marginal farmers and stabilising agricultural markets. Nevertheless, MSP policies should be designed and implemented with caution to prevent undesired outcomes, including the forced out of private trade, the discouragement of crop diversification, and inequality among regions. Governments ought to focus on maximising the positive effects of MSPs by focusing on:

1. **Expanded Crop Coverage:** Extension of MSP to more crops, especially horticulture and high-value crops, can help diversify the crops and support more farmers in terms of income.
2. **Decentralised Procurement:** Decentralisation of procurement may minimise regional disparities and enable farmers in remote areas to access price support.
3. **Effective Market Interventions:** MSPs can be used effectively with other market interventions in stabilising markets and buffering farm incomes, e.g. buffer stock management and trade policies.

4. **Technological Advancement:** The use of modern technologies in agriculture can be promoted to increase productivity and lower production costs, which makes MSPs more efficient in terms of compensating farm incomes.
5. **Regular Price Revisions:** It is important to revise MSPs regularly, depending on the costs of production and market forces, to make sure that they are also up to date and that they are still offering significant benefits to farmers.

Governments can harness the potential of MSPs to enhance agricultural development sustainably and improve the livelihood of the farming population by solving these challenges and ensuring that policies are in place to support the farmers.

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Nano-Encapsulated Organic Micronutrients: A Sustainable Approach to Improving Nutrient Use Efficiency



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Introduction

Sustainable farming is a holistic agricultural approach aimed at fulfilling present food production demands while preserving natural resources, maintaining biodiversity, and ensuring long-term economic viability. Central to sustainable farming is the optimization of nutrient use efficiency (NUE), which quantifies the effectiveness with which crops absorb and utilize nutrients from fertilizers or soil reserves. Enhancing NUE is pivotal for increasing crop productivity, reducing fertilizer input costs, and mitigating environmental pollution caused by nutrient runoff, leaching, and greenhouse gas emissions.

Micronutrients, although required in trace amounts, are indispensable for various physiological and biochemical processes in plants. Deficiencies in micronutrients such as zinc, iron, and manganese can significantly impair plant growth, reduce yield quality, and increase susceptibility to diseases. Conventional application methods of micronutrients often suffer from inefficiencies due to nutrient immobilization, leaching, and environmental degradation, necessitating innovative delivery systems. Nano-encapsulation of organic micronutrients emerges as a cutting-edge strategy to address these challenges by enhancing nutrient stability, bioavailability, and targeted delivery, thereby supporting sustainable agricultural practices.

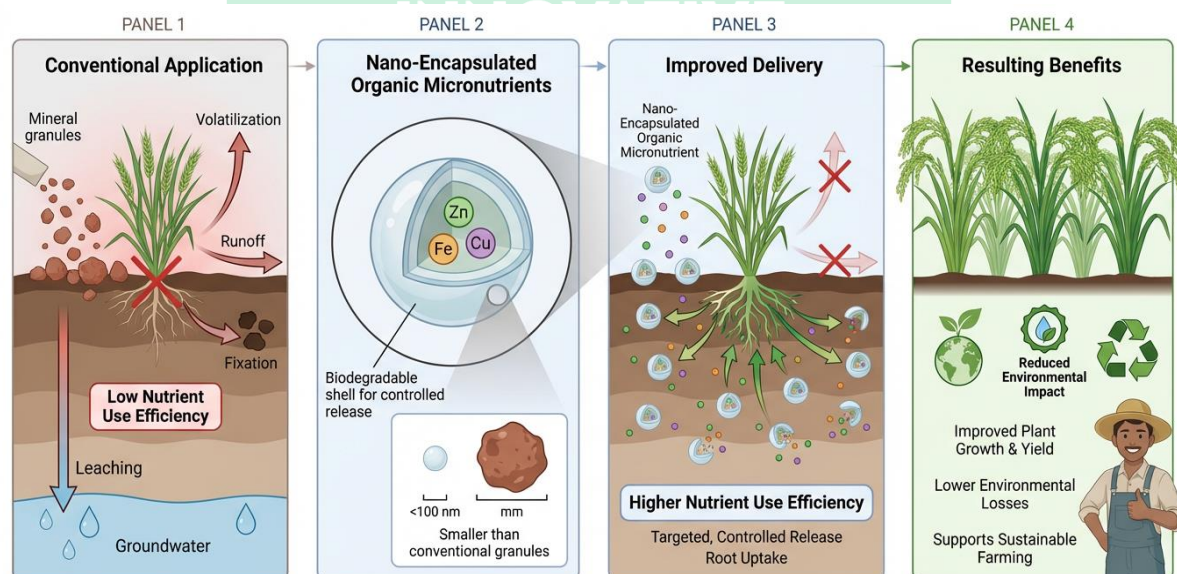


Figure 1: Enhancing Nutrient Use Efficiency through Nano-Encapsulated Organic Micronutrients

Critical Role of Micronutrients in Plant Physiology and Development

Micronutrients include essential elements such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl). Despite their minimal quantitative requirements, these elements are vital for plant metabolic functions:

- Enzymatic Cofactors:** Micronutrients serve as cofactors for enzymes involved in photosynthesis, respiration, nitrogen fixation, and other metabolic pathways.
- Photosynthetic Efficiency:** Iron and manganese are integral to chlorophyll biosynthesis and the photosynthetic electron transport chain, directly influencing photosynthetic capacity.

- c) **Hormonal Regulation and Cell Wall Integrity:** Boron regulates cell wall formation and hormone transport, affecting plant growth and development.
- d) **Stress Resistance and Disease Defense:** Copper and zinc enhance plant defense mechanisms against biotic and abiotic stresses by modulating antioxidant enzyme activities.

Micronutrient deficiencies manifest as physiological disorders including chlorosis, necrosis, stunted growth, and reduced reproductive success. Soil characteristics such as pH, organic matter content, and texture influence micronutrient availability, often resulting in fixation or leaching losses. Traditional micronutrient fertilizers typically exhibit poor solubility and rapid degradation, necessitating frequent applications with associated economic and environmental drawbacks.

Nanotechnology in Agriculture: Principles and Applications

Nanotechnology, the manipulation of materials at the nanoscale (1–100 nm), exploits unique physicochemical properties such as increased surface area, reactivity, and quantum effects. In agriculture, nanotechnology offers transformative applications including:

- a) **Nano-fertilizers:** Enhanced nutrient delivery systems with improved solubility, controlled release, and targeted uptake.
- b) **Nano-pesticides:** Precision pest control agents minimizing non-target effects and chemical residues.
- c) **Soil Remediation:** Nanomaterials facilitating detoxification of contaminated soils and promoting beneficial microbial communities.

Nano-encapsulation specifically involves the entrapment of micronutrients within nanoscale carriers, protecting them from environmental degradation, enabling controlled nutrient release, and enhancing targeted delivery to plant tissues. This technology aligns with sustainable nutrient management goals by improving fertilizer efficiency and minimizing environmental impacts.

Nano-Encapsulation: Mechanistic Insights and Organic Nanocarriers

Nano-encapsulation employs organic nanocarriers such as biopolymers (chitosan, alginate), lipids, and biodegradable synthetic polymers to encapsulate micronutrients. These carriers offer:

- a) **Protection from Environmental Degradation:** Encapsulation safeguards micronutrients against oxidative damage, hydrolysis, and photodegradation during storage and after soil or foliar application.
- b) **Controlled and Sustained Release:** The nanocarrier matrix modulates nutrient release kinetics, synchronizing nutrient availability with plant demand and growth stages.
- c) **Targeted Delivery and Uptake:** Nanocarriers facilitate adhesion to root surfaces or leaf cuticles, promoting enhanced penetration through cell walls and membranes, thus improving bioavailability.

Biodegradability and biocompatibility of organic nanocarriers ensure minimal ecological disturbance, supporting soil microbial health and reducing persistence of synthetic residues. Tailoring particle size, surface charge, and hydrophobicity allows optimization of nutrient delivery for diverse crop species and environmental conditions.

Advantages of Nano-Encapsulated Organic Micronutrients in Sustainable Agriculture

1. **Enhanced Nutrient Stability:** Encapsulation preserves micronutrient integrity against environmental factors, ensuring efficacy during storage and post-application.
2. **Improved Bioavailability and Uptake:** Nanocarriers improve penetration through plant barriers, facilitating efficient absorption and translocation.
3. **Controlled Nutrient Release:** Sustained nutrient delivery reduces losses via leaching, volatilization, and fixation, optimizing availability.
4. **Reduced Application Frequency:** Prolonged nutrient release diminishes the need for repeated fertilization, lowering labor and input costs.
5. **Minimized Environmental Footprint:** Controlled release mitigates nutrient runoff and groundwater contamination, preserving aquatic ecosystems.
6. **Economic Efficiency:** Optimized nutrient use decreases total fertilizer requirements, enhancing cost-effectiveness and farmer profitability.
7. **Compatibility with Organic and Eco-Friendly Farming:** Use of biodegradable organic nanocarriers supports organic certification standards and environmental sustainability.

Table 1: Comparison of Conventional vs Nano-Encapsulated Micronutrients

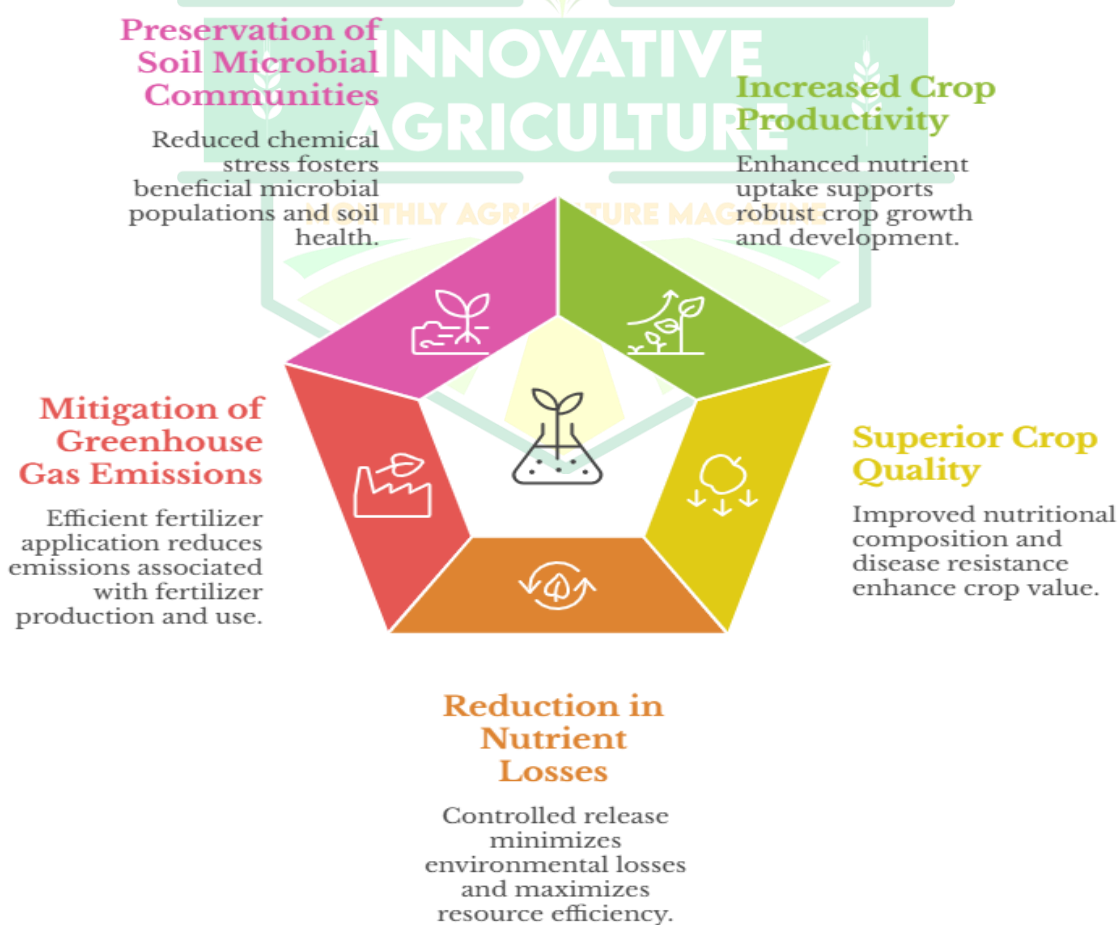
Parameter	Conventional Fertilizers	Nano-Encapsulated Fertilizers
Nutrient Use Efficiency	Low (2–5%)	High (30–70%)
Release Pattern	Rapid	Controlled
Environmental Loss	High	Low
Application Frequency	High	Reduced
Cost Efficiency	Moderate	High (long-term)

Enhancing Nutrient Use Efficiency (NUE) Through Nano-Encapsulation

Nano-encapsulated micronutrients significantly elevate NUE by maximizing the fraction of applied nutrients absorbed and metabolized by crops. Improved NUE results in:

- Increased Crop Productivity:** Enhanced nutrient uptake supports robust vegetative growth, reproductive development, and grain filling.
- Superior Crop Quality:** Adequate micronutrient nutrition improves nutritional composition, disease resistance, and post-harvest shelf life.
- Reduction in Nutrient Losses:** Controlled release minimizes losses through environmental pathways, ensuring efficient resource utilization.
- Mitigation of Greenhouse Gas Emissions:** Efficient fertilizer application reduces emissions associated with fertilizer manufacturing and field application.
- Preservation of Soil Microbial Communities:** Reduced chemical stress fosters beneficial microbial populations, promoting nutrient cycling and soil health.

Benefits of Nano-Encapsulated Micronutrients



Application Strategies for Nano-Encapsulated Micronutrients

Effective deployment of nano-encapsulated micronutrients requires strategic application tailored to crop, soil, and environmental parameters:

- Soil Application:** Incorporation of nano-fertilizers into the rhizosphere enhances micronutrient bioavailability by reducing fixation and improving mobility within the soil matrix. This method supports sustained root uptake throughout the growth cycle.
- Foliar Application:** Spraying nano-encapsulated micronutrients on leaf surfaces enables rapid absorption via stomata and cuticular pathways, providing timely correction of deficiencies during critical phenological stages.
- Seed Priming:** Coating seeds with nano-encapsulated micronutrients promotes early seedling vigor, improves root architecture, and facilitates nutrient uptake during initial growth phases.

Empirical Evidence and Case Studies

Extensive research demonstrates the efficacy of nano-encapsulated micronutrients in enhancing crop performance:

- Zinc Nano-Fertilizers in Maize:** Controlled-release zinc nano-fertilizers improved biomass accumulation, chlorophyll synthesis, and grain yield under zinc-deficient conditions compared to conventional zinc sulfate applications.
- Iron Nano-Fertilizers in Rice:** Application of iron nano-fertilizers increased chlorophyll content, photosynthetic efficiency, and grain quality, mitigating iron deficiency-induced chlorosis.
- Copper and Manganese Nano-Formulations:** Nano-encapsulated copper and manganese enhanced enzymatic activities linked to stress tolerance and disease resistance across various crop species.

Table 2: Reported Impacts of Nano-Micronutrients on Crops

Crop	Micronutrient	Observed Effect	Yield Increase (%)
Wheat	Zn	Improved grain Zn content	15–25%
Rice	Fe	Enhanced chlorophyll content	10–20%
Maize	Mn	Increased biomass	12–18%
Tomato	B	Better fruit set	20–30%

Challenges and Considerations for Implementation

Despite promising benefits, several challenges must be addressed to facilitate large-scale adoption of nano-encapsulated micronutrients:

- Regulatory and Safety Frameworks:** The absence of comprehensive, harmonized regulations for nanomaterials in agriculture necessitates development of standardized safety and efficacy assessment protocols.
- Environmental and Health Risk Assessment:** Long-term studies evaluating the fate, bioaccumulation, and ecotoxicological effects of nanoparticles on soil microbiota, plants, and human health are critical.
- Production and Cost Efficiency:** Scaling up nano-encapsulation processes while maintaining cost-effectiveness remains a technical and economic hurdle.
- Farmer Education and Extension Services:** Effective training programs are essential to disseminate knowledge on nano-fertilizer benefits, application techniques, and safety measures.
- Environmental Fate and Persistence:** Understanding degradation pathways, mobility, and potential bioaccumulation of nanocarriers in soil and aquatic systems is necessary to prevent unintended ecological consequences.

Future Directions and Innovations

Emerging trends and innovations poised to advance nano-encapsulated micronutrient technology include:

- Smart and Stimuli-Responsive Fertilizers:** Development of nanocarriers capable of releasing nutrients in response to environmental triggers such as soil pH, moisture, or root exudates, enabling precision nutrient management.

- b) **Multi-Nutrient Encapsulation:** Engineering nanocarriers encapsulating multiple micronutrients to provide balanced nutrition tailored to specific crop and soil requirements.
- c) **Integration with Precision Agriculture Technologies:** Utilizing sensors, drones, and data analytics to optimize nano-fertilizer application timing, dosage, and spatial distribution, enhancing efficiency and reducing waste.
- d) **Development of Fully Biodegradable Nanocarriers:** Advancing synthesis of nanomaterials derived from renewable resources that degrade harmlessly, minimizing environmental footprint.
- e) **Nanosensor Technologies for Soil and Plant Health Monitoring:** Deploying nanosensors for real-time assessment of nutrient status and plant physiological conditions to inform dynamic nutrient management decisions.

Environmental and Economic Implications

Nano-encapsulation technology offers substantial environmental and economic benefits:

- a) **Mitigation of Nutrient Runoff and Eutrophication:** Controlled nutrient release reduces leaching into water bodies, preventing algal blooms and aquatic ecosystem degradation.
- b) **Soil Health Preservation:** Lower chemical inputs mitigate soil acidification, salinization, and degradation processes, maintaining long-term soil fertility.
- c) **Reduction of Carbon Footprint:** Enhanced nutrient use efficiency decreases energy consumption and greenhouse gas emissions associated with fertilizer production and application.
- d) **Increased Farmer Profitability:** Improved crop yields and quality, combined with reduced input costs and application frequency, enhance overall farm income.
- e) **Alignment with Climate-Smart Agriculture Goals:** Nano-encapsulated micronutrients support sustainable intensification strategies essential for global food security under climate variability.

Conclusion

Nano-encapsulated organic micronutrients represent a paradigm shift in sustainable nutrient management, addressing critical challenges in conventional fertilization practices. By enhancing nutrient use efficiency, safeguarding environmental health, and improving crop productivity, nano-encapsulation offers a viable pathway to meet escalating global food demands sustainably. Realizing this potential requires continued interdisciplinary research, development of robust regulatory frameworks, cost-effective production methods, and comprehensive farmer education initiatives. Integration with precision agriculture and smart farming technologies will further amplify the benefits, fostering resilient and eco-friendly farming systems capable of sustaining future generations.

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Pollution-Induced Physiological and Reproductive Alterations in Freshwater and Marine Fish



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1. Introduction

Aquatic ecosystems are among the most diverse and productive environments on Earth, supporting a vast array of species, including fish that are fundamental to ecological balance and human economies. Fish contribute to nutrient cycling, serve as prey and predators within food webs, and provide essential protein sources for millions globally. However, the health and sustainability of fish populations are increasingly jeopardized by pollution. The introduction of contaminants such as heavy metals, pesticides, endocrine-disrupting chemicals (EDCs), and plastics into freshwater and marine habitats causes significant physiological and reproductive impairments. These disruptions compromise fish growth, immune function, behavior, and reproductive success, ultimately affecting population viability and ecosystem stability. This article provides an in-depth exploration of pollution-induced physiological and reproductive alterations in freshwater and marine fish, encompassing pollutant types, mechanistic impacts, species-specific responses, case studies, ecological consequences, and mitigation strategies.

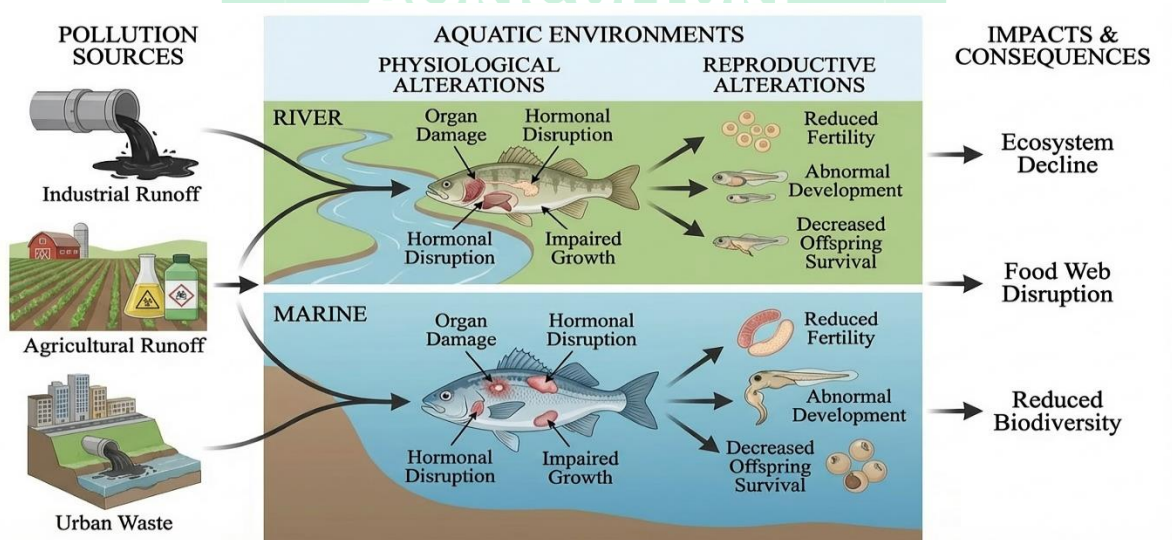


Figure 1: Impact of Aquatic Pollution on Physiological and Reproductive Functions in Fish

2. Types of Pollution Affecting Fish

2.1 Chemical Pollution

Chemical pollution represents a heterogeneous group of toxic substances entering aquatic environments primarily through anthropogenic activities. Heavy metals such as mercury, lead, cadmium, and arsenic are persistent, non-biodegradable, and bioaccumulative, posing chronic toxicity risks. These metals interfere with enzymatic functions, disrupt cellular homeostasis, and induce oxidative stress. Pesticides, including organophosphates,

carbamates, and pyrethroids, are widely used in agriculture and can contaminate water bodies via runoff. They affect nervous system function and endocrine regulation in fish. Persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs) and dioxins, resist degradation and accumulate in fatty tissues, causing long-term toxic effects. Pharmaceuticals and personal care products, now increasingly detected in aquatic systems, introduce complex chemical mixtures with largely unknown chronic impacts on fish physiology.

2.2 Nutrient Pollution and Eutrophication

Nutrient pollution results from excessive inputs of nitrogen and phosphorus, mainly from fertilizers, sewage, and animal waste. This nutrient enrichment fuels eutrophication, characterized by explosive algal growth. Algal blooms reduce water clarity and oxygen levels when decomposing, creating hypoxic (low oxygen) or anoxic (no oxygen) zones detrimental to fish respiration. Prolonged hypoxia causes physiological stress, impairs metabolism, alters behavior, and can result in mass fish kills. Additionally, some algal species produce toxins that directly harm fish health.

2.3 Plastic Pollution and Microplastics

Plastic pollution has emerged as a pervasive threat, with microplastics (<5 mm) being particularly concerning. Fish ingest microplastics either directly or indirectly through trophic transfer. These particles cause physical abrasion, blockage, and inflammation in digestive tracts, reducing nutrient absorption and feeding efficiency. Moreover, microplastics serve as vectors for adsorbed pollutants such as heavy metals and hydrophobic organic compounds, increasing chemical exposure. The chronic physiological and reproductive impacts of microplastic ingestion remain under active research but are expected to be significant.

2.4 Emerging Contaminants

The detection of novel pollutants such as nanomaterials, flame retardants, and endocrine-active pharmaceuticals in aquatic environments highlights the growing complexity of pollution. These emerging contaminants often act synergistically with traditional pollutants, exacerbating toxic effects. Their persistence, bioaccumulation potential, and subtle sub-lethal effects on fish physiology and reproduction necessitate further investigation.

3. Physiological Alterations in Fish Due to Pollution

3.1 Respiratory Impairment

Gill tissues are primary targets of aquatic pollutants. Heavy metals and pesticides induce morphological changes such as epithelial hyperplasia, lamellar fusion, and increased mucus secretion, all of which reduce the gill's respiratory surface area. These structural damages impair oxygen diffusion, leading to hypoxemia and reduced aerobic capacity. Hypoxia from eutrophication compounds these effects, forcing fish to lower metabolic rates and exhibit lethargic behavior. Reduced oxygen uptake compromises energy-dependent activities like swimming, foraging, and predator evasion, increasing mortality risk.

3.2 Oxidative Stress and Cellular Damage

Pollutant exposure triggers excessive generation of reactive oxygen species (ROS), overwhelming antioxidant defenses including enzymes like superoxide dismutase, catalase, and glutathione peroxidase. ROS damage cellular lipids, proteins, and nucleic acids, disrupting membrane integrity and enzyme functions. Oxidative stress induces inflammatory responses and apoptosis, impairing tissue repair and regeneration. Chronic oxidative damage weakens immune defenses, reduces growth rates, and predisposes fish to disease.

3.3 Immunosuppression

Pollutants modulate immune system components, decreasing the number and function of immune cells such as macrophages, neutrophils, and lymphocytes. Cytokine production and signaling pathways are disrupted, diminishing innate and adaptive immunity. Immunosuppressed fish are more vulnerable to infections, parasites, and disease outbreaks, especially in polluted habitats where pathogen loads may be elevated. This increased susceptibility contributes to population declines.

3.4 Neurotoxicity and Behavioral Changes

Neurotoxic contaminants, particularly heavy metals like mercury and lead, interfere with neurotransmitter synthesis, release, and receptor function. Neuronal damage manifests as impaired sensory perception, motor coordination, and cognitive functions. Behavioral alterations include reduced feeding motivation, impaired

predator avoidance, disrupted schooling behavior, and abnormal locomotion. These changes reduce survival probabilities and reproductive opportunities, impacting population dynamics.

3.5 Endocrine Disruption

Endocrine-disrupting chemicals (EDCs) interfere with hormone biosynthesis, secretion, receptor binding, and degradation. Common EDCs include pesticides, plasticizers (e.g., bisphenol A), and pharmaceuticals. Hormonal imbalances affect growth, metabolism, stress responses, and reproductive physiology. Chronic EDC exposure leads to developmental abnormalities, altered secondary sexual characteristics, and impaired reproductive cycles. These disruptions have population-level consequences by reducing reproductive success and altering sex ratios.

Table 1: Pollution-Induced Physiological Alterations in Freshwater and Marine Fish

Pollutant Type	Source	Physiological Alterations	Affected Organs/Systems	Observed Effects / Range
Heavy Metals (Hg, Cd, Pb)	Industrial discharge, mining	Oxidative stress, enzyme inhibition	Liver, kidney, gills	Increased lipid peroxidation (20–70%)
Pesticides	Agricultural runoff	Neurotoxicity, endocrine disruption	Nervous system, liver	Reduced acetylcholinesterase activity (15–60%)
Microplastics	Plastic waste degradation	Physical blockage, inflammation	Digestive tract	Reduced feeding efficiency (10–30%)
Oil Spills (Hydrocarbons)	Marine transport, drilling	Respiratory distress, tissue damage	Gills, skin	Increased mortality and gill damage
Nutrient Pollution (Eutrophication)	Fertilizer runoff	Hypoxia, metabolic stress	Whole organism	Oxygen depletion (<2 mg L ⁻¹ DO)
Pharmaceuticals & Hormones	Wastewater effluents	Endocrine disruption	Hormonal system	Altered hormone levels
Thermal Pollution	Power plants	Increased metabolic rate	Whole organism	Elevated respiration rate (10–25%)
Salinity Changes	Climate change, runoff	Osmoregulation imbalance	Gills, kidney	Stress response and mortality

4. Reproductive Alterations in Fish Due to Pollution

4.1 Reduced Fertility and Fecundity

Pollutants damage gonadal tissues, impairing gametogenesis. Testicular damage reduces sperm count, motility, and viability, while ovarian damage decreases oocyte number and quality. Pollutants induce apoptosis in germ cells and disrupt steroidogenesis, leading to hormonal imbalances. Reduced gamete quality diminishes fertilization success and offspring viability, threatening population recruitment.

4.2 Altered Sex Ratios and Intersex Conditions

Exposure to EDCs can skew sex ratios by causing feminization or masculinization. Some fish develop intersex conditions, possessing both ovarian and testicular tissues, which compromises reproductive function. These alterations disturb normal breeding patterns, reduce effective population size, and can lead to local population collapse.

4.3 Delayed Sexual Maturation

Pollutants interfere with endocrine pathways regulating sexual maturation, delaying the onset of reproductive capability. Prolonged juvenile phases reduce lifetime reproductive output and alter population age structures, affecting long-term population stability.

4.4 Behavioral Changes Affecting Reproduction

Neurotoxic and endocrine-disrupting pollutants alter mating behaviors, including courtship displays, spawning site selection, and territoriality. Disruption of reproductive behaviors reduces mating success and fertilization rates, compromising population growth.

4.5 Embryotoxicity and Developmental Abnormalities

Pollutants can cross egg membranes or accumulate maternally, exposing embryos to toxic substances. This results in increased embryonic mortality, deformities (e.g., spinal curvature, craniofacial malformations), and impaired larval growth and survival. Developmental abnormalities reduce recruitment and population resilience.

5. Molecular and Cellular Mechanisms of Pollution Impact

5.1 Bioaccumulation and Biomagnification

Lipophilic pollutants accumulate in fish tissues over time, with higher trophic level species exhibiting greater concentrations due to biomagnification. This accumulation exacerbates toxic effects on physiological and reproductive systems, especially in predatory fish.

5.2 DNA Damage and Genotoxicity

Pollutants cause DNA strand breaks, chromosomal aberrations, and mutations. Genotoxicity impairs cell division, repair mechanisms, and can induce carcinogenesis. Heritable genetic damage affects offspring viability and population genetic diversity.

5.3 Hormonal Pathway Disruption

EDCs mimic or antagonize natural hormones, binding to receptors and altering gene expression. Disruption of endocrine feedback loops affects growth, metabolism, and reproduction at cellular and systemic levels, leading to widespread physiological dysfunction.

6. Differences Between Freshwater and Marine Fish Responses

6.1 Environmental and Habitat Variability

Freshwater ecosystems often experience higher pollutant concentrations due to smaller volumes, proximity to pollution sources, and limited dilution capacity. Marine environments benefit from greater dilution but face chronic exposure through complex trophic interactions and longer pollutant residence times.

6.2 Salinity Effects on Pollutant Toxicity

Salinity alters chemical speciation, solubility, and bioavailability of pollutants. For example, heavy metals may form different complexes in saltwater, influencing uptake rates and toxicity. These differences affect pollutant distribution and impact in freshwater versus marine fish.

6.3 Species-Specific Adaptations

Freshwater and marine fish exhibit different osmoregulatory mechanisms, metabolic rates, and reproductive strategies, influencing their susceptibility to pollutants. Species adapted to stable marine environments may be more sensitive to pollutant fluctuations, while freshwater species may endure higher contaminant loads but with cumulative effects.

7. Case Studies and Examples

7.1 Mercury Contamination in Freshwater Fish

Mercury released from mining and industrial processes bioaccumulates in freshwater fish, causing neurotoxicity and reproductive failure. Contaminated lakes report fish with reduced growth, altered behaviors such as impaired predator avoidance, and decreased reproductive success.

7.2 Endocrine Disruption in Marine Fish

Marine fish near coastal wastewater discharge sites exhibit feminization of males and intersex conditions due to EDC exposure. These physiological changes correlate with population declines and reduced reproductive capacity.

7.3 Pesticide Effects on Freshwater Fish

Agricultural runoff introduces pesticides into freshwater streams and rivers, causing gill damage, oxidative stress, and reduced fertility in resident fish species. These effects impair population sustainability in agricultural landscapes.

7.3 Microplastic Ingestion in Marine Fish

Marine fish ingest microplastics, leading to physical gut damage, reduced feeding efficiency, and chemical exposure from adsorbed pollutants. These impacts reduce growth rates and reproductive output, with potential population-level consequences.

8. Ecological and Population-Level Impacts

8.1 Population Declines and Biodiversity Loss

Pollution-induced impairments reduce fish survival, reproductive success, and recruitment, leading to population declines. Loss of fish biodiversity disrupts food webs, reduces ecosystem resilience, and threatens ecosystem services.

8.2 Altered Community Structure

Differential sensitivity among species causes shifts in community composition, favoring pollutant-tolerant species and reducing overall biodiversity. These changes alter ecosystem functioning, nutrient cycling, and habitat structure.

8.3 Impaired Ecosystem Services

Declines in fish populations affect commercial and subsistence fisheries, nutrient recycling, and habitat maintenance. This compromises ecosystem services critical to human well-being, including food security and economic livelihoods.

9. Mitigation and Management Strategies

9.1 Pollution Control and Regulatory Frameworks

Effective pollution mitigation requires stringent regulations targeting industrial discharge, agricultural runoff, and wastewater treatment. Compliance monitoring, enforcement, and penalties are essential to reduce pollutant inputs and protect aquatic ecosystems.

9.2 Habitat Restoration and Protection

Restoration of wetlands, riparian buffers, and aquatic vegetation enhances pollutant filtration and provides refuges for fish. Establishing protected areas reduces exposure to pollutants and supports population recovery.

9.3 Monitoring and Early Warning Systems

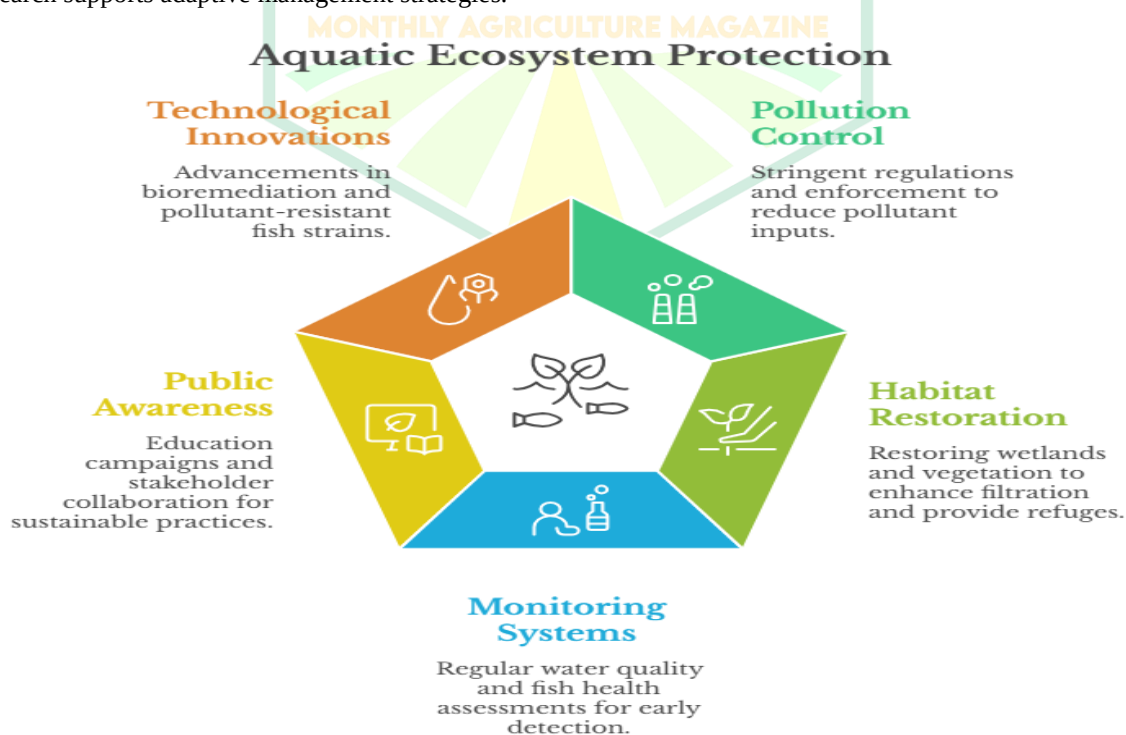
Implementing regular water quality monitoring and fish health assessments using biomarkers such as oxidative stress enzymes, immune parameters, and reproductive indices enables early detection of pollution impacts and informs management actions.

9.4 Public Awareness and Stakeholder Engagement

Education campaigns and stakeholder collaboration foster sustainable practices in agriculture, industry, and waste management. Engaged communities and policymakers are critical for successful pollution reduction and conservation efforts.

9.5 Research and Technological Innovations

Advancements in bioremediation, development of pollutant-resistant fish strains, and improved pollution detection technologies enhance mitigation capabilities. Integrating ecological, toxicological, and molecular research supports adaptive management strategies.



10. Future Directions and Challenges

10.1 Integrating Multi-Stressor Effects

Fish are exposed to complex mixtures of pollutants and environmental stressors such as temperature fluctuations and hypoxia. Research must focus on cumulative and interactive effects to improve risk assessments and management.

10.2 Climate Change Interactions

Climate change alters aquatic environments by modifying temperature, salinity, and hydrology, which influence pollutant toxicity and fish susceptibility. Understanding these interactions is vital for predicting future impacts.

10.3 Advancing Molecular and Genomic Tools

Emerging molecular and genomic techniques enable detailed investigations of pollution effects at genetic, epigenetic, and proteomic levels. These tools aid biomarker development, conservation genetics, and mechanistic understanding.

11. Conclusion

Pollution exerts multifaceted and profound impacts on the physiological and reproductive health of freshwater and marine fish, threatening biodiversity, ecosystem stability, and human livelihoods. Addressing these challenges demands integrated approaches combining pollution control, habitat restoration, scientific research, and stakeholder engagement. Sustaining fish populations is essential for preserving aquatic ecosystems and the vital ecological and socioeconomic services they provide.

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Precision nutrient management approaches for boosting maize productivity



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1. Introduction

Maize (*Zea mays* L.) stands as one of the most vital cereal crops worldwide, serving as a primary source of calories for millions and a key raw material for numerous industrial applications. Its productivity is intricately linked to nutrient availability, as maize demands substantial and balanced nutrient inputs to achieve optimal growth and yield. Traditional nutrient management practices often rely on uniform fertilizer applications, disregarding the inherent spatial and temporal variability in soil fertility and crop nutrient requirements within and across fields. This indiscriminate approach not only leads to inefficient nutrient use but also contributes to environmental degradation through nutrient runoff, leaching, and greenhouse gas emissions.

Precision Nutrient Management (PNM) emerges as an innovative agronomic practice that customizes nutrient applications based on detailed assessments of soil nutrient status, crop growth stages, and spatial variability within fields. By aligning nutrient supply precisely with crop demand, PNM enhances nutrient use efficiency, increases maize productivity, and mitigates adverse environmental impacts. This paper offers a comprehensive exploration of PNM in maize cultivation, detailing its underlying principles, enabling technologies, practical strategies, implementation frameworks, benefits, challenges, and future research directions. The goal is to provide an in-depth understanding of how PNM can transform maize nutrient management towards sustainability and productivity enhancement.

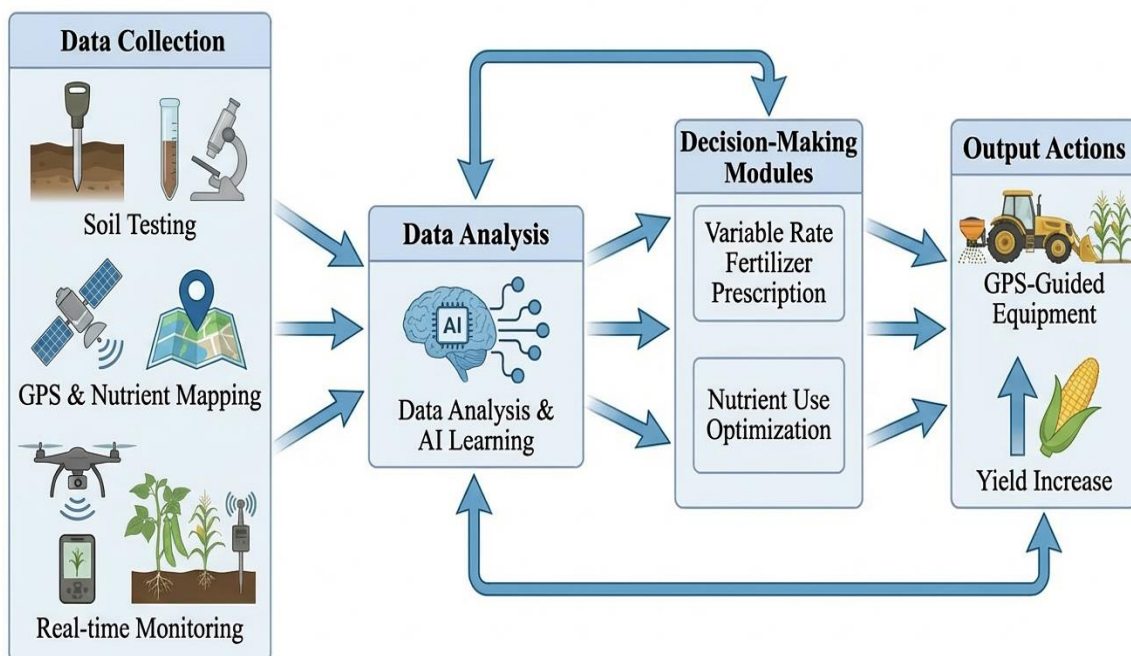
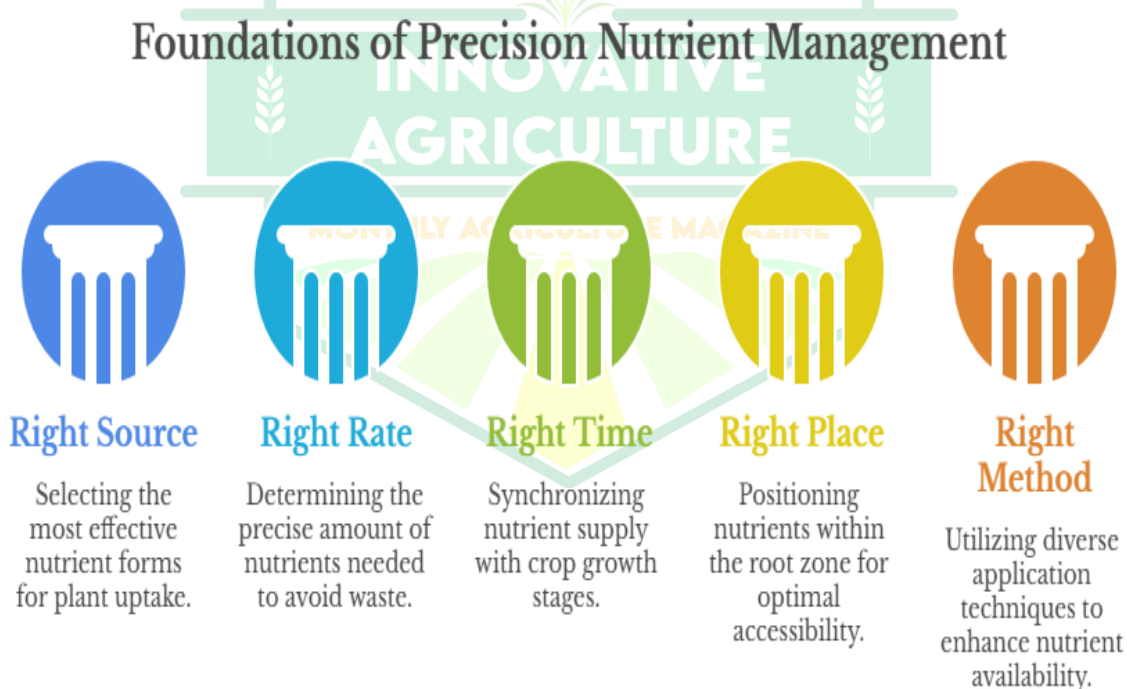


Figure 1: Precision nutrient management approaches for boosting maize productivity

2. Principles of Precision Nutrient Management

The core philosophy of PNM is founded on the optimization of nutrient inputs to meet crop needs accurately, thereby minimizing waste and environmental harm. The approach builds on the established “4Rs” nutrient stewardship framework—Right Source, Right Rate, Right Time, and Right Place—and extends it by incorporating the Right Method of nutrient application.

- **Right Source:** Selection of nutrient forms is critical, as nutrient availability and plant uptake depend on chemical forms and soil interactions. For instance, nitrogen may be applied as nitrate, ammonium, or urea, each with distinct mobility and transformation characteristics. Phosphorus sources vary in solubility and fixation potential, influencing their effectiveness.
- **Right Rate:** Accurate determination of nutrient quantities is essential to avoid deficiencies or toxicities. This requires integrating soil nutrient supply capacity, crop nutrient demand, and expected yield targets. Over-application wastes resources and risks environmental contamination, while under-application limits yield potential.
- **Right Time:** Synchronizing nutrient supply with crop uptake patterns ensures nutrients are available when needed most. For maize, nitrogen demand peaks during vegetative growth, while potassium is critical during reproductive stages. Timely applications reduce losses through leaching or volatilization.
- **Right Place:** Placement strategies aim to position nutrients within the root zone or areas of active uptake. Techniques such as banding or fertigation improve nutrient accessibility and reduce fixation or runoff.
- **Right Method:** Application methods influence nutrient availability and environmental impact. Foliar sprays, soil incorporation, fertigation, and controlled-release fertilizers represent diverse methods tailored to crop needs and field conditions.



3. Nutrient Requirements and Uptake Dynamics in Maize

Maize requires a balanced supply of macro- and micronutrients, each playing distinct physiological roles throughout the crop's development:

- 1) **Nitrogen (N):** Constituting the largest nutrient demand, nitrogen is fundamental for chlorophyll synthesis, amino acid formation, and overall vegetative growth. Nitrogen uptake is minimal during

germination but accelerates sharply during rapid vegetative growth phases, peaking before tasseling and continuing through grain filling.

- 2) **Phosphorus (P):** Critical in early plant development, phosphorus supports root growth, energy transfer via ATP, and seedling vigor. Its uptake is concentrated in early growth stages, with limited mobility in soil, necessitating placement near roots.
- 3) **Potassium (K):** Potassium regulates stomatal function, enzyme activation, and water relations, directly impacting grain filling and quality. Uptake intensifies during reproductive stages, making timely potassium supply essential.
- 4) **Secondary Nutrients and Micronutrients:** Elements such as sulfur, magnesium, zinc, boron, and manganese, though required in smaller quantities, are vital for enzymatic activities, hormonal balance, and stress tolerance.

The nutrient uptake curve for maize typically exhibits a lag phase post-germination, a rapid uptake phase during vegetative and reproductive growth, followed by a plateau as the crop approaches maturity. Understanding these dynamics enables precise timing and dosing of nutrient applications to optimize uptake and minimize losses.

4. Soil and Plant Nutrient Status Assessment

Effective PNM depends on accurate, timely assessments of nutrient availability and crop status, achieved through multiple complementary methods:

- 1) **Soil Testing:** Systematic soil sampling and laboratory analysis provide quantitative data on soil pH, organic matter, macro- and micronutrient concentrations, cation exchange capacity, and texture. These parameters inform the baseline fertility status and identify nutrient deficiencies or toxicities. Advanced soil mapping integrates spatial variability, allowing delineation of management zones.
- 2) **Plant Tissue Analysis:** Sampling of maize leaves or other tissues at critical growth stages (e.g., V6, tasseling) reveals the actual nutrient status within the plant. This approach detects nutrient imbalances before visual symptoms appear, enabling corrective interventions.
- 3) **Remote Sensing and Proximal Sensors:** Technologies such as chlorophyll meters, normalized difference vegetation index (NDVI) sensors, and multispectral imaging from drones or satellites provide rapid, non-destructive assessments of crop health and nutrient status over large areas. These tools facilitate real-time monitoring and dynamic nutrient management adjustments.

5. Technologies Enabling Precision Nutrient Management

The advancement and integration of spatial, sensor, and data technologies have revolutionized PNM implementation:

- 1) **Global Positioning System (GPS) and Geographic Information Systems (GIS):** GPS enables precise geolocation of soil sampling points, crop observations, and fertilizer applications. GIS platforms integrate and visualize spatial data, generating detailed fertility maps and management zones.
- 2) **Variable Rate Technology (VRT):** Fertilizer applicators equipped with VRT adjust nutrient rates dynamically based on prescription maps or real-time sensor inputs. This technology allows in-field variability management, optimizing nutrient distribution and reducing wastage.
- 3) **Unmanned Aerial Vehicles (UAVs) and Drones:** Equipped with multispectral, hyperspectral, or thermal cameras, UAVs capture high-resolution images for monitoring crop vigor, detecting nutrient deficiencies, and assessing stress factors. Frequent flights enable temporal monitoring of crop development.
- 4) **Soil and Plant Sensors:** Devices such as ion-selective electrodes, optical sensors, and soil moisture probes provide continuous, real-time data on soil nutrient concentrations, moisture status, and plant physiological parameters. This data supports adaptive nutrient management.
- 5) **Decision Support Systems (DSS):** Sophisticated software integrates multi-source data—including soil tests, sensor readings, weather forecasts, and crop models—to generate tailored nutrient recommendations. DSS platforms facilitate data-driven decision-making and optimize nutrient management plans.

Table 1: Precision Nutrient Management Tools and Techniques in Maize

Approach/Tool	Description	Technology Used	Function in Nutrient Management	Impact (%)
Soil Test-Based Fertilization	Nutrient application based on soil analysis	Soil testing kits, lab analysis	Determines site-specific nutrient needs	15–30% yield increase
Site-Specific Nutrient Management (SSNM)	Customized nutrient recommendations	Decision support tools (e.g., Nutrient Expert)	Balances nutrient supply with crop demand	20–40% yield improvement
Leaf Color Chart (LCC)	Real-time nitrogen assessment	Visual indicator tool	Guides nitrogen application timing	10–25% NUE improvement
Variable Rate Technology (VRT)	Spatially variable fertilizer application	GPS, sensors, machinery	Applies nutrients based on field variability	20–35% input efficiency
Remote Sensing & Drones	Crop nutrient status monitoring	Satellite/drone imagery	Detects nutrient deficiencies early	15–30% better management
IoT-Based Sensors	Soil nutrient and moisture monitoring	Smart sensors	Real-time data for precise application	10–25% efficiency gain
Fertigation	Nutrient application through irrigation	Drip irrigation systems	Improves nutrient uptake efficiency	20–40% NUE increase
Decision Support Systems (DSS)	Data-driven nutrient recommendations	AI, machine learning	Optimizes fertilizer use	15–30% productivity gain

6. Precision Nutrient Management Strategies for Maize

6.1 Site-Specific Nutrient Management (SSNM)

SSNM customizes nutrient inputs to field heterogeneity by:

- 1) Conducting detailed soil fertility mapping to identify nutrient-rich and deficient zones.
- 2) Utilizing crop nutrient uptake models to estimate nutrient requirements for each zone.
- 3) Applying fertilizers variably within fields using VRT, thereby reducing over-application in fertile zones and supplementing deficient areas.

SSNM enhances yield uniformity, reduces input costs, and minimizes environmental risks.

6.2 Nutrient Use Efficiency (NUE) Enhancement

Maximizing NUE is a primary objective of PNM, achieved through:

- 1) **Split Nitrogen Applications:** Dividing nitrogen doses into multiple applications aligned with crop demand phases reduces nitrogen losses via leaching and volatilization.
- 2) **Slow-Release and Stabilized Fertilizers:** Formulations that release nutrients gradually or inhibit nitrification extend nutrient availability and reduce environmental losses.
- 3) **Incorporation of Organic Amendments:** Addition of compost, manure, or biochar improves soil organic matter, enhances nutrient retention, and supports microbial activity beneficial for nutrient cycling.

6.3 Integration with Crop Growth Models

Crop simulation models such as DSSAT (Decision Support System for Agrotechnology Transfer) and APSIM (Agricultural Production Systems Simulator) simulate maize growth, development, and nutrient uptake under varying environmental and management scenarios. Integrating these models with real-time data allows dynamic adjustment of nutrient recommendations, optimizing fertilizer use and yield outcomes.

7. Implementation Framework for Precision Nutrient Management in Maize

Implementing PNM requires a structured, iterative process:

1. **Baseline Soil and Crop Assessment:** Systematic soil sampling and initial crop monitoring establish nutrient status and variability.
2. **Field Mapping:** GPS and GIS technologies delineate management zones based on soil and crop data.

3. **Data Integration and Analysis:** Combining soil, crop, environmental, and sensor data provides a comprehensive nutrient needs assessment.
4. **Nutrient Recommendation Generation:** Using DSS and crop models, site-specific nutrient plans are developed.
5. **Variable Rate Application:** VRT-enabled equipment applies nutrients precisely according to prescription maps.
6. **Monitoring and Feedback:** Continuous crop monitoring through sensors and remote sensing informs adaptive management, allowing nutrient plans to be refined during the growing season.

8. Benefits of Precision Nutrient Management in Maize Production

PNM offers multifaceted benefits:

- 1) **Increased Yield and Grain Quality:** Precise nutrient supply promotes vigorous vegetative growth and optimal grain filling, enhancing both yield and nutritional quality.
- 2) **Cost Savings:** Targeted fertilizer application reduces wastage, lowering input costs and improving economic returns.
- 3) **Environmental Protection:** Minimizing nutrient runoff and leaching reduces water pollution and greenhouse gas emissions.
- 4) **Soil Health Improvement:** Balanced nutrient management maintains soil fertility, promotes beneficial microbial activity, and supports long-term productivity.
- 5) **Resource Use Efficiency:** Optimized nutrient application conserves finite resources such as phosphorus and reduces energy consumption associated with fertilizer production.

These benefits contribute to sustainable intensification of maize production systems, aligning agricultural productivity with environmental stewardship.

9. Challenges and Limitations

Despite its promise, PNM adoption faces several barriers:

- 1) **High Initial Investment:** The cost of acquiring sensors, VRT machinery, UAVs, and software platforms can be prohibitive, especially for smallholder farmers.
- 2) **Technical Expertise Requirement:** Effective PNM demands skills in data collection, interpretation, and technology operation, necessitating training and capacity building.
- 3) **Data Management Complexity:** Handling large, heterogeneous datasets requires robust infrastructure and analytical tools.
- 4) **Infrastructure and Accessibility Issues:** Limited internet connectivity, power supply, and extension services hinder technology adoption in remote or resource-poor regions.
- 5) **Variability in Smallholder Farming Systems:** Fragmented landholdings and diverse cropping practices complicate standardization and scaling of PNM technologies.

10. Future Perspectives and Research Directions

Future advancements will further refine PNM effectiveness:

- 1) **Machine Learning and Big Data Analytics:** Leveraging large datasets and AI algorithms can improve nutrient requirement predictions and optimize management decisions dynamically.
- 2) **Development of Low-Cost, High-Precision Sensors:** Innovations will increase accessibility and enable real-time nutrient monitoring at finer spatial and temporal scales.
- 3) **Integration with Climate-Smart Agriculture:** Aligning PNM with climate adaptation and mitigation strategies will enhance resilience of maize production under changing environmental conditions.
- 4) **Policy and Capacity Building Initiatives:** Research into socio-economic drivers and extension models will facilitate adoption among diverse farming communities.
- 5) **Sustainability and Circular Economy Approaches:** Incorporating nutrient recycling, waste valorization, and biofertilizers into PNM frameworks will promote sustainable nutrient cycles.

11. Conclusion

Precision Nutrient Management embodies a transformative approach to maize cultivation by tailoring nutrient supply to spatial and temporal variations in crop demand and soil fertility. This alignment enhances yield

potential, economic efficiency, and environmental sustainability. Successful adoption hinges on integrating advanced technologies, robust data analytics, and adaptive management frameworks, supported by capacity building and enabling policies. Overcoming current challenges will unlock the full potential of PNM, contributing significantly to global food security and sustainable agricultural development.

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Pyramiding Multiple Resistance Genes for Durable Immunity



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1. Introduction

The agricultural industry around the world has been under an unending attack by various plant pathogens, such as fungi, bacteria, viruses, and oomycetes. These microscopic enemies do not stand still; they are under a continuous process of evolution, subjected to the pressure of selection and forced to develop, to defeat the defence systems that have been developed by the vegetation. Such single genes usually provide a high degree of immunity to certain races or strains of a pathogen. Often, this monogenic and race-specific resistance has been explained by the so-called gene-for-gene model (Flor, 1971) in which the product of an R gene in the plant directly or indirectly recognizes the product of a given avirulence (Avr) gene in the pathogen, and the product-product interaction results in a rapid and strong defensive response, often including a form of programmed cell death called the hypersensitive response (HR).

The main downside of the monogenic approach is that it is not long-term. The high selection pressure by a popular cultivar of R-genes leads to the rapid evolution of pathogen mutants capable of overcoming the resistance, usually by the loss or mutation of the target Avr gene. The phase discontinuation then occurs, which is termed the 'boom-and-bust' cycle, in which a new resistant type gains lots of popularity and is grown extensively, only to be rendered vulnerable a few years later when the population of virulent pathogens increases and disseminates. This ongoing process of identifying, verifying and implementing new R genes is a costly endeavour that poses a tough challenge in the breeding program.

2. Conceptual Framework of Gene Pyramiding

To a large extent, gene pyramiding depends on the additive and possibly synergistic effects of the overlapping R genes. The pyramidal type contrasts with single-gene resistance, which in many cases is all-or-nothing against certain races of specific pathogens, whereas the pyramidal type gives the pathogen a multifaceted and complex immune response that is much harder to avoid. The concept is based on several essential principles:

2.1 Enhanced Durability

Gene pyramiding has the most immense advantage of increased durability. The likelihood that a pathogen can achieve all the required virulence alleles to reach the required threshold of resistance to two or more genes is extremely low compared to the likelihood of achieving resistance to one gene. There is no such thing as absolute durability, but it is this large stretch of time that it takes to get a virulent pathogen into the field that maximises the profits made by breeders and guarantees larger yields by farmers (Mundt, 2014).

2.2 Broad-Spectrum Resistance

By combining R genes with varying spectrums of activity, the resulting pyramid will be capable of offering resistance to a wider variety of pathogen races, strains or even to a completely different species. As an example, using the genes that are active on various isolates of rice blast fungus (*Magnaporthe oryzae*) can produce a variety with more extensive protection than either of the constituents. This wide-spectrum resistance makes the disease management decisions easier for the farmers and adds to the stability in the region during grain production (Hittalmani et al., 2000).

2.3 Redundancy and Buffer against Partial Failure

There is a certain redundancy provided by a pyramid. When a single gene of the stacked R genes is finally defeated by a particular pathogen strain, other genes can still offer partial or total protection, so a devastating loss of crops will be avoided. Moreover, although none of the genes may be associated with complete immunity, when they combine, they may often make it possible to considerably diminish the severity of the disease, a phenomenon also known as quantitative or partial resistance (Poloni et al., 2017).

Foundations of Gene Pyramiding

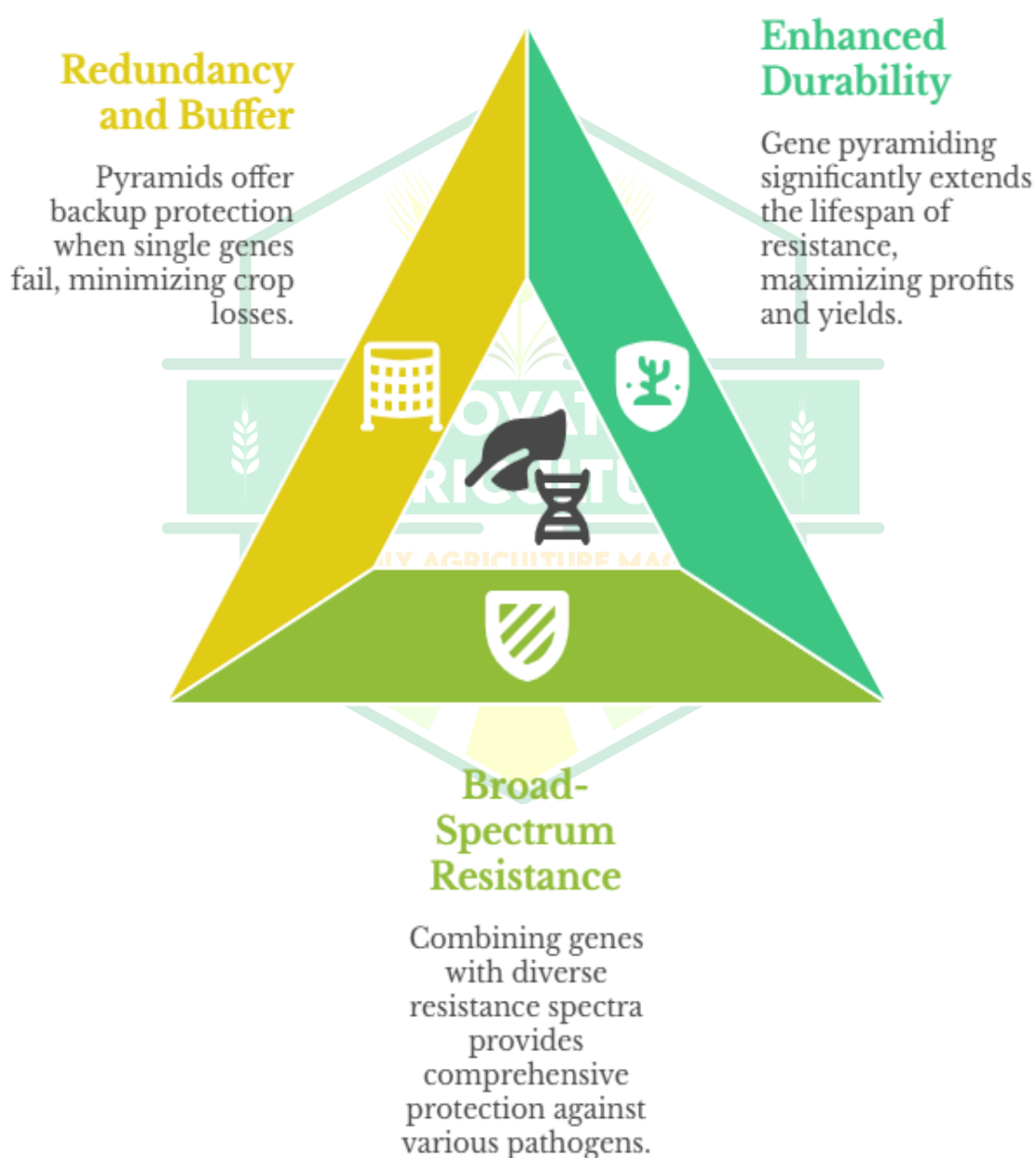


Figure 6: Foundation of gene pyramiding

Table 8. Comparison of Single Gene vs. Pyramided Resistance Strategies

Parameter	Single Gene (Monogenic) Resistance	Pyramided (Polygenic) Resistance
Genetic Basis	Single dominant or recessive gene.	Multiple genes (2+), often from diverse origins.
Durability	Typically short-lived; prone to "boom-and-bust" cycles.	Enhanced durability; resistance lasts significantly longer.
Pathogen Recognition	Often race-specific; recognises a single Avr effector.	Can be race-specific or broad-spectrum; targets multiple effects or conserved patterns.
Resistance Level	Often, complete or near-complete immunity against specific races.	Levels vary; they can be complete, additive, or partial across diverse races.
Breeding Complexity	Relatively straightforward to incorporate a single gene.	Complex; requires tracking multiple genes, large populations, and precise tools.
Selection Pressure	Exerts high selection pressure on the pathogen population.	Exerts reduced overall selection pressure, delaying pathogen evolution.
Reliance on Chemicals	Can fail, leading to heavy pesticide use.	Reduces reliance on chemical pesticides through genetic resistance.
Risk of Breakdown	High risk of sudden, widespread loss of resistance.	Reduced risk of catastrophic failure; failure is often gradual.

3. Case Studies

Gene pyramiding has been successfully applied to numerous economically critical crops, demonstrating its practical value and providing valuable insights into effective strategies.

3.1 Rice Blast and Bacterial Blight

Rice (*Oryza sativa*) is a staple crop for over half the global population and is plagued by devastating diseases like rice blast, caused by the fungus *Magnaporthe oryzae*, and bacterial blight, caused by the bacterium *Xanthomonas oryzae* pv. *oryzae* (Xoo). Breeders have extensively used marker-assisted selection (MAS) to pyramid resistance genes for both of these diseases.

For bacterial blight, pyramids of genes like *xa5*, *xa13*, and *Xa21* have been widely deployed. *Xa21* is an NLR gene that provides broad resistance, *xa5* is an elongation factor Tu receptor gene, and *xa13* is a recessive gene involved in sugar transport that the pathogen exploits. This combination of genes targeting different physiological processes in the pathogen has created rice varieties with robust and durable resistance that has been maintained in many regions for over two decades, significantly contributing to regional food security (Bhasin et al., 2012).

Similarly, for rice blast, numerous pyramids have been developed. For example, stacking genes like *Pi-z5*, *Pi-9*, *Pi-1*, *Pi-km*, *Pi-kh* has resulted in varieties with enhanced resistance to a diverse spectrum of *M. oryzae* isolates. However, the complex nature of the blast fungus and its high genetic diversity demand continuous monitoring and the regular introduction of new R genes into pyramids to stay ahead of evolving pathogen populations (Hittalmani et al., 2000).

3.2 Wheat Rust Diseases

Rust diseases, caused by fungi in the genus *Puccinia*, are a global threat to wheat (*Triticum aestivum*) production. The three main types- stem rust (*P. graminis* f. sp. *tritici*), leaf rust (*P. triticina*), and stripe (yellow) rust (*P. striiformis* f. sp. *tritici*)- can cause severe yield losses.

The challenge in wheat rust breeding is the dynamic nature of rust pathogen populations, capable of long-distance spore travel, which can quickly spread new virulent races across continents. Despite this, gene pyramiding has achieved notable successes. For example, the incorporation of multiple genes for resistance to leaf rust (e.g., *Lr16*, *Lr24*, *Lr34*, *Lr37*) and stripe rust (e.g., *Yr5*, *Yr10*, *Yr15*, *Yr18*) has contributed to stable resistance in many wheat-growing regions.

The gene *Lr34* (and its counterpart *Yr18*) is particularly noteworthy. It provides broad-spectrum, adult-plant resistance against leaf rust, stripe rust, and several other diseases, and its resistance has proven to be incredibly durable over decades. Pyramiding *Lr34* with other race-specific genes has been a cornerstone of wheat breeding

for rust resistance, highlighting the value of including durable, slow-rusting genes in pyramiding programs (Singh et al., 2011).

4. Challenges and Hurdles in Gene Pyramiding

Although the idea of gene pyramiding seems to be a simple concept, the practical implementation of this idea is fraught with serious challenges that demand proper planning, scientific skills, and immense resources.

4.1 Difficulty in Identifying and Tracking Genes

Phenotypic masking is one of the crucial difficulties. When a powerful R gene (e.g. Gene A) is present, we cannot ascertain the presence or effectiveness of any other R genes (e.g., Gene B, Gene C) by any traditional disease resistance screen. This masking effect implies that traditional breeding can hardly stack genes due to the most effective gene hiding the existence of other genes.

4.2 Large Population Sizes and Linking Drag

Multiple-gene pyramiding can easily be done through the screening of huge breeding populations. Meanwhile, in the scenario of stacking, say four independent dominant R genes, a minor proportion of the resulting products (1 in 256, in a simple example) will have all four genes of interest. The size of the program should be big enough to produce enough plants of the desired genotype to carry out what is needed to test them further.

Moreover, the R genes are usually closely paired on the chromosomes with unwanted characteristics (e.g., low yield, low quality, prone to other stresses). This drag of linkage is typical of crop perfection. Introgression of an R gene into a wild relative or a reduced-yielding variety commonly carries with it recessive genes that are hard to decouple from the resistant gene, and many backcrosses are performed to obtain the high-yielding genetic background back (Tanksley and McCouch, 1997).

Table 9. Comparison of Molecular Tools for Tracking Resistance Genes

Feature	RAPD (Random Amplified Polymorphic c DNA)	AFLP (Amplified Fragment Length Polymorphism)	SSR (Simple Sequence Repeats)	SNP (Single Nucleotide Polymorphism)	MAS (Marker- Assisted Selection) / GBS (Genotyping-by- Sequencing)
Genetic Analysis	Based on a single primer; less reproducible.	Based on restriction digest, complex fingerprinting.	Based on a variable number of short repeats.	Single base pair difference.	Large-scale SNP genotyping for MAS or GBS.
Reproducibility	Low to Moderate	High	High	High	Very High
Throughput	Low	Low to Moderate	Moderate to High	Very High	Ultra-High
Cost (per assay)	Moderate	High	High	Moderate (at scale)	Moderate to Low (at scale)
Automation Potential	Low	Low to Moderate	Moderate to High	Very High	Ultra-High
Dominance/Codominance	Dominant	Predominantly Dominant	Predominantly Codominant	Codominant	Predominantly Codominant
Requirement for Pri- or Knowledge	None	Low	Medium	High (need reference genome/sequence)	High (need reference genome/sequence)

5. Molecular Tools and Technologies Revolutionising Gene Pyramiding

The effective and viable success of pyramiding the genes is closely associated with the establishment of potent molecular tools and technologies. These technologies are turning breeding into a science, as data rather than a form of art, which is grounded in phenotype.

5.1 The Rise of Marker-Assisted Selection (MAS)

The pyramid of genes in MAS is the major tool. With the help of DNA markers strongly associated with resistance genes, breeders are able to accurately select plants with the desired combination of genes, irrespective of the effect on the phenotype or masking phenotype. Many generations of MAS have passed, starting with RAPDs and

RFLPs, to recent high-throughput systems that use Simple Sequence Repeats (SSRs) and, to a greater degree, Single Nucleotide Polymorphisms (SNPs).

5.2 The Power of Genome Sequencing and Gene Cloning

The development of next-generation sequencing (NGS) and the dramatic reduction in the cost of whole-genome sequencing have played a critical role. This technology enables:

- **R Gene Discovery:** An expedited approach to novel resistance gene discovery and cloning of novel resistance genes, including wild relatives. This gives the basic elements on which new pyramids are constructed (Kandath et al., 2021).
- **Pathogen Genome Sequencing:** This is used to monitor changes in the population of different pathogen species regarding their virulence and to determine exactly what genes they are mutating to defeat the resistance.

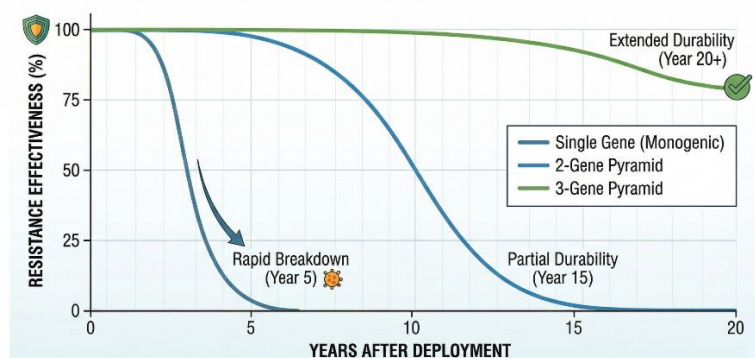


Figure 7. Durability of Resistant Cultivars based on Gene Numbers

6. Conclusion

Gene pyramiding has already become an effective tool in the quest to obtain long-term, broad-spectrum resistance to disease in crops, especially in such notoriously difficult-to-manage diseases as wheat rusts, rice blast, and potato late blight. Pyramiding breaks the predictable pattern of the boom-and-bust cycle by subjecting the pathogen to numerous and independent hurdles, which extends the useful lifespan of desirable resistance genes to a considerable degree. Even though the idea inherent in the pyramiding of genes is conceptually strong, its implementation would require a high level of technical complexity, solid molecular instruments and resources. Several of the challenges are phenotypic masking, linkage drag, and epistatic interactions, which are important yet can be further controlled through the introduction of modern MAS, genome sequencing, and new biotechnologies such as CRISPR/Cas9.

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Role of Legumes in Promoting Sustainable Cropping Systems

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Introduction

Legumes are indispensable components of sustainable cropping systems worldwide, providing Legumes hold a central position in sustainable cropping systems due to their unique biological, ecological, and socio-economic attributes. Their ability to fix atmospheric nitrogen through symbiotic relationships with rhizobia bacteria significantly reduces the dependency on synthetic nitrogen fertilizers, thereby lowering production costs and minimizing environmental pollution. Beyond nitrogen fixation, legumes contribute to soil health by enhancing organic matter content, improving soil structure, and fostering beneficial microbial communities. These improvements boost nutrient cycling, water retention, and overall soil fertility, which are critical for sustainable agricultural productivity. Additionally, legumes play a vital role in diversifying cropping systems, breaking pest and disease cycles, and supporting biodiversity, which collectively enhance ecosystem resilience. Economically, legumes provide farmers with diversified income sources through the production of pulses, oilseeds, and fodder, while also stabilizing yields and reducing input costs. Socially, they contribute to nutritional security by supplying high-quality protein and essential micronutrients, particularly in regions vulnerable to malnutrition. The integration of legumes into cropping systems aligns with global sustainability goals by promoting climate resilience, reducing greenhouse gas emissions, and supporting rural livelihoods. This comprehensive role underscores the importance of legumes as key components in advancing sustainable agriculture and achieving long-term food security.

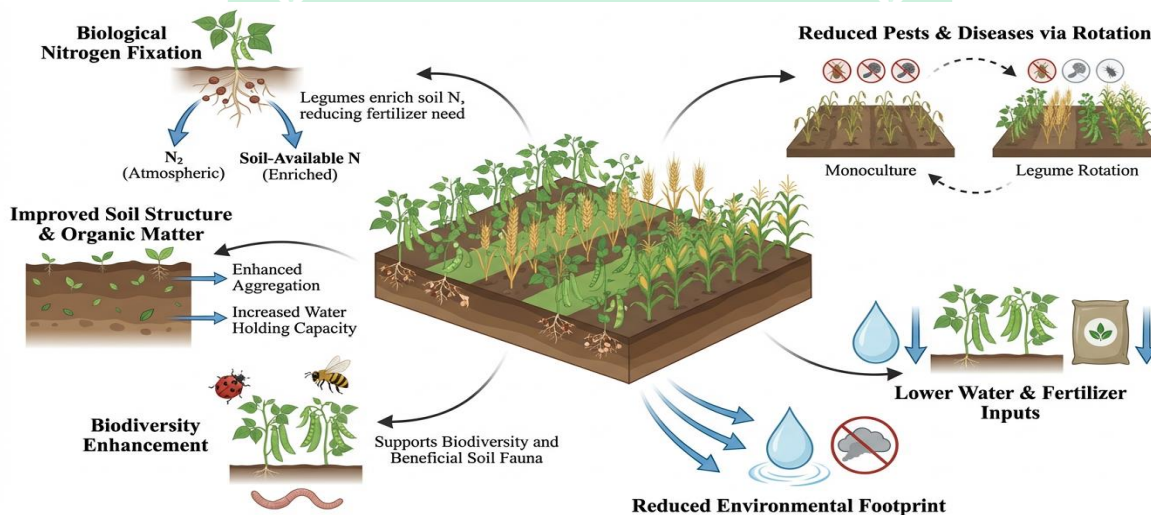


Figure 1: Role of Legumes in Promoting Sustainable Cropping Systems

1. Biological and Ecological Functions of Legumes

1.1 Advanced Biological Nitrogen Fixation (BNF) Dynamics

- Symbiotic Specificity and Adaptation:** The legume-rhizobia symbiosis is highly species- and strain-specific. Advances in microbial ecology and genomics have identified elite rhizobial strains adapted to diverse soil types and climatic stresses, including drought, salinity, and acidity. Tailored inoculants optimized for local environments significantly enhance nitrogen fixation efficiency.
- Molecular and Genetic Regulation:** Nodule development and nitrogenase enzyme activity are regulated by complex molecular signaling pathways involving flavonoids, Nod factors, and

phytohormones. Understanding and manipulating these pathways through breeding and biotechnological tools can improve nodule formation and fixation rates, even under adverse conditions.

- c) **Nitrogen Economy and Soil Fertility:** Quantitative nitrogen budgets indicate legumes can fix 50–300 kg N/ha per season, depending on species and conditions. Fixed nitrogen enriches soil pools through root turnover, rhizodeposition, and residue decomposition, benefiting subsequent non-legume crops and reducing synthetic fertilizer dependence.

1.2 Soil Health Enhancement

- a) **Soil Organic Matter (SOM) Accumulation:** Legume biomass, rich in nitrogen and carbon, accelerates SOM formation, improving soil aggregation, porosity, water-holding capacity, and nutrient retention. Enhanced SOM supports robust microbial communities critical for nutrient cycling and soil resilience.
- b) **Microbial Biodiversity and Function:** Legumes stimulate diverse soil microbiomes, including beneficial fungi (e.g., mycorrhizae), phosphate-solubilizing bacteria, and biocontrol agents. This microbial diversity enhances nutrient availability, disease suppression, and overall soil health.
- c) **Soil Enzymatic Activities:** Elevated activities of enzymes such as phosphatases, cellulases, and dehydrogenases in legume rhizospheres accelerate organic matter turnover and nutrient mineralization, facilitating plant nutrient uptake.

1.3 Ecosystem Services and Biodiversity

- a) **Pollinator Support:** Legume flowers provide essential nectar and pollen resources, sustaining pollinator populations that are vital for crop productivity and ecosystem stability.
- b) **Habitat Provision:** Legume cover crops and intercrops offer habitat and refuge for beneficial arthropods, predatory insects, and soil fauna, enhancing natural pest regulation and biodiversity.
- c) **Carbon Sequestration:** Through above- and below-ground biomass inputs and SOM formation, legumes contribute to soil carbon sequestration, mitigating greenhouse gas emissions and enhancing climate resilience.

1.4 Pest, Disease, and Weed Management

- a) **Disruption of Pest and Disease Cycles:** Legume rotations break monoculture pest and disease cycles, reducing pathogen build-up and pest populations, thereby lowering pesticide reliance.
- b) **Allelopathy:** Certain legumes produce allelochemicals that suppress weed germination and growth, contributing to integrated weed management.
- c) **Natural Enemy Enhancement:** Legumes support populations of natural enemies such as parasitoids and predators, enhancing biological control within agroecosystems.

Table 1: Ecological and Agronomic Functions of Legumes in Cropping Systems

Function	Mechanism	Impact on Soil/Crop System	Quantitative Contribution	Sustainability Benefit
Biological Nitrogen Fixation (BNF)	Symbiosis with <i>Rhizobium</i> bacteria	Converts atmospheric N ₂ into plant-available form	30–300 kg N ha ⁻¹	Reduces fertilizer requirement
Soil Organic Matter Enhancement	Addition of residues and root biomass	Improves soil structure and fertility	10–25% increase in SOC	Long-term soil health
Nutrient Cycling	Deep rooting and residue decomposition	Mobilizes nutrients (P, K, micronutrients)	10–20% improved nutrient availability	Efficient nutrient use
Soil Structure Improvement	Root exudates and aggregation	Enhances porosity and aeration	Reduced bulk density (5–15%)	Better root growth
Weed Suppression	Dense canopy and allelopathy	Reduces weed competition	10–30% weed reduction	Lower herbicide use
Pest and Disease Break	Crop rotation effect	Disrupts pest cycles	15–25% reduction in pest incidence	Reduced pesticide use
Carbon Sequestration	Biomass addition to soil	Increases soil carbon stocks	0.2–0.5 t C ha ⁻¹ yr ⁻¹	Climate mitigation
Biodiversity Enhancement	Supports soil microbes and fauna	Improves ecosystem stability	Increased microbial diversity	Ecological balance

2. Economic Contributions and System Productivity

2.1 Input Cost Reduction and Profitability

- a) **Nitrogen Fertilizer Savings:** Legumes' BNF significantly reduces synthetic nitrogen fertilizer requirements, lowering production costs and mitigating exposure to fertilizer price volatility.
- b) **Reduced Chemical Inputs:** Crop diversification and natural pest suppression reduce pesticide and herbicide expenditures.
- c) **Labor and Mechanization Efficiency:** Improved legume management practices and mechanization compatibility enhance labor productivity and operational efficiency.

2.2 Yield Stability and Risk Mitigation

- a) **Resilience to Abiotic Stress:** Many legumes possess inherent drought tolerance and adaptability to marginal soils, contributing to yield stability amid climatic variability.
- b) **Crop Insurance Access:** Stable yields and organized production systems, often facilitated by Farmer Producer Organizations (FPOs), improve eligibility for crop insurance and credit, enhancing financial security.

2.3 Income Diversification and Market Opportunities

- a) **Multiple Product Streams:** Legumes provide food (pulses), feed, fodder, oilseeds, and green manure, diversifying farm income sources and reducing economic risk.
- b) **Value Addition and Certification:** Collective marketing via FPOs enables value addition, certification (organic, fair trade), and branding, accessing premium and niche markets.
- c) **Export Potential:** Nutrient-rich legumes meet increasing global demand, especially in health-conscious and vegetarian markets, offering lucrative export opportunities.

3. Social and Nutritional Dimensions

3.1 Nutritional Security and Public Health

- a) **High-Quality Protein Source:** Pulses provide essential amino acids critical for populations with limited access to animal protein.
- b) **Micronutrient Supply:** Legumes are rich in iron, zinc, folate, and other micronutrients, combating hidden hunger and improving public health outcomes.
- c) **Dietary Fiber and Chronic Disease Prevention:** High fiber content supports digestive health and reduces risks of cardiovascular diseases, diabetes, and obesity.
- d) **Food Sovereignty:** Local legume production fosters self-sufficiency and reduces dependence on imports.

3.2 Gender and Community Empowerment

- a) **Women's Economic Participation:** Legume cultivation and processing often involve women, providing income and enhancing their socio-economic status.
- b) **Community Development:** Collective legume enterprises foster social capital, knowledge sharing, and rural development.
- c) **Capacity Building:** Training and extension linked to legumes improve literacy, skills, and social inclusion.

4. Integration Strategies for Legumes in Cropping Systems

4.1 Crop Rotation and Sequential Cropping

- a) **Multi-Year Rotations:** Incorporating legumes in rotations enhances nutrient cycling, pest suppression, and soil health, improving long-term system productivity.
- b) **Site-Specific Planning:** Tailoring legume species and rotation sequences to local agro-ecological and market conditions optimizes benefits.

4.2 Intercropping and Polyculture

- a) **Resource Complementarity:** Legumes intercropped with cereals or tubers optimize light, water, and nutrient use through complementary growth patterns and rooting depths.

- b) **Weed Suppression and Risk Diversification:** Dense legume canopies reduce weed pressure; intercropping buffers against crop failure.
- c) **Mechanization Compatibility:** Designing intercropping systems compatible with mechanization facilitates scalability.

4.3 Cover Cropping and Green Manuring

- a) **Soil Protection:** Legume cover crops reduce erosion, suppress weeds, and improve moisture retention.
- b) **Nutrient Supply:** Green manures enrich soil nitrogen and organic matter, benefiting subsequent crops.
- c) **Pest and Weed Management:** Cover crops disrupt pest life cycles and reduce weed seed banks.

4.4 Agroforestry and Perennial Legumes

- a) **Multi-Strata Systems:** Integration of leguminous trees and shrubs enhances biodiversity, nutrient cycling, and microclimate regulation.
- b) **Livestock Integration:** Perennial legumes provide high-quality fodder, supporting mixed crop-livestock systems.
- c) **Carbon and Water Cycling:** Agroforestry systems sequester carbon and improve watershed management.

Table 2.: Role of Legumes in Sustainable Cropping Strategies

Cropping Strategy	Legume Integration Approach	Mechanism	Impact on Yield/System (%)	Outcome
Crop Rotation	Legume–cereal rotation	Residual nitrogen benefit	10–30% yield increase in cereals	Improved system productivity
Intercropping	Legume + cereal/other crops	Complementary resource use	15–35% higher land equivalent ratio (LER)	Efficient land use
Mixed Cropping	Multiple crops with legumes	Risk diversification	Yield stability under stress	Reduced risk
Green Manuring	Incorporation of legume biomass	Nutrient enrichment	20–40% soil fertility improvement	Sustainable soil management
Agroforestry Systems	Legume trees/shrubs	Nitrogen enrichment and microclimate	10–25% productivity gain	Climate resilience
Cover Cropping	Legume cover crops	Soil protection and nutrient addition	Reduced erosion (15–40%)	Soil conservation
Integrated Nutrient Management (INM)	Legumes + fertilizers	Balanced nutrient supply	10–20% fertilizer saving	Sustainable input use
Climate-Smart Agriculture	Drought-tolerant legumes	Efficient water and nutrient use	15–30% yield stability	Climate adaptation

5. Challenges and Barriers

5.1 Agronomic and Biological Constraints

- a) **Variable BNF Efficiency:** Environmental stresses and soil conditions affect nodulation and nitrogen fixation.
- b) **Pest and Disease Susceptibility:** Legumes face specific biotic stresses requiring integrated management.
- c) **Seed and Inoculant Quality:** Access to high-quality seeds and rhizobial inoculants remains limited in many regions.

5.2 Market and Institutional Limitations

- a) **Price Volatility:** Market fluctuations discourage legume cultivation expansion.

b) **Infrastructure Deficiencies:** Inadequate storage, processing, and transport facilities limit value addition.

c) **Policy Gaps:** Insufficient incentives and research support for legumes compared to cereals.

5.3 Knowledge and Extension Deficits

a) Limited awareness of legume benefits and management restricts adoption.

b) Extension services often lack capacity in legume agronomy and integrated system management.

6. Innovations and Future Perspectives

6.1 Breeding and Biotechnology

a) Development of high-yielding, stress-resilient, and nutrient-rich legume varieties through genomic selection and gene editing.

b) Engineering rhizobia for enhanced nitrogen fixation and stress tolerance.

c) Development of bioinoculants and microbial consortia to improve soil health.

6.2 Digital and Precision Agriculture

a) Use of remote sensing, drones, and IoT for real-time monitoring of legume crop health, soil moisture, and nutrient status.

b) AI-driven decision support systems optimize input use and pest management.

c) Mobile platforms provide farmer advisory and market information.

6.3 Value Chain and Market Development

a) Strengthening FPOs for aggregation, quality control, certification, and collective marketing.

b) Promotion of contract farming and public-private partnerships.

c) Development of niche markets for organic, fair trade, and climate-smart legume products.

6.4 Climate-Smart and Circular Agriculture

a) Integration of legumes within climate adaptation and mitigation frameworks.

b) Promotion of circular economy principles including nutrient recycling, waste valorization, and water reuse.

c) Carbon credit schemes rewarding legume-based sustainable practices.

6.5 Policy and Institutional Support

a) Formulation of supportive policies, subsidies, and extension programs focused on legumes.

b) Investment in infrastructure, research, and capacity building.

c) Multi-stakeholder platforms fostering collaboration among farmers, researchers, industry, and policymakers.

Conclusion

Legumes are foundational to sustainable cropping systems, delivering extensive ecological, economic, and social benefits. Their biological nitrogen fixation, soil health enhancement, and ecosystem services underpin environmental sustainability. Economically, legumes reduce input costs, diversify income, and stabilize farm profitability. Socially, they improve nutrition, empower marginalized groups, and support resilient livelihoods. Strategic integration of legumes through rotations, intercropping, cover cropping, and agroforestry, supported by innovations, policy frameworks, and market development, is essential to unlock their full potential. Addressing challenges through research, capacity building, and institutional strengthening will enable legumes to drive sustainable agriculture and global food security effectively.

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Use of Satellite Remote Sensing for Early Detection of Crop Stress in Precision Agriculture



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1. Introduction

Precision agriculture represents a transformative approach to modern farming, leveraging advanced technologies to optimize crop production by managing spatial and temporal variability in crop and soil conditions. Early detection of crop stress is paramount in this context, enabling timely interventions that can prevent yield losses, reduce input costs, and minimize environmental impacts. Satellite remote sensing has emerged as a pivotal technology in this domain, offering large-scale, non-invasive, and repetitive monitoring capabilities that facilitate continuous assessment of crop health over extensive agricultural landscapes.

This comprehensive article delves into the principles underlying satellite remote sensing, the characteristics of satellite sensors, spectral indicators of crop stress, data processing methodologies, and practical applications within precision agriculture. It further explores challenges faced in operationalizing satellite data for early stress detection and outlines future innovations poised to enhance this technology's efficacy. The integration of satellite remote sensing with other precision agriculture tools and decision support systems (DSS) is also examined, emphasizing the role of remote sensing in fostering sustainable, efficient, and resilient agricultural systems.

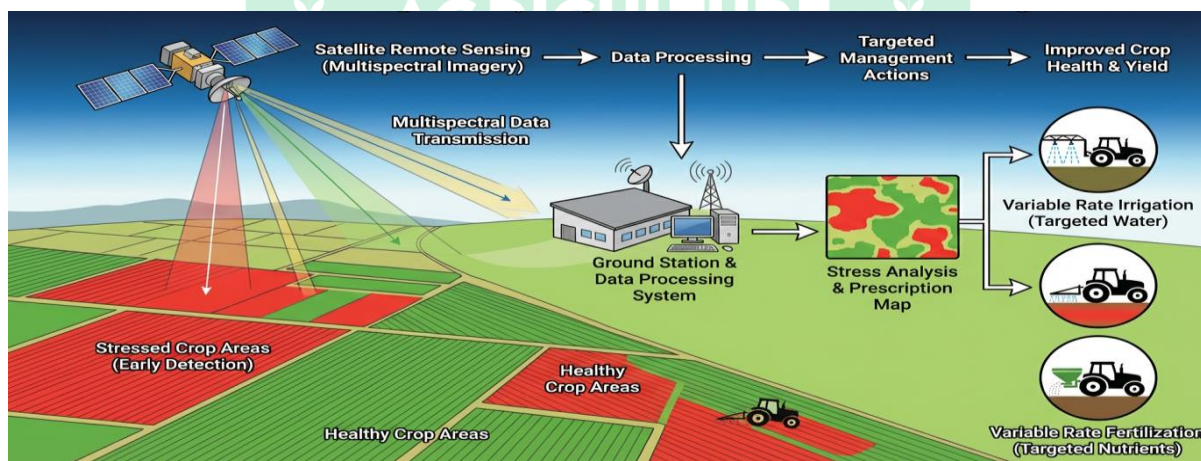


Figure 1: Use of Satellite Remote Sensing for Early Detection of Crop Stress in Precision Agriculture

2. Fundamentals of Satellite Remote Sensing in Agriculture

2.1 Principles of Satellite Remote Sensing

Satellite remote sensing involves the acquisition of data by sensors aboard satellites that detect electromagnetic radiation reflected or emitted from the Earth's surface. The interaction of sunlight with vegetation and soil produces unique spectral signatures reflective of physiological and biochemical conditions. These spectral signatures vary according to factors such as chlorophyll concentration, leaf structure, water content, and canopy architecture, which are influenced by crop health and stress status.

The effectiveness of satellite remote sensing for agricultural monitoring depends on four key sensor characteristics:

1. **Spectral Resolution:** Refers to the number and width of spectral bands a sensor can detect. Multispectral sensors capture data in discrete bands, typically including visible (VIS), near-infrared (NIR), shortwave infrared (SWIR), and thermal infrared (TIR) regions. Hyperspectral sensors provide continuous spectral data with hundreds of narrow bands, enabling detailed discrimination of subtle physiological changes.
2. **Spatial Resolution:** Defines the smallest ground area represented by a pixel in an image. High spatial resolution (1–10 meters) is ideal for field-level monitoring, enabling detection of localized stress, whereas moderate to coarse resolution (10–1000 meters) suits regional or landscape-scale assessments.
3. **Temporal Resolution:** Indicates the frequency with which a satellite revisits the same location. High temporal resolution facilitates monitoring of dynamic crop growth and rapid stress developments, critical for early detection and intervention.
4. **Radiometric Resolution:** Represents the sensor's sensitivity to detect small differences in reflected or emitted radiation, influencing the precision of stress detection.

2.2 Spectral Bands and Crop Stress Indicators

Different spectral bands provide complementary information relevant to crop health:

- **Visible Bands (400–700 nm):** Sensitive to chlorophyll absorption, changes in these bands often indicate pigment degradation associated with nutrient deficiencies or disease.
- **Near-Infrared Bands (700–1300 nm):** Reflectance in the NIR region correlates with leaf cellular structure and biomass. Stress-induced structural damage reduces NIR reflectance.
- **Shortwave Infrared Bands (1300–2500 nm):** Sensitive to water content and biochemical constituents, enabling detection of water stress and biochemical alterations.
- **Thermal Infrared Bands (8–14 μ m):** Measure canopy temperature, an indirect indicator of water stress due to changes in transpiration and stomatal conductance.

3. Satellite Platforms and Sensors for Crop Stress Detection

3.1 Moderate-Resolution Satellites

- **Landsat Series:** Providing 30-meter spatial resolution and a 16-day revisit period, Landsat satellites have been instrumental in vegetation monitoring. Their multispectral sensors capture key bands for vegetation indices, enabling assessment of crop vigor and stress.
- **Sentinel-2:** Operated by the European Space Agency, Sentinel-2 offers 10 to 20-meter spatial resolution with a 5-day revisit frequency. Its 13 spectral bands, including red-edge bands, enhance sensitivity to chlorophyll and stress detection.
- **MODIS (Moderate Resolution Imaging Spectroradiometer):** With daily global coverage but coarser spatial resolution (250–1000 meters), MODIS supports large-scale crop monitoring and early warning systems.

3.2 High-Resolution Commercial Satellites

- **PlanetScope:** Provides near-daily imagery at 3–5 meter resolution, enabling detailed monitoring of smallholder farms and heterogeneous landscapes.
- **WorldView and GeoEye:** Offer sub-meter spatial resolution, allowing precise detection of field-scale stress patterns and management zones.

3.3 Hyperspectral Satellites

- **PRISMA and EnMAP:** These missions provide hyperspectral data with hundreds of narrow bands, facilitating advanced analyses such as nutrient deficiency discrimination and disease stress differentiation.

4. Vegetation Indices and Spectral Metrics for Early Stress Detection

Vegetation indices (VIs) are mathematical combinations of spectral bands designed to amplify vegetation signals and suppress background noise. They serve as proxies for physiological attributes such as chlorophyll content, leaf area index (LAI), photosynthetic efficiency, and water status.

1. **Normalized Difference Vegetation Index (NDVI):** Calculated from NIR and red bands, NDVI is widely used to estimate green biomass and photosynthetic activity. Early stress reduces NDVI values, signaling declining plant health.

2. **Enhanced Vegetation Index (EVI):** Adjusts NDVI by correcting for atmospheric effects and soil background, providing improved sensitivity in dense canopies and enabling earlier stress detection.
3. **Soil-Adjusted Vegetation Index (SAVI):** Incorporates a soil brightness correction factor, useful during early crop growth stages when soil exposure is significant.
4. **Photochemical Reflectance Index (PRI):** Reflects changes in photosynthetic efficiency and carotenoid pigment dynamics, offering early detection of stress before visible symptoms.
5. **Normalized Difference Water Index (NDWI):** Sensitive to canopy water content, NDWI facilitates early detection of drought stress.
6. **Thermal Indices:** Canopy temperature derived from thermal bands indicates water stress through stomatal closure and reduced transpiration.

Table 1: Types of Crop Stress and Their Spectral Indicators

Stress Type	Cause	Spectral Response	Key Indicator/Index	Detection Stage
Nitrogen Deficiency	Low N availability	Reduced chlorophyll, low NIR reflectance	NDVI, NDRE	Early–Mid growth
Water Stress (Drought)	Soil moisture deficit	Increased canopy temperature, reduced reflectance	NDWI, Thermal Index	Early stage
Pest/Disease Stress	Pathogen/insect attack	Patchy reflectance, chlorosis	NDVI, PRI	Early–Visible stage
Salinity Stress	High salt concentration	Reduced growth, spectral distortion	SI, NDVI	Mid stage
Heat Stress	High temperature	Increased canopy temperature	Thermal indices	Early stage

5. Data Processing and Analytical Techniques

5.1 Preprocessing Steps

To ensure data accuracy and comparability, satellite imagery undergoes several preprocessing steps:

1. **Radiometric Calibration:** Converts raw digital sensor data to physical reflectance values.
2. **Atmospheric Correction:** Removes effects of atmospheric scattering and absorption to retrieve true surface reflectance.
3. **Geometric Correction:** Aligns images spatially to real-world coordinates, enabling accurate overlay with other spatial datasets.
4. **Cloud and Shadow Masking:** Identifies and excludes cloud-contaminated pixels to prevent inaccuracies.

5.2 Time-Series and Change Detection Analysis

Temporal analysis tracks vegetation index dynamics over the growing season, identifying deviations from expected growth patterns indicative of stress. Change detection techniques compare images across time points to highlight emerging stress zones.

5.3 Machine Learning and Artificial Intelligence

Advanced algorithms such as Random Forest, Support Vector Machines, and deep learning models classify stress types and severity by integrating spectral, temporal, and ancillary data. These methods improve discrimination between biotic and abiotic stresses and enhance prediction accuracy.

5.4 Data Fusion

Combining data from multiple satellite platforms, UAVs, and ground sensors enhances spatial, temporal, and spectral resolution, improving early stress detection capabilities.

6. Applications of Satellite Remote Sensing for Early Crop Stress Detection

6.1 Water Stress Monitoring

Satellite-derived water indices and thermal data enable detection of canopy water deficits, facilitating timely irrigation scheduling to mitigate drought impacts. Early identification of water stress allows farmers to optimize irrigation, conserving water resources and maintaining crop health.

6.2 Nutrient Deficiency Detection

Changes in chlorophyll-sensitive spectral bands and vegetation indices allow identification of nitrogen and other nutrient deficiencies prior to visual symptoms, enabling targeted fertilization. This precision reduces fertilizer overuse, lowering costs and environmental pollution.

6.3 Disease and Pest Stress Identification

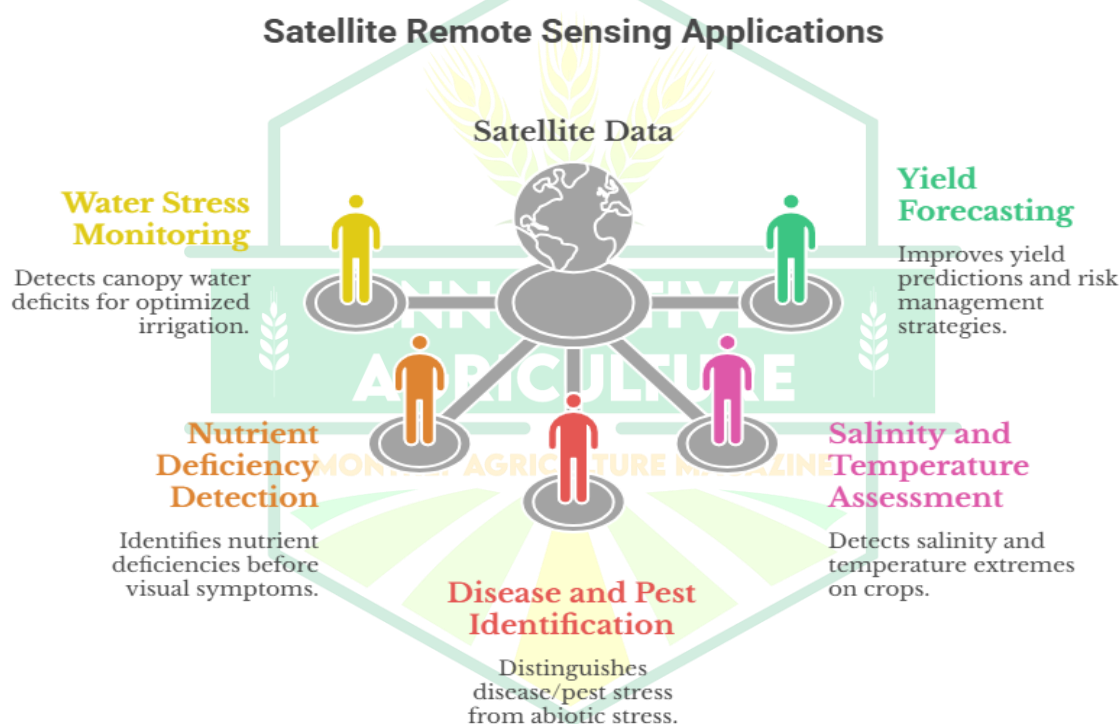
Spectral and thermal anomalies associated with disease or pest damage can be distinguished from abiotic stress through pattern recognition and temporal analysis, supporting precision pest management. Early detection aids in timely application of control measures, minimizing crop losses.

6.4 Salinity and Temperature Stress Assessment

Spectral indices sensitive to pigment degradation and water content detect salinity-induced stress, while thermal data monitor frost and heat stress effects on crops. These assessments help in managing salinity and temperature extremes through adaptive practices.

6.5 Yield Forecasting and Risk Assessment

Early stress detection data integrate into crop growth models to improve yield predictions and inform risk management strategies. Accurate forecasting supports market planning and resource allocation.



7. Integration with Precision Agriculture Systems

7.1 Decision Support Systems (DSS)

Satellite data feed into DSS platforms that synthesize multi-source information to provide actionable recommendations for input management. DSS facilitate data-driven decisions, improving efficiency and sustainability.

7.2 Variable Rate Technology (VRT)

Stress maps derived from satellite data guide VRT-enabled machinery to apply water, fertilizers, and pesticides precisely where needed, optimizing resource use and minimizing environmental impacts. This targeted application enhances input efficiency and reduces costs.

7.3 Farm Management Information Systems (FMIS)

Integration of satellite data with ground sensors, weather stations, and historical records supports comprehensive farm management and adaptive decision-making. FMIS enable real-time monitoring and dynamic response to crop stress.

8. Challenges and Limitations

1. **Spatial and Temporal Resolution Trade-offs:** High spatial resolution data often have lower revisit frequencies, limiting the ability to monitor rapid stress developments. Conversely, high temporal resolution sensors may have coarse spatial resolution unsuitable for field-level analysis.
2. **Atmospheric and Environmental Interference:** Cloud cover, aerosols, and soil background can obscure or distort spectral signals, complicating stress detection.
3. **Complexity of Stress Factors:** Multiple overlapping stresses (e.g., drought, nutrient deficiency, pests) can produce similar spectral responses, challenging accurate diagnosis.
4. **Calibration and Validation:** Ground truth data collection is essential for algorithm development and validation but can be resource-intensive and logistically challenging.
5. **Data Accessibility and Cost:** High-resolution commercial satellite data may be prohibitively expensive for smallholders and resource-poor regions, limiting widespread adoption.

9. Future Perspectives and Innovations

1. **Advancements in Satellite Technology:** Upcoming satellite missions with improved spectral, spatial, and temporal capabilities will enhance early stress detection accuracy and timeliness.
2. **Hyperspectral Data Integration:** Increased availability and utilization of hyperspectral sensors will allow finer discrimination of stress types and severity through detailed spectral signatures.
3. **Artificial Intelligence and Big Data Analytics:** Enhanced machine learning models and cloud computing platforms will facilitate near real-time processing and interpretation of large datasets, enabling proactive crop management.
4. **Synergistic Multi-Platform Approaches:** Combining satellite data with UAV and ground sensor information will provide comprehensive, multi-scale assessments of crop health.
5. **User-Friendly Platforms and Mobile Applications:** Development of accessible tools will democratize satellite data use, empowering farmers and agronomists worldwide.

10. Conclusion

Satellite remote sensing stands as a cornerstone technology for early detection of crop stress in precision agriculture, enabling proactive management that enhances crop health, optimizes input use, and promotes sustainable production. Despite challenges related to resolution, data interpretation, and accessibility, ongoing technological advancements and integration with precision agriculture systems promise to revolutionize crop monitoring and management. Continued research, validation, and capacity building are essential to fully realize the potential of satellite remote sensing in fostering resilient and productive agricultural systems.

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Comparative Evaluation of Different Substrates for Oyster Mushroom Spawn Production Without CaCO_3 Supplementation



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Abstract

The quality of spawn plays a vital role in the successful cultivation of oyster mushrooms. In this study, different substrates like sorghum, pearl millet, maize, cocopeat, vermicompost, and sawdust were evaluated for spawn production without the addition of calcium carbonate (CaCO_3). Among the substrates tested, pearl millet showed the fastest and most vigorous mycelial growth, followed by maize. In contrast, organic substrates such as cocopeat, vermicompost, and sawdust exhibited slower colonization. The results indicate that cereal grains, particularly pearl millet, can effectively support spawn production even without the use of pH-adjusting additives.

1. Introduction

Oyster mushrooms (*Pleurotus* spp.) are widely cultivated due to their high nutritional value and ability to grow under diverse environmental conditions (Chang & Miles, 2004). One of the most important factors influencing successful mushroom cultivation is the quality of spawn, which acts as the planting material (Royse et al., 2017). Spawn is commonly prepared using cereal grains such as wheat, sorghum, and maize because of their rich nutrient content and favorable physical structure (Stamets, 2000). These grains provide essential nutrients like carbohydrates, proteins, and minerals that support rapid mycelial growth (Kurtzman, 2010). In conventional spawn preparation, calcium carbonate (CaCO_3) is added to maintain pH balance and prevent grains from sticking together (Oei, 2003). However, the absence of CaCO_3 may influence the performance of substrates, especially in terms of pH stability and mycelial spread (Ragunathan & Swaminathan, 2003). Recently, there has been increasing interest in exploring alternative substrates such as cocopeat, vermicompost, and sawdust due to their low cost and availability (Philippoussis, 2009). However, their effectiveness in spawn production without chemical additives is still not well understood. Therefore, this study was conducted to compare the performance of both conventional grain substrates and alternative organic substrates for oyster mushroom spawn production without CaCO_3 supplementation.

2. Materials and Methods

2.1 Experimental Design

The experiment was carried out under controlled laboratory conditions to evaluate the growth of oyster mushroom mycelium on six different substrates: sorghum, pearl millet, maize, cocopeat, vermicompost, and sawdust.

2.2 Substrate Preparation

Grain Substrates (Sorghum, Pearl Millet, Maize)

The grains were first cleaned thoroughly to remove dust and damaged seeds (Stamets, 2000). They were then soaked in water for 12 hours to ensure proper hydration (Chang & Miles, 2004). After soaking, excess water was drained, and the grains were air-dried to remove surface moisture. The moisture content was adjusted to approximately 60%, and 250 g of grains were filled into sterilized plastic bags.

Organic Substrates (Cocopeat, Vermicompost, Sawdust)

Cocopeat was soaked and washed to remove excess salts and impurities (Philippoussis, 2009). Vermicompost was sieved to obtain uniform particles (Edwards et al., 2004), while sawdust was collected from untreated wood and sieved to remove coarse materials (Ragunathan & Swaminathan, 2003). All substrates were adjusted to a moisture content of 60–65% and packed into sterilized bags.

2.3 Sterilization

The prepared substrates were sterilized at 121°C for 20 minutes under 15 psi pressure (Stamets, 2000). This step ensured the elimination of contaminants and maintained aseptic conditions. After sterilization, the substrates were transferred to a laminar airflow chamber.

2.4 Mother Culture Preparation

The mother culture was prepared using commercially available oyster mushroom spawn. It was maintained as a pure culture in test tubes. From these, plate cultures were prepared and incubated at $25 \pm 2^\circ\text{C}$ for 7 days to obtain actively growing mycelium.

2.5 Inoculation

After cooling, the sterilized substrates were inoculated under aseptic conditions using actively growing plate cultures (Kurtzman, 2010). Equal amounts of inoculum were used for all treatments. Typically, 2–3 small pieces from the actively growing edge of the culture were transferred into each bag.

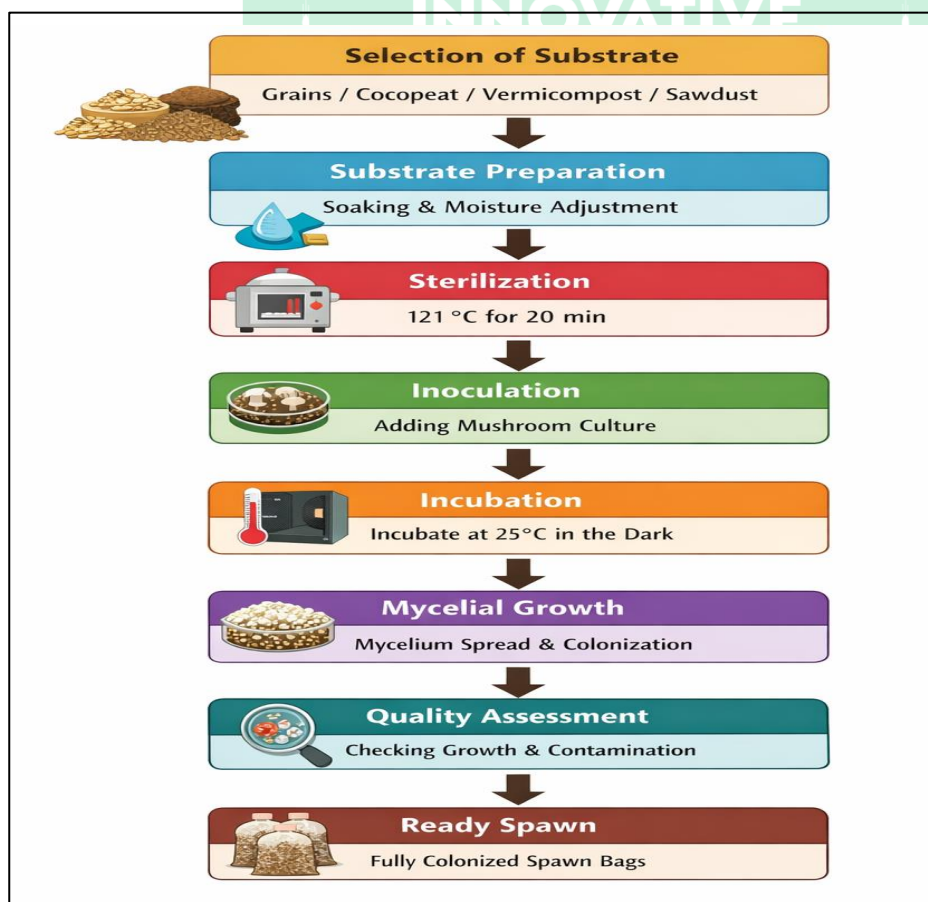
2.6 Incubation

The inoculated substrates were incubated at $25 \pm 2^\circ\text{C}$ in dark conditions (Royse et al., 2017). Observations were recorded daily to monitor mycelial growth, colonization rate, and contamination.

2.7 Parameters Recorded

- Time taken for initial mycelial appearance
- Rate of mycelial growth
- Time required for complete colonization
- Density of mycelial growth
- Fresh mycelial weight
- Contamination incidence

2.8 Process flow chart



3. Results and Discussion

3.1 Mycelial Growth Performance

Among all the substrates tested, pearl millet showed the fastest and most vigorous mycelial growth, followed by maize and sorghum. Organic substrates such as cocopeat, vermicompost, and sawdust showed comparatively slower growth.

This may be due to the higher nutrient availability in cereal grains, especially pearl millet, which is rich in carbohydrates and proteins that promote fungal growth (FAO, 2011).

3.2 Pearl Millet as the Best Substrate

Pearl millet showed:

- Rapid colonization
- Dense and uniform mycelial growth
- Lower contamination levels

Its smaller grain size provides a larger surface area, allowing faster mycelial penetration (Chang & Miles, 2004). In addition, its balanced nutrient composition supports continuous growth (Kurtzman, 2010).

3.3 Performance of Maize and Sorghum

Maize supported good mycelial growth but was slightly slower than pearl millet, possibly due to its larger grain size (Stamets, 2000). Sorghum also supported growth but was less efficient, which may be related to differences in nutrient composition and texture (Oei, 2003). The reduced performance of sorghum may also be influenced by the absence of CaCO_3 .

3.4 Performance of Organic Substrates

Cocopeat:

Cocopeat showed slow mycelial growth due to its low nutrient content, although it retained moisture well (Philippoussis, 2009). However, high moisture also increased contamination risk.

Vermicompost:

Vermicompost supported moderate growth but showed higher contamination due to its microbial load (Edwards et al., 2004).

Sawdust:

Sawdust showed minimal growth because it mainly contains complex lignocellulosic compounds that require more energy for breakdown (Ragunathan & Swaminathan, 2003).

3.5 Effect of Absence of CaCO_3

The absence of CaCO_3 did not significantly affect grain substrates such as pearl millet and maize. This suggests that these grains may naturally maintain suitable pH conditions (Chang & Miles, 2004). However, organic substrates showed inconsistent performance, indicating that CaCO_3 may be more important for non-grain materials (Oei, 2003).

3.6 Contamination Observations

Grain substrates showed lower contamination compared to organic substrates. Some contamination was observed due to physical damage in the bags, leading to fruit fly infestation. Organic substrates were more prone to contamination, particularly by *Trichoderma* spp., likely due to higher moisture retention and microbial load.



Fig 1: Different substrates used in the spawn production where incubated.

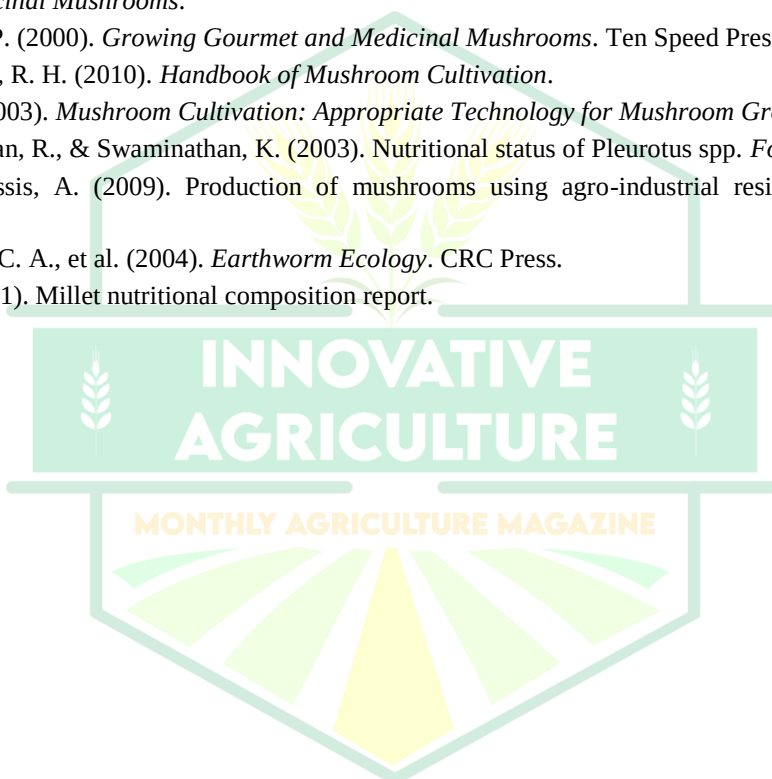
4. Conclusion

The study clearly shows that substrate selection significantly affects oyster mushroom spawn production. Among the tested substrates, pearl millet proved to be the most effective, showing rapid and dense mycelial growth even without CaCO_3 supplementation. Maize and sorghum also performed well but were slightly less efficient.

Organic substrates such as cocopeat, vermicompost, and sawdust were less suitable due to slower growth and higher contamination risk. Overall, pearl millet can be recommended as an economical and efficient substrate for spawn production, especially in low-resource conditions where additives like CaCO_3 are not used. Additionally, pearl millet is often more affordable compared to other grains, making it a practical choice for farmers and small-scale producers.

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Climate Change and Fish Diseases: An Emerging Threat to Aquatic Health and Fisheries Sustainability



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Abstract

Climate change is increasingly recognized as a major driver of emerging fish diseases, posing significant threats to aquatic ecosystems, fisheries productivity, and global food security. Rising water temperatures, ocean acidification, altered hydrological cycles, and extreme weather events disrupt aquatic environments and weaken fish physiological and immune responses. These environmental stressors enhance pathogen growth, transmission, and virulence, leading to more frequent and severe disease outbreaks in both wild and cultured fish populations. Climate-induced changes also alter host-pathogen interactions and facilitate the expansion of diseases into new geographic regions, increasing risks to previously unaffected ecosystems. The combined impacts result in reduced fish survival, productivity losses, and economic challenges for fisheries-dependent communities, particularly in developing countries like India. Addressing these challenges requires integrated and adaptive management approaches, including improved aquaculture practices, disease surveillance systems, selective breeding of resilient species, and ecosystem-based strategies. Strengthening policy frameworks and stakeholder collaboration is essential to enhance resilience and ensure sustainable fisheries. Understanding the link between climate change and fish diseases is therefore critical for safeguarding aquatic health, securing livelihoods, and maintaining long-term food security under changing climatic conditions.

Keywords- Climate change; Fish diseases; Aquaculture; Pathogens; Food security; Fisheries sustainability

Introduction

Climate change is a profound global challenge characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, all of which disrupt natural ecosystems and human societies. Its impacts extend beyond environmental degradation to threaten food security, livelihoods, and economic stability worldwide. Fisheries are especially important in this context, providing a critical source of animal protein, employment, and income for millions globally. In India, fisheries contribute about 12% of animal protein intake and support numerous coastal communities whose livelihoods depend heavily on both capture fisheries and rapidly growing aquaculture sectors (Dutta et al., 2020). The significance of fisheries is even more pronounced in vulnerable delta regions like the Ganges-Brahmaputra-Meghna and Mahanadi deltas, where fish form a dietary staple and underpin local economies. However, climate change-induced environmental shifts such as rising water temperatures, ocean acidification, salinity changes, and altered hydrological cycles are increasingly linked to the emergence and spread of fish diseases that threaten both wild stocks and aquaculture productivity (Okon et al., 2024).

The rise in fish diseases under changing climatic conditions is driven by complex interactions between stressed fish populations and evolving pathogen dynamics. Elevated temperatures can accelerate pathogen growth rates and increase susceptibility of fish to infections, while changes in water chemistry further exacerbate disease risks (Okon et al., 2024). These health challenges undermine fish population dynamics by affecting reproduction,

growth, and survival rates, thereby reducing overall fisheries productivity. For communities dependent on fisheries for food security and income particularly small-scale fisherfolk who often have limited adaptive capacity the consequences are severe. Climate variability also disrupts traditional fishing practices and access to resources, compounding socio-economic vulnerabilities. This situation calls for urgent attention to how climate change influences aquatic ecosystems' health and the cascading effects on human well-being.

Understanding these linkages is crucial for developing effective adaptation strategies that safeguard fisheries sustainability and food security in India and other vulnerable regions. This article aims to elucidate the pathways through which climate change affects fish diseases and their broader implications for fisheries-dependent communities. It highlights the need for integrated management approaches combining improved aquaculture practices, ecosystem restoration, disease surveillance technologies, selective breeding for resilient species, and robust policy frameworks. Addressing these challenges will require coordinated efforts among scientists, policymakers, industry stakeholders, and local communities to build resilience against climate-driven threats. Ultimately, sustaining fisheries under climate change is essential not only for ecological balance but also for securing nutrition and livelihoods for millions now and in the future.

2. Fish Health in Aquatic Ecosystems

Fish health refers to the overall physiological and immunological condition of fish, which enables them to grow, reproduce, and resist diseases within their aquatic environment. Healthy fish maintain a balance with their ecosystem and can adapt to environmental changes without significant stress or disease (Shrivastava et al., 2025).

Types of Fish Diseases

- **Infectious Diseases:** These include bacterial, viral, fungal and parasitic infections that can spread rapidly, especially under stressful or crowded conditions. Common pathogens like *Aeromonas hydrophila* are part of natural microbial communities but can cause disease when fish immunity is compromised (Malik et al., 2020).
- **Non-infectious Diseases:** These arise from environmental stressors such as poor water quality (e.g., low dissolved oxygen, pollutants), temperature fluctuations, or nutritional deficiencies that weaken fish immune defenses and increase susceptibility to infections (Malik et al., 2020).

Role of Water Quality

Water quality parameters such as dissolved oxygen, pH, temperature, salinity and presence of pollutants directly affect fish health by influencing oxidative stress levels and immune function. Poor water quality leads to physiological stress that impairs immunity and promotes disease outbreaks (Malik et al., 2020).

Immunity and Ecosystem Balance

Fish immunity involves innate and adaptive responses that protect against pathogens. The gut microbiota also plays a crucial role in modulating immune responses and maintaining health. A balanced aquatic ecosystem supports fish health by regulating pathogen populations and reducing stressors; disruption of this balance through pollution or habitat changes leads to increased disease incidence (Xiong et al., 2018).

3. Climate Change: Key Drivers Affecting Aquatic Systems

3.1 Rising Water Temperature

Global warming has led to a consistent increase in water temperatures across aquatic ecosystems, driven by elevated greenhouse gas emissions. Rising water temperature accelerates fish metabolic rates, increasing their oxygen demand while simultaneously reducing oxygen solubility in water, which can cause hypoxic stress. This imbalance affects growth, reproduction, and survival of aquatic species and alters food web dynamics. Warmer waters also promote longer stratification periods in lakes and oceans, leading to reduced mixing and oxygen depletion in deeper layers. These changes contribute to habitat loss for cold-water species and increase vulnerability to diseases and harmful algal blooms (Muruganandam et al., 2023).

3.2 Ocean Acidification

Increased atmospheric CO₂ is absorbed by oceans, causing a reduction in pH known as ocean acidification. This shift in acidity disrupts physiological processes in fish and other marine organisms, including impaired sensory functions, altered behaviour, and reduced calcification in shell-forming species. Acidification can weaken immune responses and affect reproduction success, threatening biodiversity and fisheries productivity. The

combined effects of acidification with warming exacerbate stress on marine ecosystems, potentially leading to irreversible ecological shifts (Muruganandam et al., 2023).

3.3 Changes in Rainfall and Hydrology

Climate change alters precipitation patterns, causing more frequent floods, droughts, and shifts in river flow regimes. These hydrological changes impact freshwater fisheries by modifying habitat availability, water quality, and nutrient cycling. Floods can lead to habitat destruction and pollutant runoff, while droughts reduce water volume and concentrate contaminants. Altered timing of snowmelt and runoff affects spawning cycles and aquatic food webs. Regional variability means some areas experience increased rainfall while others face drying trends, complicating management strategies (Muruganandam et al., 2023).

3.4 Extreme Weather Events

The frequency and intensity of extreme weather events such as cyclones, heatwaves, and storms have increased due to climate change. These events cause sudden disturbances in aquatic habitats through physical damage, sediment displacement, salinity changes, and temperature spikes. Such rapid environmental changes disrupt ecosystem structure and function, leading to loss of biodiversity and altered species interactions. Extreme events also exacerbate contaminant mobilization affecting water quality. Improved monitoring and adaptive management are critical to mitigate these impacts on aquatic systems (Bolan et al., 2024).

4. Link Between Climate Change and Fish Diseases

4.1 Temperature-Driven Pathogen Growth

Rising water temperatures due to climate change create favourable conditions for the growth and proliferation of bacterial pathogens such as *Aeromonas* and *Vibrio*. Warmer waters accelerate pathogen metabolism, replication, and virulence, leading to more frequent and severe disease outbreaks in fish populations. Additionally, parasite life cycles shorten with increased temperature, allowing faster reproduction and transmission rates. This temperature-driven enhancement of pathogen activity disrupts aquatic health by increasing infection pressure on fish hosts, especially in aquaculture settings where density is high. The combined effect of accelerated pathogen growth and weakened host defenses under thermal stress significantly raises disease risks (Rud et al., 2020).

4.2 Stress-Induced Immunosuppression

Fish exposed to climate-induced stressors such as elevated temperatures, hypoxia, and acidification experience compromised immune function. Stress triggers physiological changes that suppress both innate and adaptive immune responses, making fish more susceptible to infections. Chronic stress reduces the ability to fight off pathogens effectively, increasing disease prevalence and severity. This immunosuppression is a key factor linking environmental changes to heightened vulnerability in both wild and farmed fish populations. The interaction between stress and immunity highlights the importance of managing environmental conditions to maintain fish health under climate change (Agarwal et al., 2024).

4.3 Altered Host-Pathogen Interaction

Climate change modifies the dynamics between fish hosts and their pathogens by altering environmental conditions that influence infection processes. Changes in temperature, pH, salinity, and oxygen levels can shift the balance in favor of pathogens or hosts depending on species-specific tolerances. These shifts may lead to new disease patterns, including altered timing of outbreaks, increased pathogen virulence, or emergence of novel diseases. The complexity of these interactions means that predicting disease outcomes requires understanding both ecological context and physiological responses of hosts and pathogens under changing climates (Gallana et al., 2013).

4.4 Expansion of Disease Range

Warming waters enable tropical pathogens and parasites to expand their geographic range into temperate regions previously unsuitable for their survival. This expansion increases the risk of introducing exotic diseases into new ecosystems where native fish may lack immunity. Examples include northward spread of bacterial diseases like *Lactococcus garvieae* in Europe and extended seasonal outbreaks of viral diseases such as koi herpesvirus in carp fisheries. The shifting distribution of diseases poses significant challenges for fisheries management and biosecurity efforts worldwide.

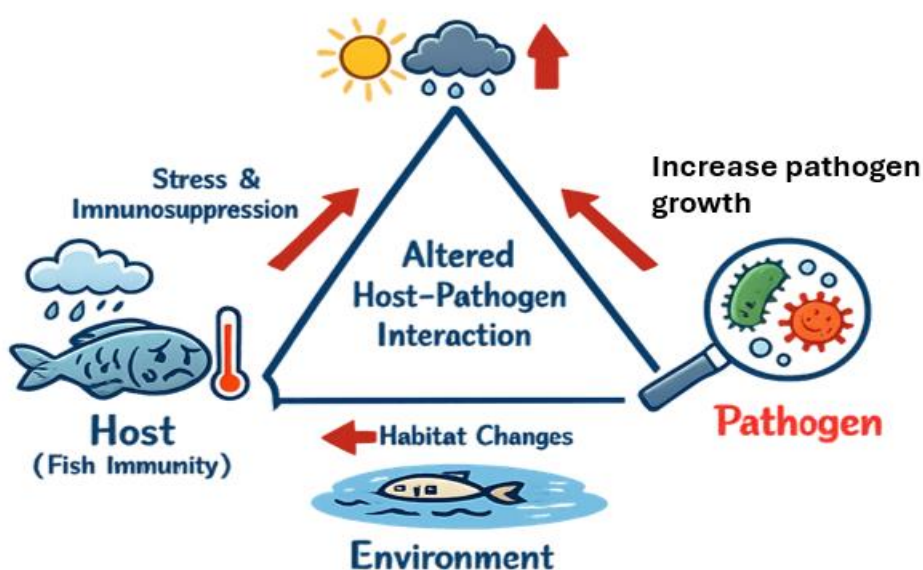


Fig. 1. Host–Pathogen–Environment Interaction

5. Major Fish Diseases Influenced by Climate Change

5.1 Bacterial Diseases

Bacterial diseases such as Motile Aeromonas Septicaemia are strongly influenced by rising water temperatures linked to climate change. Warmer waters enhance bacterial growth rates and virulence, increasing the frequency and severity of outbreaks in both wild and farmed fish populations.

These conditions Favor opportunistic pathogens like *Aeromonas* and *Vibrio* species, which thrive in warmer, oxygen-depleted environments. The increased prevalence of bacterial infections poses significant challenges for aquaculture productivity and fish health management, often leading to high mortality rates if not controlled effectively. Preventive measures including vaccination and improved biosecurity are critical to mitigate these impacts.

Examples: Motile Aeromonas Septicaemia (Karvonen et al., 2010)

5.2 Viral Diseases

Viral diseases such as Koi herpesvirus (KHV) and Viral haemorrhagic septicaemia (VHS) show temperature-dependent outbreak patterns, with warmer conditions often triggering more frequent or severe epidemics. Elevated temperatures can accelerate viral replication and transmission, while also stress fish hosts and compromise their immune defenses. Climate change-driven temperature shifts may extend the seasonal window for viral outbreaks or introduce viruses into new geographic areas. These dynamics increase risks for both wild fisheries and aquaculture operations, necessitating enhanced monitoring and adaptive disease management strategies (Okon et al., 2024). **Examples:** Koi herpesvirus (KHV), Viral haemorrhagic septicaemia (VHS)

5.3 Parasitic Infections

Parasitic infections tend to increase under warmer water conditions as higher temperatures boost parasite development rates, reproduction, and transmission efficiency. This leads to more intense infestations that can severely impact fish health by causing tissue damage, anaemia, and secondary infections. Parasites such as *Ichthyophthirius multifiliis* have shown increased prevalence with rising temperatures in long-term studies. However, responses vary by parasite species and local environmental factors, highlighting the complexity of predicting disease outcomes under climate change (Woo et al., 2020).

5.4 Fungal Diseases

Fungal infections often act as opportunistic diseases in fish stressed by environmental changes like warming or hypoxia. Climate-induced stress weakens fish immune systems, making them more susceptible to fungal pathogens that can cause skin lesions, systemic infections, or mortality. While fungal diseases are less studied

compared to bacterial or viral infections, they represent an important threat especially in aquaculture where high stocking densities amplify disease risks. Effective management requires addressing underlying stressors alongside direct treatment of fungal pathogens (Woo et al., 2020).

6. Impacts on Fisheries and Aquaculture

Climate change is causing significant economic losses in fisheries and aquaculture due to mass fish mortality and reduced productivity. Studies show that global marine fisheries productivity has declined by about 4.1% between 1930 and 2010, with some regions experiencing losses up to 35%, directly impacting livelihoods and economies dependent on fishing.

Small-scale fishers, especially in developing countries like India, face heightened vulnerability as they rely heavily on fisheries for income and food security; climate change exacerbates this by reducing fish stocks and altering species distributions (Cinner et al., 2022). In tropical coastal communities, potential losses to fisheries are often greater than those to agriculture, threatening food availability and increasing socioeconomic disparities.

Aquaculture is also affected by warming waters, sea-level rise, and salinization, which reduce farm productivity and increase operational risks, particularly in vulnerable regions such as Egypt (Yacout et al., 2025). These combined impacts raise serious food security concerns in developing countries where fish constitute a major protein source, underscoring the urgent need for adaptive management strategies and climate-smart policies to sustain fisheries-dependent livelihoods and ensure nutritional security (Lam et al., 2020).

8. Ecological Consequences

Climate change is causing significant loss of biodiversity in aquatic ecosystems by altering habitats and shifting species distributions, often leading to declines in native species and changes in community composition. These changes disrupt aquatic food webs by affecting species interactions, productivity, and trophic diversity, which can reduce ecosystem stability and resilience (Kawade et al., 2025). Warming waters and altered hydrological patterns also facilitate the spread and establishment of invasive species, which compete with native organisms, alter habitat conditions, and increase nutrient loading, further destabilizing ecosystems (Sarkar et al., 2018). Additionally, climate change increases the prevalence and virulence of pathogens in aquatic environments, compounding stress on native species and contributing to ecosystem imbalance. The combined effects of biodiversity loss, food web disruption, invasive species expansion, and heightened disease risks pose profound challenges for maintaining ecosystem functions and services critical to human well-being. Understanding these interconnected impacts is essential for developing adaptive management strategies that address both direct climate effects and indirect consequences mediated by biological invasions (Debnath et al., 2024).

9. Mitigation and Adaptation Strategies

Improved Aquaculture Management

Effective aquaculture management under climate change involves stringent biosecurity measures to prevent disease outbreaks and reduce antimicrobial resistance risks. Enhanced farm biosecurity includes controlling pathogen entry, improving hygiene, and vaccination programs, which collectively protect fish health and productivity. Additionally, continuous water quality monitoring is essential to detect changes in temperature, oxygen levels, and pollutants that stress aquatic organisms. Technologies such as sensors and automated systems enable real-time tracking of water parameters, allowing timely interventions to maintain optimal conditions for fish growth and survival (Adhikari et al., 2018).

9.2 Climate-Resilient Fish Species

Selective breeding programs aim to develop fish strains with increased resistance to diseases and tolerance to abiotic stresses like temperature fluctuations and salinity changes caused by climate variability. These genetic improvements enhance the robustness of aquaculture species, ensuring stable production despite environmental challenges. Incorporating species diversification alongside selective breeding further strengthens resilience by reducing dependency on a single species vulnerable to climate impacts. Such approaches are critical for sustaining aquaculture yields and food security in a changing climate (Yadav et al., 2024).

9.3 Early Warning and Surveillance Systems

Early warning systems integrate disease monitoring technologies with environmental data collection to provide timely alerts about emerging threats in aquaculture settings. Real-time surveillance using molecular diagnostics,

remote sensing, and data analytics helps detect pathogen outbreaks or harmful environmental changes before they escalate. This proactive approach enables rapid response measures that minimize economic losses and ecological damage while supporting adaptive management strategies tailored to local conditions (Paul et al., 2023).

9.4 Ecosystem-Based Approaches

Ecosystem-based adaptation includes restoring wetlands that serve as natural buffers improving water quality, providing habitat for juvenile fish, and enhancing biodiversity essential for resilient fisheries. Sustainable fisheries practices such as ecosystem-based management promote balanced harvesting, habitat conservation, and integration of multi-trophic aquaculture systems that recycle nutrients and reduce environmental impacts. These approaches maintain ecosystem functions critical for long-term productivity and climate resilience of aquatic resources (Debnath et al., 2024).

9.5 Policy and Governance

Robust policy frameworks are vital for integrating climate adaptation into fisheries management through regulations that enforce sustainable harvest limits, protect critical habitats, and support adaptive governance structures responsive to ecological changes. Strengthening fisheries regulations involves stakeholder engagement, cross-sector collaboration, and incorporation of scientific knowledge into decision-making processes. Effective governance ensures equitable resource use while enhancing the capacity of communities and industries to adapt to climate-induced challenges (Panja et al., 2024).

12. Conclusion

Climate change poses a serious and multifaceted threat to fish health, impacting both wild and cultured fisheries through altered water temperatures, habitat degradation, and increased disease prevalence. These changes undermine fish population dynamics and reduce productivity, directly affecting food security and the livelihoods of millions, especially in India's vulnerable coastal and inland fishing communities. Research highlights that adaptive strategies such as climate-resilient aquaculture practices, ecosystem-based management, livelihood diversification, and community-based governance are essential to mitigate these impacts and enhance resilience. Indigenous knowledge and locally tailored interventions also play a crucial role in sustaining fisheries under changing climatic conditions. However, the effectiveness of these strategies depends on coordinated policy support, technological innovation, and capacity building among fishers to cope with increasing environmental stressors. Urgent implementation of sustainable and adaptive management approaches is critical to safeguard fisheries resources, ensure food security, and maintain economic stability in the face of ongoing climate challenges.

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Government Initiatives for Promoting Floriculture in Himachal Pradesh



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Introduction

Himachal Pradesh, a state in the Western Himalayas is well known for its stunning natural beauty, rich flora and ideal environment for floriculture. Some farmers in Himachal Pradesh are now shifting from conventional crops to flower crops. The elevation of Himachal Pradesh ranges from about 350 meter to 6,975 meter above mean sea level, showing highly diversified agro-climatic conditions ranging from sub-tropical to dry temperate which assures that flowers from many climatic zones are available throughout the year. In the sub-tropical low hill zone, districts such as Bilaspur, Una, Hamirpur and lower parts of Kangra and Sirmaur, farmers mainly grow flowers like marigold, carnation, gerbera, gladiolus, chrysanthemum, tuberose and rose. The mid hill zone, including Solan, Mandi, Kangra and parts of Shimla and Sirmaur, is known for commercial cultivation of carnation, rose, chrysanthemum, gladiolus, lilium and marigold. The high hill temperate zone covering upper Shimla, Kullu and Chamba is suitable for different bulbous flower crops such as lilium, tulip and alstroemeria, while the cold dry zone of Lahaul and Spiti supports seasonal cultivation of lilium, gladiolus and other bulbous flower crops during the summer months and quality of flowers producing in the region is generally superior.

The total area under floriculture cultivation in Himachal Pradesh is about 285.74 hectares. Among the various flower crops, chrysanthemum occupies the largest area (95.66 ha), followed by carnation (85.09 ha). Marigold is grown on around 55.35 ha, while comparatively smaller areas are recorded under gladiolus (13.09 ha), rose (11.49 ha), lily (6.52 ha) and gerbera (4.20 ha).

Like all other agricultural farmers, floriculture farmers faces some challenges including unpredictable weather events, fluctuating market prices and pest attack. Thus, crop insurance serves as a vital safety net for floriculture farmers by mitigating the financial risks, providing compensation for crop losses, helps recover from unforeseen setbacks, enabling farmers to continue their farming operations and maintain their livelihood. By mitigating financial risks, crop insurance promotes more resilient and sustainable floriculture industry.

Challenges faced by floriculture farmers

1. **Climate change:** Unpredictable weather patterns including excessive rainfall, drought and hailstorm poses a constant threat to flower crops leading to significant losses.
2. **Market instability:** Price changes in the floral market, driven by seasonal demand and competition which cause financial instability for growers making it difficult to assure constant profitability.
3. **Limited access to resources:** Farmers frequently encounter barriers to getting critical resources such as quality seeds, fertilizers and pest control measures which affect crop output and overall productivity.

Schemes by Government of India

1. **Restructured Weather Based Crop Insurance Scheme:** RWBCIS is a crop insurance program in India that provides financial protection to farmers against crop losses due to adverse conditions. The scheme is implemented by GOI and is available to farmers growing a variety of crops. The scheme uses weather data from automated weather stations and satellite imagery to assess crop losses and provide payouts to farmers. The scheme covers the crops such as cereals, millets, pulses, oilseeds and commercial horticultural crops.

2. **Pradhan Mantri Fasal Bima Yojna:** PMFBY is a crop insurance scheme which was launched by Government of India (GOI) in 2016. The scheme aims to provide financial protection to the farmers in case of yield loss due to natural calamities with a low premium rate of 2% for Kharif crops, 1.5% for Rabi crops and 5% for commercial horticultural crops.
3. **Mission for Integrated Development of Horticulture (MIDH):** The MIDH is a centrally sponsored scheme launched by the Government of India to promote the holistic development of the horticulture sector, including floriculture. The scheme provides financial assistance to farmers for activities such as **protected cultivation, establishment of nurseries, production of quality planting material, post-harvest management and capacity building**. Under MIDH, support is also provided for the cultivation of high-value flower crops like **rose, carnation, gerbera, gladiolus and lilium**, particularly under protected structures such as polyhouses and shade nets. The scheme aims to enhance productivity, improve quality of horticultural produce and increase the income of farmers through the adoption of modern technologies.

Schemes by Government of Himachal Pradesh

1. **Himachal Pushp Kranti Yojna:** Himachal Pushp Kranti Yojana was launched by the Government of Himachal Pradesh in **2018–19** to promote commercial floriculture in the state. The scheme encourages farmers to adopt modern floriculture practices and cultivate high-value flower crops. Under this scheme, the Department of Horticulture provides **subsidy up to 85%** for the cultivation of flowers such as **rose, carnation, gerbera and lilium**, mainly under protected cultivation structures. Financial assistance is also provided for the purchase of planting materials. The scheme has played an important role in expanding floriculture activities particularly in the cultivation of flower crops such as marigold, chrysanthemum, gladiolus, carnation, rose, lily and gerbera, thereby contributing in improving the farmer's income.
2. **Installation of Anti Hail Nets:** Hailstorms frequently occur in several parts of Himachal Pradesh and often cause serious damage to floriculture crops. To reduce these losses, the government provides financial assistance to farmers for the **installation of anti-hail nets**. These nets act as protective barriers that prevent hailstones from directly hitting the crops. The use of anti-hail nets helps protect flowers such as **rose and chrysanthemum**, ensuring better crop protection and stable production.
3. **Krishi Utpad Sarankshan Yojna (KUSHY):** Krishi Utpad Sanrakshan Yojana is implemented by the Government of Himachal Pradesh to protect agricultural and horticultural crops from natural hazards such as hailstorms and adverse weather conditions. Under this scheme, farmers receive financial assistance for installing **protective structures such as anti-hail nets and crop protection systems**. The scheme helps reduce crop losses and supports sustainable production of floriculture crops.
4. **MEHAK:** MEHAK is a state government initiative primarily aimed at promoting the cultivation of **medicinal and aromatic crops** in Himachal Pradesh. Under this scheme, farmers are provided **subsidy up to 85%** for the establishment and promotion of aromatic crops. In addition, limited support is also extended to certain **flower crops such as wild marigold, rose geranium** in the form of quality planting material, technical guidance and adoption of improved cultivation practices. The scheme helps in enhancing crop productivity, improving produce quality and promoting diversification of farming systems in the state.
5. **Mukhya Mantri Greenhouse Renovation (MMGRS):** The Mukhya Mantri Greenhouse Renovation Scheme supports farmers in **renovating and repairing existing polyhouses and greenhouses** that were established under earlier subsidy programs. Over time, these structures may become damaged or require maintenance. Under this scheme, farmers receive financial assistance to repair structures and replace polythene sheets. This helps farmers continue the cultivation of high-value floriculture crops such as **carnation, gerbera and lilium** under protected conditions.

The main objectives of the schemes are

- **Facilitate protected infrastructure:** Help growers to establish new protected infrastructure and improve existing ones for flower crops.

- **Increase productivity:** Boost productivity per unit area of commercially viable floricultural and ornamental crops under protected cultivation.
- **Promote diversification:** Encourage progressive growers to diversify into more viable and profitable farming options.
- **Guide growers:** Assist growers in selecting quality planting material for commercial flower crops.

Some of the key components of the scheme include

- **Protected cultivation:** Provides financial assistance for erecting poly houses, poly tunnels, and high-tech poly houses.
- **Elite planting material:** Provision of elite planting material for high-value flower crops.
- **Human resource development:** Training programs for farmers and capacity building initiatives.
- **Anti-hail nets:** Financial assistance for installing anti-hail nets to protect crops from hailstorms.

Benefits of schemes

1. **Financial protection:** Provide financial protection against unpredictable events ensuring that growers can recover from losses and continue their farming.
2. **Improved access to credit and financial support:** Crop insurance can make it easier for floriculture business to secure loans and other forms of financing, as lenders may view insured farms as less risky.
3. **Increased market stability:** Helps to stabilize the market by mitigating the impact of unexpected events, ensuring a consistent supply of flowers and ornamental plants for consumers.
4. **Enhanced sustainability:** By providing a financial cushion during challenging times, crop insurance helps growers to weather unexpected events and continue their operations, fostering long term viability of the industry.

Conclusion

Himachal Pradesh has immense potential for floriculture due to suitable agroclimatic conditions. The state's farmers produce a range of commercial flowers, however, farmers face challenges such as unpredictable weather, climatic risk and limited resources. To support farmers at different stages of crop production, various government schemes have been implemented. At the initial stage of crop establishment and production, schemes like MIDH, Himachal Pushp Kranti Yojna and MEHAK provide financial assistance for cultivation of crops, provide quality planting material and adoption of improved technologies, while Pradhan Mantri Fasal Bima Yojna and Restructured Weather based Crop Insurance Scheme offer financial assistance against crop losses. After crop establishment, schemes such as Installation of Anti Hail Nets and Krishi Utpad Sanrakshan Yojna help in protecting crops from adverse weather conditions. Further, for infrastructure development and long term sustainability Mukhya Mantri Greenhouse Renovation Scheme support farmers in improving and adopting modern practices. These schemes play an important role in enhancing productivity, reducing crop losses and improving the livelihood of floriculture farmers in the state. With continued government support and adoption of modern cultivation practices, floriculture has the potential to become a major source of income and employment in Himachal Pradesh. Also there are High value flowers crops like Orchid, Anthurium, Tulip and Bird of Paradise that can be grown in different zones of H.P.

The Hidden Power of *Tamarindus indica*: A Natural Remedy for Modern Health Challenges



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Abstract

Tamarindus indica L., commonly known as tamarind or "imli," is a versatile evergreen tree of the Leguminosae family with a rich history spanning from its native East Africa to global naturalization across tropical regions. This article explores the plant's multifaceted profile, ranging from its unique botanical characteristics, such as its "sleeping" leaves and deep taproot system, to its complex phytochemical makeup. Tamarind is a powerhouse of active compounds, including tartaric acid, polyphenols and essential amino acids, making it a vital nutritional resource in regions facing protein malnutrition.

Scientific evidence increasingly supports its traditional use as a natural digestive aid and a supportive therapy for lifestyle diseases. Research highlights its ability to regulate blood glucose through a low glycemic index and support cardiovascular health by modulating lipid profiles and blood pressure. Furthermore, its potent antioxidant and anti-inflammatory properties, driven by high flavonoid and phenolic content, offer analgesic effects and immune system regulation. As a multi-industrial resource used in food, pharmaceuticals and textiles, *T. indica* stands as a highly beneficial, accessible alternative to synthetic treatments for modern health challenges.

Key words: *Tamarindus indica*, Phytochemicals, Nutritional Richness, Lifestyle Diseases, Traditional Medicine, Antioxidant Activity, Anti-inflammatory, Digestive Aid

Introduction:

Tamarind is a tree-grown fruit of *Tamarindus indica* L., belonging to the family Leguminosae (Caesalpiniaceae). It is native to Eastern Africa, including parts of Madagascar's dry deciduous forests. Tamarind is believed to have spread to Asia during the first millennium BC. Its cultivation in Egypt was documented around 400 BC and it was mentioned in Indian *Brahmasamhita* scriptures between 1200 and 200 BC. Around 370–287 BC, Theophrastus also described tamarind in his writings, likely based on sources from East Africa. The tree grows naturally in the wild, although it is also cultivated to some extent. Today, it is widely found across tropical and subtropical regions of the world and has become naturalized in many areas, particularly in India, Southeast Asia, tropical America, the Pacific Islands and the Caribbean.

The fruit of the tamarind tree, also known as the "Assam tree," is commonly called "imli" or "Indian date." This versatile tree can grow in a wide range of soils and is tolerant to both frost and drought. It is mainly valued for its fruits, which are consumed raw or processed, used as a spice or condiment and also processed along with the seeds for various applications. In India, the tamarind tree is widely found in states such as Madhya Pradesh, Bihar, Andhra Pradesh, Chhattisgarh, Karnataka, Tamil Nadu and West Bengal. It is an important cash crop in the country.

Botanical

Tamarind is an evergreen tree that can reach up to 30 m in height, with a trunk about 8 m in diameter and light grey to brown, fissured, scaly bark. It has a dense crown spreading up to 12 m, with wide, drooping branches that exude a reddish substance when damaged. The root system is deep, consisting of a strong taproot and lateral roots.

The leaves are paripinnate, alternately arranged and borne on short petioles and they fold in the absence of light due to lupeol degradation. The plant produces terminal raceme inflorescences with up to 18 flowers, with bud development occurring in about 20 days and flowering completed within 18–26 days. The flowers are bisexual, protogynous, nectariferous and insect-pollinated, promoting cross-pollination, with anthesis around 6 AM. They possess a turbinate calyx and corolla ranging from cream and pale yellow to pink or white. The androecium has three fertile stamens with longitudinally dehiscing anthers, while the gynoecium is superior, with an adnate ovary containing up to 18 ovules. Tamarind produces elongated pods with a brown shell, reddish pulp

and typically six seeds. The fruits measure about 2.50–3.00 cm in transverse diameter and 1.30–1.70 cm in longitudinal diameter, with lengths ranging from 3.70 to 11.10 cm.

Phytochemical profile:

Tamarindus indica contains a wide variety of active compounds, including phenolic compounds, cardiac glycosides, malic and tartaric acids, as well as mucilage, pectin and sugars such as arabinose, xylose, galactose, glucose and uronic acid.

The pulp consists of different organic acids (tartaric, acetic, citric, formic, malic and succinic acids), along with amino acids, invert sugars (25–30%), pectin, proteins, fats and aromatic compounds like pyrazines and thiazoles. The seeds are rich in polysaccharides, proteins, lipids and fatty oils, while the leaves contain triterpenes such as lupanone and lupeol.

The leaf oil of *Tamarindus indica* is composed of 13 components, with limonene and benzyl benzoate as the major constituents. Phytochemical analysis of the root bark has revealed compounds such as n-hexacosane, eicosanoic acid, β -sitosterol, octacosanyl ferulate, 21-oxobehenic acid and pinitol, with the latter being reported in this plant for the first time.

The fruit pulp primarily contains volatile constituents, mainly furan derivatives (44.4%) and carboxylic acids (33.3%). The seeds contain fatty acids, including palmitic, oleic, linoleic and eicosanoic acids. Moreover, the unsaponifiable portion of the seed oil includes β -amyrin, campesterol, β -sitosterol and several hydrocarbons.

Nutritional Richness of Tamarind:

Tamarind can range from very sour to mildly sweet, depending on its growing season. According to the World Health Organization, it is a valuable source of essential amino acids, lacking only tryptophan. Its seeds also possess similar nutritional qualities, making tamarind an important and affordable protein source, especially in regions where protein malnutrition is common. In addition, *Tamarindus indica* is rich in natural plant compounds, including phenolics and organic acids, along with beneficial carbohydrates and fibres such as pectin and mucilage, which contribute to its overall nutritional value.

Tamarind as a Natural Digestive Aid

In traditional medicine, the fruit of *Tamarindus indica* acts as a gentle laxative, largely due to its high content of organic acids such as malic acid and tartaric acid, along with potassium, which helps regulate bowel movements. Traditionally, the leaves are used to manage diarrhoea, the ripe fruit is taken to relieve constipation and the soft inner parts of the bark and root are employed to ease abdominal pain and cramping.

Role of Tamarind in Managing Lifestyle Diseases

Tamarind may play a supportive role in managing lifestyle diseases. It can help regulate blood sugar levels due to its low glycemic index and its ability to slow down carbohydrate digestion. Additionally, the potassium present in tamarind supports heart health by helping to control blood pressure and reducing the risk of cardiovascular diseases.

Antioxidant and Anti-inflammatory Properties

The leaves, seeds and other parts of *Tamarindus indica* show anti-inflammatory activity, although weaker than acetylsalicylic acid. It also has analgesic effects in different pain models. Tamarind helps stabilize red blood cell membranes and reduces inflammation by inhibiting prostaglandins (PG) and nitric oxide (NO), similar to diclofenac. It also limits the action of phospholipase A2 during cell damage, thereby decreasing the inflammatory response. These effects are mainly due to its polyphenol and flavonoid content, which also contribute to its pain-relieving properties.

Tamarind seeds and leaves have demonstrated significant antioxidant activity in various studies. Both raw and heat-treated seeds retain these properties. Like other phenol-rich foods, tamarind exhibits antioxidant, anti-inflammatory and immunomodulatory effects. Its fruit and seeds are rich in organic acids, pectin, vitamins, minerals, polyphenols and flavonoids, which also help regulate immune responses.

Effect on the cardiovascular system and blood

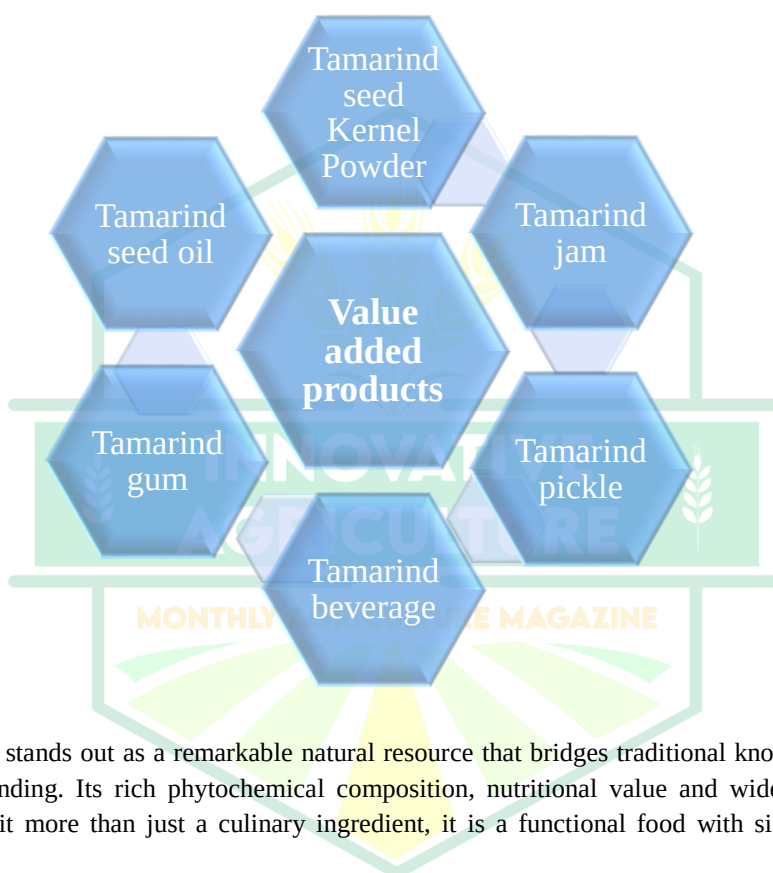
In Bangladesh, the fruits of *Tamarindus indica* have been studied for their effects on lipid profile, blood pressure (both systolic and diastolic) and body weight in humans. In animal studies using hypercholesterolemic hamsters, crude pulp extract was evaluated for its impact on serum lipid levels and atherosclerotic lesions, showing strong

potential in reducing the risk of atherosclerosis. Another study in hamsters demonstrated that a hydroalcoholic extract of tamarind pulp can influence inflammatory mediators.

Traditional Uses and Modern Scientific Evidence

Tamarindus indica is widely used as a traditional medicine in countries such as India, Sudan, Nigeria and Bangladesh, as well as across most tropical regions. It is often readily available and serves as an accessible alternative to pharmaceuticals. Almost all parts of the plant are utilized in food, chemical, pharmaceutical and textile industries and also as fodder, timber and fuel.

Nutritionally, *T. indica* contains proteins with essential amino acids that support muscle development, along with carbohydrates that provide energy. It is also rich in minerals such as potassium, phosphorus, calcium and magnesium and provides smaller amounts of iron and vitamin A. Due to its wide range of medicinal and industrial applications, the plant is highly beneficial for human use.



Conclusion

Tamarindus indica stands out as a remarkable natural resource that bridges traditional knowledge with modern scientific understanding. Its rich phytochemical composition, nutritional value and wide range of bioactive compounds make it more than just a culinary ingredient, it is a functional food with significant therapeutic potential.

Scientific studies increasingly validate its traditional uses, particularly in improving digestion, regulating blood glucose levels, supporting cardiovascular health and reducing inflammation. The presence of antioxidants such as polyphenols and flavonoids further enhances its role in protecting the body against oxidative stress and lifestyle-related disorders.

In addition to its health benefits, tamarind's versatility across food, pharmaceutical and industrial sectors highlights its economic and practical importance. As the demand for safer, plant-based alternatives continues to grow, *Tamarindus indica* emerges as an accessible and effective natural remedy.

Overall, the integration of tamarind into daily diets and healthcare practices offers a promising, sustainable approach to managing modern health challenges while reinforcing the value of traditional medicinal plants in contemporary science.

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Sorghum - A Potential Bioenergy Crop



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ABSTRACT

This article highlights sorghum as a promising bioenergy crop due to its high photosynthetic efficiency, adaptability, and diverse uses. Compared to fossil fuels, it offers a renewable, low-emission alternative. Its fermentable sugars, biomass potential, and flexible cultivation make it suitable for sustainable energy production, while targeted improvements can further enhance its efficiency and utilization.

INTRODUCTION

Existing economies are tied to the flexibility of non-renewable fossil energy sources, primarily in the form of petroleum, coal, and natural gas. Petroleum provides the single largest fraction of the world's energy (40% of total world energy used) and for most countries (IEA, 2002). Burning non-renewable fossil energy sources contributes to carbon dioxide and other greenhouse gas emissions in the atmosphere, raising concerns about global climate change. Non-renewable fossil energy sources are not sustainable; therefore, it is imperative that renewable, less-polluting energy sources to be identified and implemented into current energy markets. Renewable energy sources are needed to address a range of important economic and environmental issues and to ensure a continuous energy supply. The production of biofuel from plant-based biomass is becoming an attractive alternative to non-renewable fossil energy sources. The advantage of plant-based biomass material lies in its photosynthetic ability. Nature has designed a sophisticated solar conversion system that self-assembles from water, nutrients in the soil and carbon dioxide (CO₂) in the air with energy input from the sun. Critical factors in utilizing biomass as an alternative energy source will be the ability of the plant to achieve high biomass yields, grow in diverse climates under various environmental conditions, and be economically converted into a bio-based product. Sorghum is a C₄ crop in the grass family and is characterized by its high photosynthetic efficiency. Sorghum is an annual crop with considerable variability in growth characteristics. Grain, sweet, and forage type sorghums are all compatible with current agricultural production systems. Crops with (C₄) photosynthetic pathways produce 30% more dry matter (DM) per unit of water than three-carbon (C₃) crops and are more adapted to semiarid production regions (Samson and Knopf, 1994). Sorghum plants have the ability to counterbalance production situations. Habyarimana et al. (2004) reported that lower plant density results in higher leaf weight per plant, higher grain weight per panicle and higher tillering ability. Sorghums have an extensive root system that can penetrate 1.5 to 2.5 meters into the soil and extend one meter away from the stem. The large amount of root material contributes to the build-up of soil organic carbon after removal of the aerial parts of the plant, and can alleviate concerns about depletion of soil organic matter resulting from the removal of stover (Wilhelm et al., 2004). Sorghum requires less fertilizer than corn to achieve high yield (Lipinsky and Kresovich, 1980), can tolerate a wide range of soil conditions, from heavy clay soils to light sand, with pH ranging from 5.0 to 8.5 (Smith and Frederiksen, 2000). Sorghums become dormant in the absence of adequate water but do not wilt readily and are more efficient than corn in utilizing phosphorus and potassium. These characteristics make sorghum suitable for cultivation as a crop in optimal conditions and on marginal lands.

WHY SORGHUM AS AN ENERGY CROP?

Among potential annual bioenergy crops, sorghum may be advantageous where drought tolerance is important and it can enhance production of other crops (e.g. as a seasonal cover crop or in rotations). Sorghum allows farmers flexibility in the choice of crop from year to year. It has the potential for high yields. Sorghum is

characterized by a vastly diverse germplasm in terms of phenotypic and morphological traits (Shoemaker and Bransby, 2010). Sorghums have generated interest as an alternative bioenergy feedstock since the 1970s. Sorghum cultivars are primarily processed for the production of table syrups and livestock feed. Sorghum cultivars are now being considered as a candidate in the search for efficient energy crops due to an increased interest in the conversion of biomass to energy. Sorghum cultivars possess readily available fermentable sugars within the culm, therefore enzymatic conversion of starch to sugar is not necessary, which gives sorghum an economical advantage over starch-based crops. The juice from sorghum can be converted to alcohol using currently available, conventional fermentation technology. The bagasse can be utilized to generate electricity or steam as part of a cogeneration scheme or as a biomass feedstock for cellulosic biofuel production. Research interest in sorghum cultivars has focused on the general aspects of sugar production, disease resistance, cultural practices, and agronomic aspects of production such as total biomass yield. Future research into multiple planting dates to increase annual biomass yields and extend seasonal availability of sorghum cultivars needs to be considered because sorghum cultivars have a short growing cycle and are adapted to a wide array of environmental conditions with less nutrient requirements (Turhollow et al., 2010). Sorghums can be classified into the following groups depending on their production characteristics:

(i) Sweet Sorghum

Sweet sorghum yields vary considerably depending on the varieties, location grown (soil, water, climate, pests and diseases), inputs, and agronomic practices. When considering sweet sorghum for biofuel production via conventional fermentation, biomass yield, juice yield, and sugar production per acre are the most important characteristics. Sweet sorghum cultivars are characterized by the accumulation of high levels of fermentable carbohydrates (FC) (15-23%) within the culm. Total FC are comprised of three main sugars; sucrose (70%), glucose (20%), and fructose (10%) variation in percentages depends on variety and environmental conditions (Sarath, et al., 2008). Sweet sorghum requires less water and contains higher FC levels than corn, making it a favourable biofuel crop for semi-arid temperate climate regions (Reddy et al., 2007). Sugar content in the juice increases with maturity and is low prior to seed development. The ideal seeding rate for most sweet sorghum varieties is 3-4 seeds per linear foot of row with a final stand of 2-3 plants per linear foot of row. If plant populations are too high, the stalks will be spindly and contain less juice. Sweet sorghum varieties can grow 14 feet tall and produce 20 to 50 tons of biomass (fresh weight) per acre. Sweet sorghum requires less than 50% total nitrogen to produce similar ethanol yields as corn and is capable of removing 62% of total nitrogen with no difference in DM yield (Bean et al., 2008). Ethanol production from sweet sorghum (5,600 litres ha⁻¹ year⁻¹ from 140 t ha⁻¹ per two crop annum⁻¹ @ 40 L t⁻¹) is comparable to ethanol production from sugarcane (6,500 litres ha⁻¹ from 85-90 t ha⁻¹ per crop @ 75 L t⁻¹).

(ii) Forage Sorghum

Forage sorghums are coarse, fast-growing, warm-season grasses that provide livestock feed in mid-summer. Sugar in the stalk is not the primary focus. Sorghum varieties are currently bred to produce high biomass yields. Forage sorghum utilized as silage, hay and direct grazing represents approximately five million acres of production. Forage sorghum has the potential to grow tall (6 to 15 ft) and can produce a large amount of vegetative growth. Compared with corn, forage sorghum is cheaper to produce, has comparable yields and slightly lower forage quality for silage. These qualities give forage sorghum potential for use in biofuel production (Oliver et al. 2005). The primary sorghums used for forage are grouped as forage sorghums, sudangrass, and sorghum-sudangrass hybrids with each having specific growth characteristics. Typically forage sorghums are used for silage or for a single hay cutting. Sudangrass is used for grazing, multiple hay cuttings and silage. Sorghum-sudangrass hybrids are a cross between sorghum and sudangrass with smaller diameter stems, high tillering capacity, rapid re-growth potential and low grain yield and are best suited for hay and grazing. Optimum growth occurs in sustained elevated temperatures of 75 to 80°F. Introduction of traits such as brown midrib and photoperiod-sensitivity have expanded the use of forage sorghums. The brown midrib (BMR) forage genotypes usually contain less lignin and have reduced lignin chemical composition (Oliver et al. 2005). The reduced lignin content of BMR sorghum increases its energy conversion efficiency and its nutritive value as a livestock feed (Gressell 2008). The BMR mutant genes most commonly used are BMR-6, BMR-12 and BMR-18, and refer to

the reddish-brown pigmentation of the leaf mid-rib (Sarath et al., 2008). Decreased DM yield, plant height, and tillering with increased lodging are potential negative characteristics of BMR sorghum. The lodging potential of BMR forage sorghum can be minimized by adjusting the seeding rate and managing nitrogen fertilization.

(iii) High-Tonnage (Energy) Sorghum

High-tonnage (energy) sorghum can produce increased levels of cellulose material, with reduced grain production depending upon the environment. These are usually classified as hybrid photoperiod-sensitive forage sorghums (PS). Photoperiod-sensitive sorghums delay the flowering, which in turn will delay the decline in forage quality, providing flexibility in harvest management. Photoperiod-sensitive sorghum will not produce grain at most latitudes in the United States. The PS characteristic allows these sorghum hybrids to accumulate vegetative dry matter for longer periods throughout the growing season. Photoperiod-sensitive hybrids can be derived from the cross of two photoperiod-insensitive parental sorghum lines (Rooney et al., 2007). McCollum et al. (2005) reported dry matter yields of PS sorghum to be 26% to 43% greater than non BMR and BMRs forage sorghums with less overall water use. Photoperiod-sensitive sorghum has characteristically high lignin content in the stalks, which minimizes lodging but decreases nutritive quality as a livestock feed. Although cellulosic biomass is receiving growing attention as a bioenergy feedstock, the concept is not well understood for sorghum biomass because scientific information on using forage sorghums for biofuel production is limited.

WHAT ARE THE FURTHER IMPROVEMENTS NEEDED IN SORGHUM?

Genetic mapping combined with a relatively fast breeding and field-testing cycle facilitates further improvements for bioenergy once desired feedstock characteristics and site requirements are clearly defined. Acknowledging that improvements for bioenergy could potentially diverge from those for feed and food, the following research agenda is proposed: 1) Define traits important for bioenergy and characterize sorghum collections for these traits 2) Develop cost-effective means to stabilize sweet sorghum juice so it does not need immediate processing 3) Increase sugar yields of sweet sorghum for use in the near term as an ethanol feedstock (or to supplement sugar from sugarcane) 4) Increase grain yields for sweet and energy sorghums to explore multi-product potential 5) Develop varieties for high biomass yields (energy sorghum) 6) High and low lignin varieties (high lignin for thermochemical conversion such as gasification or pyrolysis and low lignin for ethanol feedstock) 7) Research cropping systems including (i) double cropping where sorghum supplements other grain production to increase overall output while reducing environmental impacts (ii) cover crop and inter-crop sorghum that helps control weeds and pests for high-value crops (vegetables) while improving soils While perennial biomass crops may be preferred for environmental benefits (e.g. lower soil erosion, lower fertilizer requirements), annuals such as sorghum provide farmers with more agility to shift crop production in response to market signals. Sorghum's fast breeding cycle, compared to perennials, can help increase bioenergy feedstock production while perennials are being developed. Both perennials and annuals can play important roles in an integrated system designed to minimize input requirements and maximize production of multiple food, feed, fiber and fuel products (Turhollow et al., 2010). Advances in molecular breeding, including marker-assisted selection and genomic selection, can accelerate trait improvement and cultivar development. Integration of precision agriculture practices, such as efficient water and nutrient management, can further enhance biomass productivity and sustainability. Although perennial biomass crops offer environmental advantages like reduced soil erosion and lower fertilizer inputs, annuals such as sorghum provide greater flexibility for farmers to respond to changing market demands. Its rapid breeding cycle supports quicker genetic gains and increased feedstock production. Together, annuals and perennials can contribute to integrated, resilient systems aimed at maximizing food, feed, fiber, and fuel production while minimizing inputs.

CONCLUSION

Sorghum emerges as a versatile and sustainable bioenergy crop due to its high productivity, adaptability, and efficient resource use. Its potential for multi-product utilization and economic advantages highlights its importance. With targeted research and improved cultivation strategies, sorghum can significantly contribute to renewable energy systems and sustainable agricultural development.

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Automation and Robotics in Post-Harvest Handling Systems



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Abstract

Post-harvest handling plays a crucial role in maintaining the quality, safety, and market value of agricultural produce. In India, a significant portion of fruits, vegetables, and other perishables is lost due to inefficient handling, manual operations, and lack of modern technologies. Automation and robotics have emerged as advanced solutions to address these challenges by improving efficiency, precision, and consistency in post-harvest operations. Technologies such as robotic sorting, automated grading, smart packaging, and robotic storage systems are increasingly being adopted. This article highlights the role of automation and robotics in post-harvest handling systems, along with their applications, benefits, challenges, and future scope in the agricultural sector.

Keywords: Automation, Robotics, Post-Harvest Management, Smart Agriculture, Food Processing, Supply Chain

1. Introduction

India is one of the largest producers of agricultural commodities, including fruits, vegetables, cereals, and dairy products. However, post-harvest losses remain a major concern, estimated at 15–30%, primarily due to improper handling, lack of infrastructure, and dependence on manual labor (FAO, 2019).

Post-harvest operations such as sorting, grading, packaging, storage, and transportation significantly influence the quality and shelf life of produce. Traditional methods are often inefficient and inconsistent. The integration of automation and robotics into post-harvest systems offers a modern solution by enhancing operational efficiency, reducing human error, and ensuring product quality (Kumar et al., 2021).

Automated Robots



2. Objectives

- ❖ To understand the role of automation and robotics in post-harvest management
- ❖ To improve quality and reduce losses of agricultural produce
- ❖ To enhance efficiency and productivity in handling systems
- ❖ To promote adoption of modern technologies among farmers and stakeholders

3. Automation and Robotics Technologies

3.1 Automated Sorting and Grading Systems

Automated sorting and grading systems use computer vision and sensor technologies to classify produce based on size, color, shape, and quality. These systems ensure high accuracy and speed compared to manual methods (Patel et al., 2020).

3.2 Robotic Handling Systems

Robotic arms and automated systems are used for handling delicate fruits and vegetables. These systems reduce mechanical damage and improve efficiency in handling operations (Singh et al., 2022).

3.3 Automated Packaging Systems

Automated packaging machines perform weighing, filling, sealing, and labeling operations. These systems ensure uniform packaging and reduce labor dependency (Sharma and Gupta, 2021).

3.4 Smart Storage Systems

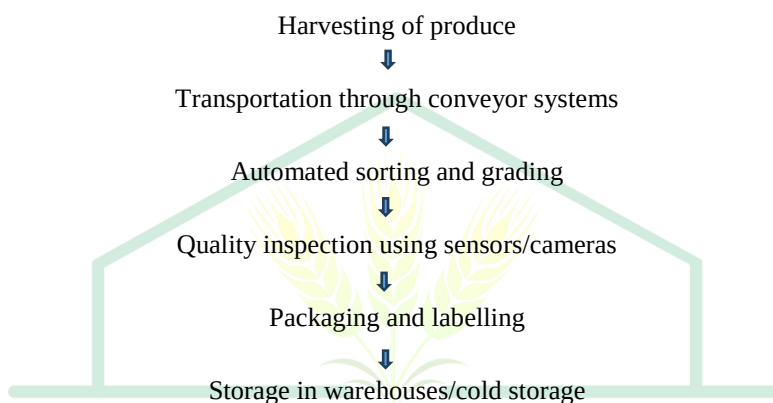
Smart storage systems use sensors and automation to maintain optimal temperature and humidity levels. These systems improve shelf life and reduce spoilage of perishable commodities (ICAR, 2020).

3.5 Conveyor and Material Handling Systems

Conveyor belts and automated transport systems enable efficient movement of produce within processing units, reducing manual labor and handling time.

4. Working Flow (Process Flow of Automation)

Post-Harvest Automation Process Flow



Distribution to markets

5. Applications

1. Fruit and Vegetable Industry

Used for grading and sorting of mango, apple, tomato, etc.

2. Food Processing Industry

Automation in processing, packaging, and quality control.

3. Dairy Industry

Automated milk processing and packaging systems.

4. Grain Storage Systems

Smart warehouses and automated storage management.

6. Benefits

- ❖ Reduction in post-harvest losses
- ❖ Improved product quality and uniformity
- ❖ Reduced labor cost
- ❖ Increased efficiency and productivity
- ❖ Time-saving operations
- ❖ Enhanced market value

7. Constraints

- ❖ High initial investment
- ❖ Lack of technical knowledge
- ❖ Limited access for small farmers
- ❖ Maintenance challenges

8. Recommendations

- ❖ Conduct training programs through KVKs
- ❖ Promote government subsidies and schemes
- ❖ Encourage Farmer Producer Organizations (FPOs)
- ❖ Develop low-cost automation technologies

- ❖ Increase awareness and capacity building

9. Conclusion

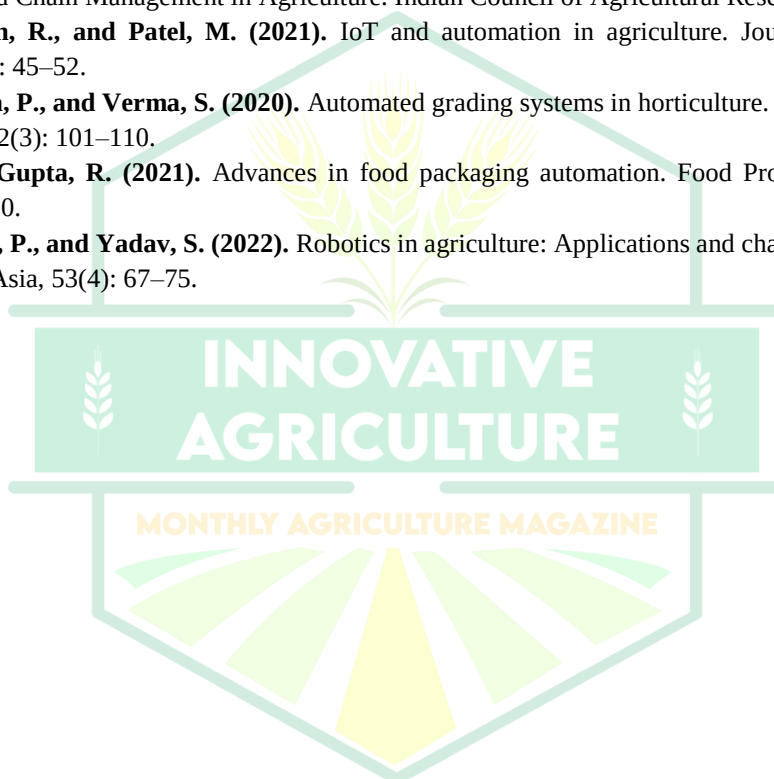
Automation and robotics are transforming post-harvest handling systems by improving efficiency, reducing losses, and ensuring better quality of agricultural produce. With proper support, training, and infrastructure, these technologies can significantly enhance the profitability and sustainability of agriculture in India.

10. Future Scope

- ❖ Integration of Artificial Intelligence (AI)
- ❖ Development of cost-effective robotic systems
- ❖ Use of drones and robotics in agriculture
- ❖ IoT-enabled smart warehouses
- ❖ Expansion to small and marginal farmers

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APPLICATION OF ARTIFICIAL INTELLIGENCE IN EARLY DETECTION OF DISEASES IN PROTECTED CROPS



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Abstract

Artificial Intelligence (AI) is revolutionizing agriculture by improving the early detection of diseases in protected crops grown in environments like greenhouses and polyhouses. Application of AI methods, including machine learning and deep learning, to detect the diseases of plants at their early stages, which will help decrease the destruction of crops and increase their quality. The image processing programs, and convolutional neural networks (CNNs) can be used to monitor the health of plants in real-time by using both images of the leaf and the surroundings. Also, sensors and Internet of Things (IoT) technologies can be used to predict diseases and monitor such factors as temperature, humidity, and soil conditions. Due to the large amount of data trained in AI systems, it is capable of identifying fine-tuning disease symptoms that could not be noticed by people. Early identification facilitates prompt and effective measures to reduce the application of pesticides and promote environmentally-friendly activities. On the whole, AI-based solutions enhance the productivity of agricultural enterprises and help farmers to make decisions as well as add to the more efficient and safer agricultural systems.

Keywords: Artificial Intelligence, Protected cultivation, Disease, Internet of Things, Machine learning

1. Introduction

The modern agricultural era is characterized by a lot of problems including climatic change, rapid population growth, and the spreading intensity of plant diseases. These problems have a significant impact on the crop health and productivity, and hence low yield. Consequently, they are one of the major enemies of world food security and sustainable agricultural development (Sahoo *et al.*, 2024). Protected cultivation comprises of the controlled cultivation of crops in the form of greenhouses, polyhouses, and net houses. These structures also aid in retention of optimum temperatures, humidity, and light resulting in better crop growth and increased yields (Jain *et al.*, 2023). Nevertheless, crops may still get diseases due to fungi, bacteria, viruses and environmental stress factors even in such controlled environments. Early detection of diseases plays an important role in reducing the spread and loss incurred. Conventional methods of detecting forest fires are mostly based on human perception and as such, this may be subjective and thus inaccurate. The implementation of Artificial Intelligence (AI) has significantly improved this process giving it faster, more precise, and automated methods of disease diagnosis.

2. Artificial Intelligence in Agriculture

Artificial Intelligence (AI) refers to the capability of machines to accomplish tasks which should have been carried out by intelligent humans like learning through the data, identifying patterns and making decisions. More commonly applied in agriculture, AI is already being utilized to enhance crop output, use resources more wisely, and monitor the health of plants at an even more efficient rate (Oliveira & Silva, 2023). Artificial intelligence, cloud computing, robotics and the Internet of Things (IoT) are modern technologies that are changing the detection of crop diseases and contributing to the agriculture 4.0. They can also make farming smarter as they enhance the precision of disease identification and more effective utilization of pesticides and treatments (Rajasri *et al.*, 2025).

Some of the key technologies involved in AI include:



Machine learning



Deep learning



Computer vision



Internet of Things

- **Machine Learning (ML):** It helps systems learn from previous data and gradually improve their performance without direct programming.
- **Deep Learning (DL):** An advanced type of ML that uses layered neural networks to analyse complex data.
- **Computer Vision:** Enables machines to interpret and analyse images, which is especially useful for detecting plant diseases.
- **Internet of Things (IoT):** Uses interconnected sensors and devices to gather and exchange real-time data from agricultural fields.

Why early detection of diseases is important?

- Helps in controlling the rapid spread of diseases within enclosed systems.
- Minimizes the excessive use of chemical pesticides.
- Reduces financial losses of the farmers.
- Ensures better quality and higher yield of those crops.
- Encourages sustainable farming practices environmentally.

3. Applications of AI in early detection of diseases

3.1. Image-Based Disease Detection

Protected cultivation has extensively been applied in imaging systems powered by AI to check the health of plants. These systems record the specifics of crops in the setup like a greenhouse and a poly house. The images retrieved are then processed through some very sophisticated algorithms of the Deep Learning paradigm, specifically, models such as Convolutional Neural Networks (CNNs) are the main components of the AI-assisted disease detection systems since they are very efficient in locating and classifying the image based on visual patterns (Sahoo *et.al.*, 2024).

- They are able to correctly spot the symptoms that are visible: spots on the leaves, yellowing, discolouration, wilting, and others.
- The ability of these systems to identify diseases at a very early stage is possible.
- The image analysis relying on AI is more accurate and consistent, which is less likely to be misdiagnosed.
- These systems greatly conserve time and effort saved by farmers since human labour is not required to guarantee the automation of the monitoring process.

3.2. Sensor-Based Monitoring

Environmental data are collected with the help of sensors in guarded cultivation systems, and it includes: temperature, humidity, soil moisture and light intensity (Khan *et. al.*, 2024). AI uses this information to forecast the occurrence of diseases. Excessive humidity in this case can provide favourable environment and growth of fungal diseases like powdery mildew.

3.3. Predictive Analytics and Disease Forecasting

The AI systems are used to forecast the potential outbreaks of diseases in crops by merging the previous data with real-time data. Through the analysis of past data like past disease trends, weather trends and crop yield and present environmental data, AI can detect trends and risk factors that can cause infections. Predictive analysis and disease forecasting can estimate the likelihood of development of disease, can guide farmers to take preventive measures and also aid in efficient irrigation and ventilation mechanisms. It limits the excess usage of pesticides by applying them selectively.

3.4. AI-Enabled Robotics

Robots with AI are now an inseparable part of the secure agricultural systems. Such robots scan crops continuously to understand the health of the plants, recognize the earliest cases of infection, accurately identify infected plants or areas, spray specific plants or remove infected plants, and results in more accurate and effective control or prevention of the disease (Balaska *et. al.*, 2023).

3.5. Mobile Applications for Farmers

AI-based mobile applications are also emerging as useful tools that farmers can use to work on crop health, detect plant diseases, and track pests. The farmers will be able to take pictures of diseased plants and upload them to get an immediate analysis. Get proper and immediate diagnosis and proper treatment recommendations, including advisable pesticides, organic treatments or cultural practices. Receive appropriate treatment prescriptions. Such applications enable the use of advanced technology by more people particularly small-scale and limited resource farmers. Empowering them to make sound choices and make action at the right time to save their crops (Ibrahim *et. al.*, 2025).

4. Advantages of AI in Disease Detection

- **High Accuracy:** AI technology is capable of detecting the slightest manifestations of plant diseases and making an accurate diagnosis and minimizing errors in comparison with the standard manual checks.
- **Rapid Response:** AI can analyse data much faster and provide immediate notifications, thus farmers can react timely to problems before the diseases become widespread.
- **Cost Effectiveness:** Data Mining and targeted treatment saves the human labour required day in day out, thereby cutting down on the cost of operation and improving resource utilisation.
- **Less Chemicals:** AI means that pesticides will be used in the most crucial areas, which will reduce excessive consumption and promote more sustainable and eco-friendly farming.
- **Ongoing Surveillance:** AI is a combination of sensors and cameras and real-time analytics that ensure constant monitoring of crops and promotes the detection of possible issues in the early stages.
- **Increased Productivity:** Early disease outbreaks and interventions will reduce disease outbreaks, protect plant health, and lead to increased crop yields and quality.

5. Disadvantages of AI in Disease detection

- **High Initial Investment:** The implementation of AI in agriculture comes with significant costs in terms of equipment, sensors, cameras and software that might be unfeasible to the small farmers or farmers who have limited resources.
- **Lack of Technical Capability:** A lot of farmers lack the technical expertise and training needed to run AI systems and therefore this can be a barrier to the general uptake.
- **Large, Quality Data Required:** AI models require large high-quality data to be trained, and small and poor-quality data may lead to a reduction in accuracy and reliability of predictions.
- **Lack of Rural Infrastructure:** Lots of rural areas do not have stable internet, electricity, and tech support that are required to ensure the effective operation of AI technologies.
- **Potential to Error:** The AI systems may make wrong predictions due to biased, incomplete, or inaccurate training data, which causes wrong actions and can cause losses of crops.

Conclusion

AI has become a revolutionary technology in the early detection of diseases in crops that are under protection. It integrates machine learning, deep learning, IoT, and computer vision, which can identify the issues in the health of plants quickly, accurately, and efficiently to help farmers react in time. This is not only a way of reducing crop

losses but also sustainable farming, as it encourages a specific treatment and also curbs excessive use of chemicals. Despite the set of difficulties including expensive setups and the technical skills required it is observed that with the continuous technological advancements and rising awareness of farmers, these setbacks are being counterbalanced leading to AI becoming a crucial instrument of contemporary, smart, and sustainable farming.

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Dynamics and Management of Non-Infectious Diseases in Commercial Shrimp Farming



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Abstract:

Non-infectious diseases pose a major but often underestimated challenge in commercial shrimp farming. Intensification of shrimp culture practices led to a wide variety of physiological and metabolic disorders. Unlike infectious diseases, non-infectious conditions involve no pathogenic agent, but they arise from environmental stressors, nutritional deficiencies, mechanical injuries, and management failures. Thus, reducing growth and survival. Non-infectious conditions have been linked with major economic losses, severely reducing market value and farm profitability. A clear understanding of the dynamics of non-infectious diseases is essential for early diagnosis, effective farm management, and sustainable production. This article summarizes the major non-infectious diseases affecting farmed shrimp, their causative factors, clinical manifestations, and practical management strategies to minimize economic losses and enhance shrimp health under commercial aquaculture conditions.

Keywords: Non-Infectious Diseases, Shrimp Aquaculture, Stress Factors, Nutritional Disorders, Health Management

Introduction

Increasing global demand for seafood has led to the commercialization of shrimp culture industry. Diseases caused by infectious agents are said to be of great deal whereas non-infectious diseases act as silent killers and as great significance in relation to the impact on shrimp health and productivity in culture. They mainly arise from stress, nutritional imbalances, improper management, and injuries. High stocking density, variability of water quality factors, inappropriate formulation of shrimp diet, and poor management of shrimp ponds impair physiological processes of shrimp, thus provoking metabolic disorders, tissue deterioration, and immune system deficiency. Non-infectious diseases may serve as predisposing agents, thereby raising vulnerability of shrimp to secondary infections. This is a challenge in terms of diagnosis and treatment. The dynamics of non-infectious diseases must be thoroughly understood for effective health management in shrimp farming (Holt et al, 2021). This article focuses exclusively on major non-infectious diseases observed in commercial shrimp culture, emphasizing their causes, clinical signs, and management strategies, with the aim of promoting sustainable and responsible aquaculture practices.

Non-Infectious Diseases in Commercial Shrimp Farming

1. Melanosis (Melanization / Dark Blotching)

Shrimp melanosis is caused by the enzymatic oxidation of phenolic compounds using polyphenol oxidase (PPO) to form melanin pigments at ruptured or swollen areas. The condition is commonly triggered by mechanical trauma, chemical irritation, or lack of good handling, aggravated by the low standard of water and physiological stress. Melanosis would decrease the quality of products and their market value because it creates unattractive black spots even though it is not a health risk. The management methods include minimization of physical damage, optimization of handling and storage, and application of PPO inhibitors, including modified atmosphere packaging, or plant polyphenols, to slow down the process of melanosis and preserve the quality of shrimp (Fig 1a).



Fig.1 Non-Infectious Diseases in Commercial Shrimp Farming

2. **Muscle Cramp Syndrome / White Muscle (Muscle Necrosis)**

Muscle cramp syndrome and the white muscle in shrimp are caused by acute metabolic and ionic changes in form of acid-base imbalance and lactic acid, which causes muscle necrosis. The causes of such problems are usually caused by the rapid salinity, temperature variations, the modified dissolved oxygen or crowding stress. The clinical signs of affected shrimp include cramping, tail flexion, and white muscle, and severe cases lead to secondary or rapid death. Management includes stabilization of the environmental conditions, proper aeration, and keeping a check on the ionic content to prevent the occurrence of acute stress (Fig 1b).

3. **Vitamin deficiencies (Vitamins C and E)**

Vitamins C and E are critical in the protection of connective tissue and help in cellular functions. Vitamin C and E deficiencies in shrimp cause impaired antioxidant defenses, tissue repair, poor molting, weak exoskeletons, discoloured muscles, and high-mortality rates. Treatment involves nutritional supplementation with vitamins and specific supplementation in stress (Fig 1c).

4. **Gill Choke**

This is a clogging of gill surfaces by particulates, silt, algal aggregates or mineral precipitates which damages respiratory efficiency. It is brought about by turbidity, algal blooms, and poor water management. Affected shrimps exhibit decreased feeding, flocking at the surface and are also more vulnerable to hypoxia which leads to stunted growth and mortality. The precautionary steps involve screening of the intake water, pond bottoms management, and clarification of water to lessen the particulate loads (Fig 1d) (Zhang et al, 2024).

5. **Colour Differentiation**

Carotenoid metabolism is affected in shrimps due to nutritional deficiencies and environmental stress. This results in colour change in shrimps. Thus, serving as an early warning of deplorable conditions. The management approaches include eliminating nutrient deficiencies, enhancing husbandry, and eliminating stressors to restore normal pigmentation (Fig 1e) (Han et al, 2024).

6. **Deformities (Developmental Abnormalities)**

Genetic factors, nutritional imbalances, bad management of broodstocks, and environmental contaminants are some of the causes of deformities in shrimp. Abnormalities are seen in the rostrum, antennae, carapace, and limbs which tend to lead to runt and abnormal growth. The prevention measures are genetic screening, optimal feeding of larvae, maintenance of proper hygiene at the hatchery and avoidance of contaminants (Fig 1f).

7. **Hepatopancreatic Whitening (HP Atrophy / Lipid Depletion)**

In shrimp, non-infectious whitening and atrophy of the hepatopancreas is a sign of lipid depletion and poor digestion, which is usually caused by chronic nutritional stress or environmental influences. Such symptoms include emaciation and pale hepatopancreas, and in histological findings, there is atrophy without pathogens. Balanced feeding, correct feed storage, pond preparation, and biosecurity are the management strategies that prevent secondary infections (Fig 1g).

8. **External Damage / Blotch (Rostrum Attack) (Cannibalism / Mechanical Wounds)**

Mechanical injuries related to the attack of the rostrum or abrasive contact may result in the appearance of local wounds becoming melanized and infected, especially when the stocking is dense, or the feeding conditions are poor. These kinds of injuries have adverse effects on market value and survival. The prevention of this involves management of the stocking density, adequate feeding, grading, sheltering and water quality to facilitate healing and prevent infection (Fig 1h).

Conclusion

Non-infectious diseases pose a great challenge to sustainable shrimp farming, especially when it comes to intensive and semi-intensive production. Melanosis, muscle necrosis, vitamin deficiencies, gill choke, deformities, hepatopancreatic atrophy, colour abnormalities, and external injuries mainly originate from environmental stress, nutrient imbalances, as well as poor management. For non-infectious diseases, preventive and controlling measures entail ensuring that water is of optimal quality, the diet is well balanced, densities are appropriate, and proper handling and management strategies are followed. Early detection of symptoms is extremely important so that corrective actions are taken and things do not progress further into secondary infections. Emphasis on better management practices and preventive healthcare strategies will not only help reduce incidences of non-infectious diseases but will also result in increased productivity as well.

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Scents of Nature: The Science Behind Floral Fragrance



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Introduction

Floral fragrance is among the most captivating traits in ornamental floriculture, shaping consumer preference, pollinator behaviour, and even plant defence strategies. In modern horticulture, the chemistry and biology of floral volatiles are no longer treated as mere sensory phenomena; they are quantified traits whose biosynthesis, regulation, and genetic control are being dissected in major ornamental species such as *Jasminum*, *Lilium*, *Petunia*, *Dendrobium*, and *Paeonia*. This article outlines the scientific basis of floral scent in ornamental flowers, focusing on the underlying volatile chemistry, biosynthetic pathways, ecological roles, and recent advances in breeding and genetic engineering.

What are floral volatiles, and why do flowers emit scent?

Floral fragrance arises from a complex bouquet of volatile organic compounds (VOCs) released mainly by petals, tepals, and nectarines. These VOCs form odour “plumes” that can be detected by pollinators, herbivores, and competing plants at distances of meters to tens of meters, effectively turning the flower into a chemical signal generator. In ornamental species, floral scent serves multiple, partially overlapping functions:

- Pollinator attraction: Bees, butterflies, hawkmoths, and bats select flowers based on volatile profiles, with specific compounds acting as olfactory cues.
- Defence and deterrence: Some volatiles repel florivores or pathogens, while others induce systemic defence responses in neighbouring tissues.
- Reproductive signalling: Post-pollination down-regulation of scent emission can reduce excess visitation and thus resource wastage and self-pollination-related damage.

From an ornamental-horticulture perspective, these same VOCs are marketed as aesthetic assets—the “signature” of roses, jasmine, lilies, or gardenias—making scent a key trait in cultivar ranking and breeding pipelines.

Major chemical families in ornamental floral scents

Across ornamental floriculture, the volatile inventory of scented flowers is dominated by three biosynthetic lineages:

1. Terpenoids

Terpenoids, including monoterpenes (C₁₀) and sesquiterpenes (C₁₅), form the backbone of many floral aromas. Common examples: linalool, limonene, β -ocimene, α -phellandrene, and verbenone. (Note: citrus-like, green, woody, or spicy).

In orchids such as *Dendrobium chrysotoxum* and *Cymbidium* spp., terpenoids often dominate the emitted bouquet, with linalool and β -ocimene among the most abundant compounds. In *Lilium*, certain terpenoids contribute to oriental and trumpet-type lily scents, which are strongly olfactively distinct.

2. Benzenoids and phenylpropanoids

Derived from the phenylalanine/shikimate pathway, benzenoids and phenylpropanoids are responsible for sweet, rosy, hyacinth-like, and spicy notes. Key volatiles are phenylethyl alcohol, benzaldehyde, eugenol, methyl benzoate and phenylacetaldehyde. In petunia cultivars, intensive phenylacetaldehyde emission underpins the “Evening Scentsation” aroma, whereas blue-flowered petunias show weak scent due to low phenylacetaldehyde levels. In jasmine and *Paeonia* (peonies), benzenoids contribute heavily to the characteristic sweet-floral note, making them central to wine-, rose-, and hyacinth-style perfumery notes.

3. Fatty-acid-derived volatiles

Oxidative breakdown of fatty acids yields aldehydes, alcohols, and ketones. Common: nonanal, decenal, hexanal, and related C6–C10 compounds. These volatiles often add green, “leafy,” or soapy facets to the floral bouquet. In several ornamental species, they are minor scent components but can become prominent after mechanical damage or during senescence-linked stress. Across ornamental floriculture, terpenoids and benzenoids together account for the majority of economically relevant floral volatiles, with the relative ratios determining the perceived “quality” of the scent (e.g. rose, hyacinth, citrus, or tea-like).

Biosynthesis and emission patterns in key ornamentals

Jasminum spp. (jasmine)

Jasmine is a top-value scented cut flower and perfumery crop. In multi-petal “Hutou” jasmine, sesquiterpenes and benzenoids dominate the floral bouquet, with sesquiterpenes prevailing at full bloom. Terpene synthase (TPS) and methylerythritol phosphate (MEP) pathway genes are upregulated in late bud and early anthesis, while shikimate- and phenylpropanoid/benzenoid-pathway genes are co-expressed with TPS, indicating a coordinated “scent program” starting before anthesis. Maximum VOC emission occurs in early morning and late evening, matching nocturnal/ crepuscular pollinator activity and peak human sensory perception.

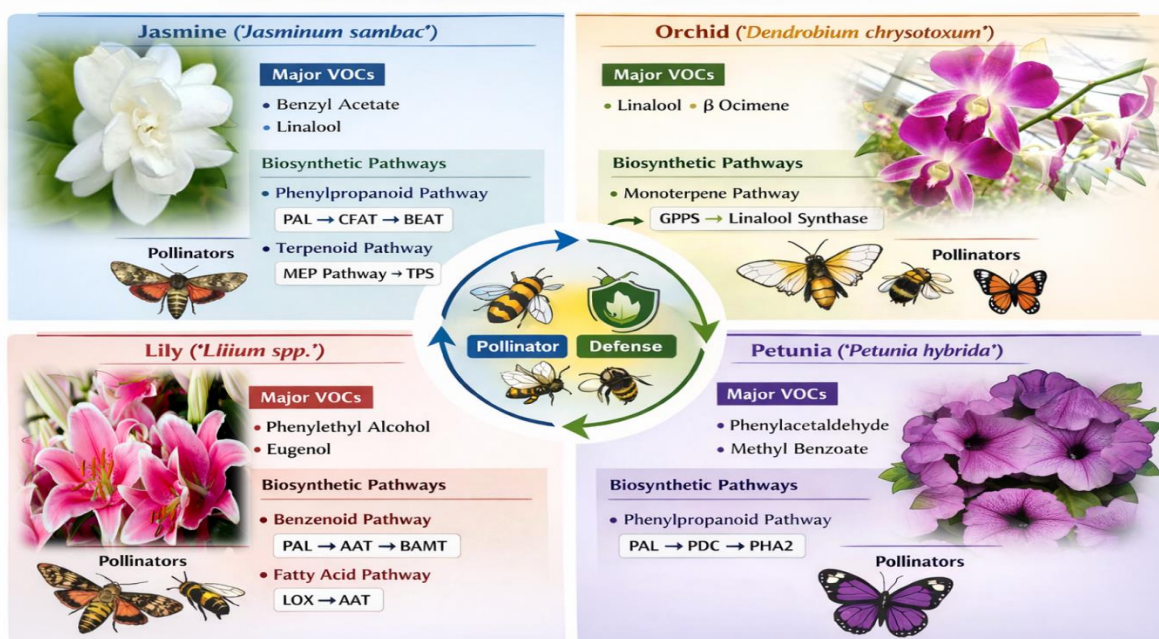
Orchids and *Dendrobium*

In *Dendrobium chrysotoxum*, the floral scent is dominated by monoterpenes (α -phellandrene, β -ocimene, linalool) and aromatic benzene acetaldehyde. Volatilomics plus RNA-seq show that many fragrance-related terpene and shikimate genes are expressed at the bud stage, although VOC accumulation peaks at full bloom. This suggests additional regulatory layers such as compartmentalization in oil cells or nectaries, post-translational modification of enzymes, and transporter-mediated VOC release. Terpeneoid pathways in *Cymbidium* remain partially characterized, but geranyl diphosphate synthase (GPPS), linalool synthase, and benzaldehyde synthase are emerging as key regulators of floral aroma.

Lilium spp. (lilies)

Scent is a key grading trait in lily cut-flower markets. Across *Lilium* species, terpenoids (linalool, limonene), benzenoids (phenylethyl alcohol, benzaldehyde), and fatty-acid-derived aldehydes form species-specific blends. Oriental lilies are typically more intense and sweeter, while “trumpet” and some Asiatic types are milder or nearly scentless. The expression of terpene synthases, phenylalanine ammonia-lyase (PAL), and acetyl-CoA-dependent alcohol acetyltransferases in petals and tepals correlates with these emission profiles and with night-peaking expression linked to moth pollination and human sensory perception.

Floral Scent Biosynthesis in Ornamental Flowers



Petunia and bedding ornamentals

The petunia cultivar TX-794 “Evening Scentsation” exemplifies targeted breeding of floral scent, with its intense, sweet, hyacinth- and rose-like fragrance dominated by phenylacetaldehyde, at levels several-fold higher than in non-fragrant blue petunias. This is driven by strong upregulation of phenylalanine decarboxylase and dehydrogenase genes in the phenylacetaldehyde pathway, plus reduced flux into non-volatile phenylpropanoids. Analogous phenylpropanoid/benzenoid tuning in roses and other ornamentals shows this pathway is a versatile target for engineering custom-scented bedding plants and cut flowers.

Floral scent in *Paeonia* (peonies) and other genera

Recent reviews show that scented *Paeonia* cultivars combine diverse flower forms, rich colours, and delightful fragrances governed by overlapping developmental and metabolic pathways. VOC profiling reveals blends of terpenoids (linalool, limonene), benzenoids (phenylethyl alcohol, benzaldehyde), and fatty-acid-derived C6 aldehydes; their ratios define olfactory “styles” (tea-like, rose-like, citrusy). Genomic and transcriptomic studies identify clusters of phenylpropanoid and terpenoid biosynthesis genes whose expression correlates with scent intensity, providing targets for marker-assisted breeding. Parallel work in *Rosa*, *Chrysanthemum*, and *Impatiens* confirms that floral scent variability is largely controlled by tissue-specific expression of VOC-biosynthesis genes and their regulatory networks rather than by novel pathway evolution.

Ecological and commercial implications in floriculture

Floral volatiles mediate not only attraction but also plant–pollinator coevolution and plant–enemy interactions. In some ornamental species, high-level VOC emission can inadvertently attract florivores or seed-eating insects, so selective breeding now targets “pollinator-optimized” scent profiles that balance attraction with defence. From a commercial-horticulture standpoint, scent is increasingly treated as a multi-dimensional trait:

- Chemical profiling: head-space SPME-GC-MS or broader-targeted volatilomics define the aroma “fingerprint” of a cultivar.
- Temporal dynamics: bud vs. anthesis, day vs. night, and pre- vs. post-senescence profiles inform harvest timing and postharvest handling in cut-flower chains.
- Sensory-chemical correlation: trained panels rate perceived intensity and quality (e.g., fresh, sweet, spicy), and these sensory scores are regressed against VOC composition to identify signature compounds.

Reviews emphasize that such combined analytical and sensory approaches are essential for consumer-oriented breeding in floriculture, where floral beauty is defined by colours, forms, and scents acting in concert.

Conclusion

Floral fragrance in ornamental plants is a sophisticated trait shaped by the interplay of terpenoid, benzenoid, and fatty-acid-derived metabolic pathways, finely regulated in time and space. Modern omics approaches have revealed that scent-related genes are often activated early in development, setting up a precisely timed emission program that matches pollinator activity and human sensory preferences. This knowledge is now being harnessed in breeding and biotechnology to design scented ornamentals with tailored aroma profiles, linking ecological function with aesthetic appeal and commercial value.

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Biofortification Meets AI: Smarter Breeding for Nutrient-Rich Crops



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1. Introduction

For decades, plant breeding was evaluated mainly by one question: how much grain can a field produce? That question still matters, but it no longer captures the full purpose of agriculture. In many regions, food systems have become efficient at delivering calories while remaining inadequate at delivering essential micronutrients. Wheat, rice, and maize dominate diets across much of the world, yet the grain produced from these staples often does not supply enough iron, zinc, provitamin A, or high-quality protein to meet human nutritional needs. Biofortification emerged in response to this gap, not as a luxury trait, but as a breeding strategy with direct public-health value. After two decades of investment, biofortified staple crops are now being grown in more than 40 countries and consumed by hundreds of millions of people.

But biofortification has now reached a point where the easy phase is over. The first generation of work proved that nutrient-rich crops can be developed and adopted. The harder question is how to improve nutrient density faster, more accurately, and without sacrificing yield, adaptation, and grain quality. That is where artificial intelligence enters the story. AI is not important here because it sounds modern; it is important because biofortification is exactly the kind of breeding problem that overwhelms conventional selection. Nutrient traits are polygenic, expensive to phenotype, strongly affected by environment, and often entangled with trade-offs that cannot be resolved by visual field selection alone. Recent reviews in plant breeding now frame AI and machine learning as tools that can help integrate genomic selection, phenomics, and environmental prediction into a more intelligent breeding system.

2. Biofortification: Breeding Crops for Better Health

Biofortification involves increasing the concentration or bioavailability of nutrients in crops through breeding, genomics, or agronomic strategies. Unlike food fortification, which adds nutrients during processing, biofortification builds nutrition directly into the crop. This approach is particularly valuable in low-resource settings where supplementation programs may not reach all populations. Staple crops such as wheat, rice, maize, pearl millet, sweet potato, and pulses are key targets due to their widespread consumption. Even modest increases in nutrient levels can significantly improve public health when scaled across populations, making biofortification a sustainable and cost-effective strategy.

3. Why nutrient breeding is harder than it looks?

Hidden hunger is often described as a silent crisis because people may consume enough calories while remaining deficient in vitamins and minerals. The problem is especially severe where diets rely heavily on staple cereals and where access to diverse foods is limited by income, geography, or seasonality. Biofortification addresses this by improving the nutritional value of foods people already grow and eat, which is why it has been promoted as one durable and scalable strategy within broader nutrition policy.

The challenge is biological. Micronutrient concentration in grain is not determined by a single pathway or a single gene. Grain zinc and iron depend on uptake from soil, transport across tissues, remobilization during grain filling, root-soil interactions, fertilizer regime, stress environment, and the plant's own yield physiology. Even when favorable alleles are present, expression can shift across locations and seasons. This means that breeders are rarely selecting for "high iron" or "high zinc" as isolated traits. They are selecting for nutrient density under moving environmental conditions while also trying to preserve yield, adaptation, and market quality.

Recent evidence shows how stubborn this problem remains. A 2026 *Nature Food* analysis of 243 field studies reported that zinc, iron, and protein concentrations in modern wheat cultivars have declined since the 1960s and often fall short of nutritional targets for human health. The same analysis found that while genetic and agronomic biofortification can improve zinc, the probability of reaching target iron levels remains much lower. In rice, a 2025 analysis covering 530 biofortified genotypes across 294 tests in India found that breeding progress for zinc, iron, and protein remains constrained by performance trade-offs, including lower average yield relative to national field averages and negative correlations between high grain zinc and yield or quality at higher thresholds.

That is the real bottleneck: nutrient breeding is not failing because breeders do not know what matters. It is difficult because the trait architecture is complex and the measurement burden is heavy. Laboratory nutrient assays are slower and more expensive than routine agronomic scoring. Large populations cannot be screened deeply across many environments without major cost. In practical terms, biofortification is not just a nutrition problem; it is a prediction problem.

4. When Breeding Becomes Smarter: The AI Advantage

This is where AI becomes genuinely useful. Its value is not that it replaces breeder judgment, but that it allows breeder judgment to operate on far more information than could otherwise be handled. Modern breeding produces genome-wide marker data, high-throughput phenotypes, multi-environment trial outputs, soil and climate records, and historical performance datasets. AI and machine learning can turn these scattered data streams into ranked predictions: which parents deserve crossing, which lines are worth advancing, which genotypes are likely to remain nutritionally stable, and which materials should be discarded before they consume field space and budget. Recent reviews describe this as a shift from descriptive breeding toward predictive breeding.

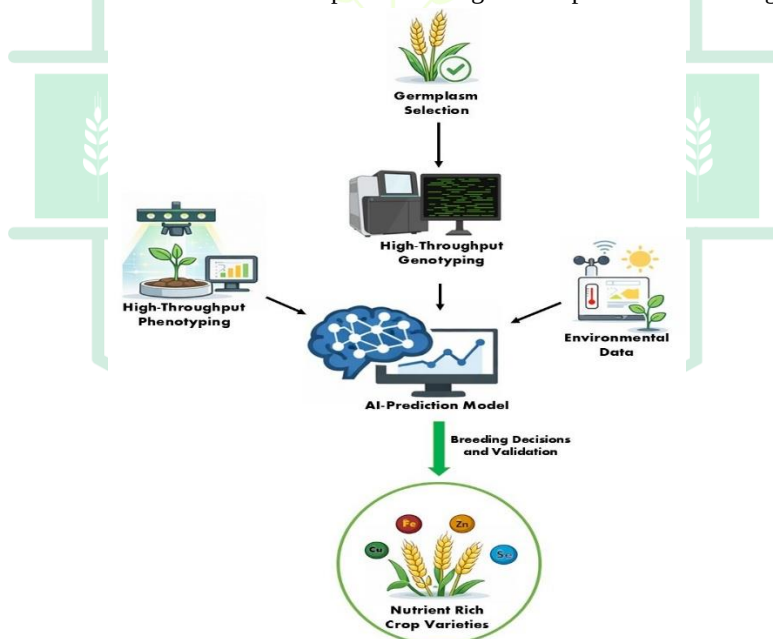


Figure 1. Artificial intelligence-enabled pipeline for biofortified crop development.

4.1 AI in Genomic Prediction

Instead of waiting for every candidate line to be fully phenotyped, breeders can estimate nutritional potential from marker data using models trained on existing genotype–phenotype relationships. This is especially valuable for micronutrients because direct phenotyping is costly and population sizes are large. In rice, genomic prediction has already been used to estimate zinc-biofortification potential across thousands of gene bank accessions, showing how predictive models can search germplasm collections far beyond what could be screened practically by wet chemistry alone.

4.2 AI in Trait Discovery

Nutrient improvement cannot be treated separately from yield, quality, maturity, and adaptation. AI is useful because it can handle multi-trait selection and non-linear relationships better than simplistic threshold-based screening. In crops such as sorghum and rice, current research has shown that multi-trait prediction strategies can improve the efficiency of selecting for iron and zinc while still accounting for agronomic performance. That matters because a nutritionally superior line that collapses under field conditions is not a breeding success.

4.3 AI in Environment-Aware Breeding

For biofortification, stability is often more important than peak performance. A genotype with high zinc in one environment but unstable expression elsewhere is less valuable than one that performs consistently across target production systems. AI models can incorporate genotype $\times$ environment information more effectively, helping breeders identify lines that hold their nutritional advantage under realistic variation in soil, temperature, and management. Recent AI-in-breeding reviews place strong emphasis on integrating phenotypes and envirotypes precisely for this reason.

4.4 AI in Phenomics

High-throughput phenotyping combined with AI enables rapid and non-destructive assessment of plant traits. This is especially useful where nutrient assays are costly and time-consuming.

4.5 AI in Breeding Decisions

AI supports critical decisions such as parent selection, line advancement, and resource allocation, improving overall breeding efficiency and reducing costs.

Table 1. Role of AI in different stages of biofortification breeding

Stage	Conventional Approach	AI-Enabled Approach	Benefit
Trait selection	Limited screening	Data-driven prioritization	Faster targeting
Parent selection	Based on phenotype	Predictive modeling	Better crosses
Screening	Large field trials	Early prediction	Reduced cost
Stability testing	Multi-location trials	G $\times$ E modeling	Better adaptation
Line advancement	Sequential selection	Multi-trait optimization	Efficient breeding

5. Crops Ready for the AI–Biofortification Revolution

5.1 Wheat

Wheat is perhaps the clearest test case for AI-enabled biofortification. It is globally important, genomically well characterized, and central to discussions of hidden hunger because it contributes major calories but often insufficient micronutrients. The 2026 global wheat synthesis did not just show that targets are being missed; it showed how hard they are to recover through conventional gains alone. That makes wheat an ideal crop for predictive breeding systems that combine genomic information, nutrient phenotypes, and multi-environment validation instead of relying on slow observational selection.

5.2 Rice

Rice offers a different but equally compelling case. Because rice gene banks are immense and rice feeds billions, the breeding challenge is partly one of search efficiency. AI and genomic prediction can help identify nutrient-rich donors from enormous diversity sets, reducing the need to phenotype every accession and allowing breeding resources to focus on the most promising material. The recent long-term Indian dataset also makes rice a strong example of why smarter selection is needed: when nutrient targets begin to conflict with yield and quality, breeders need models that optimize across multiple goals, not one trait at a time.

5.3 Pearl millet and Sorghum

Dryland staples such as pearl millet and sorghum may prove even more strategically important. These crops already have strong relevance for iron and zinc nutrition and are critical in regions facing climatic stress and nutritional vulnerability. Here, AI is not just about maximizing accuracy; it is about using limited breeding budgets more intelligently. In low-resource breeding systems, better prediction can be as valuable as bigger infrastructure. Recent breeding reviews emphasize exactly this practical role for AI: increasing efficiency where trait measurement and field testing are expensive.

6. A New Breeding Pipeline for Nutrient-Rich Crops

The older breeding logic was simple: develop populations, phenotype heavily, and advance the best performers. The new logic is more selective. It begins with defining nutritional targets, then assembling germplasm from elite lines, landraces, released cultivars, and useful exotic sources. Phenotyping, genotyping, and environmental characterization still remain essential, but they now feed into prediction layers rather than serving only as end-stage filters. AI-assisted models can rank nutrient potential, identify favorable crosses, estimate stability, and narrow the number of candidates entering expensive downstream trials. Validation still matters, but blind screening gives way to informed prioritization.

This matters because the future of biofortification will not be decided only by discovering another useful allele. It will be decided by whether breeding systems can combine biological complexity with operational efficiency. In that sense, AI is best understood not as a separate technology, but as the infrastructure for decision-making in complex trait breeding.

7. Big Promise, Real Challenges

Despite its potential, AI-enabled biofortification faces several challenges. Data quality and availability remain major limitations, as accurate models require large, well-curated datasets. Infrastructure constraints, especially in public breeding programs, can limit the adoption of advanced technologies. Additionally, AI models must be interpretable and reliable to gain trust among breeders and policymakers. Addressing these challenges will require collaboration between biologists, data scientists, and agricultural institutions.

8. Conclusion and Future Outlook

The promise is real, but it is not automatic. AI models are only as strong as the data that train them, and plant breeding still suffers from inconsistent phenotyping, fragmented databases, and uneven environmental metadata. Public breeding programs will also need interpretable tools, not opaque systems that produce rankings without biological confidence. The future of AI in biofortification therefore depends as much on data quality, metadata standards, and institutional workflow as on algorithms themselves. Recent reviews make this point clearly: the bottleneck is no longer just model development, but the integration of prediction outputs into real breeding pipelines.

India is especially well positioned to lead this transition. Its crop diversity, large public breeding system, and nutritional needs create exactly the kind of setting where smart biofortification could have global significance. If AI is linked effectively with national breeding programs for wheat, rice, maize, millets, and pulses, India could move beyond being a user of biofortification technologies to becoming one of the major architects of predictive nutrition breeding. That would matter not just for agriculture, but for public health, food policy, and rural development.

The deeper lesson is this: the next agricultural advance will not be measured only by how much grain a field produces. It will be measured by whether that grain carries more nutrition, more resilience, and more biological intelligence. Biofortification gave plant breeding a human-health mission. AI may give it the precision needed to fulfill that mission at scale.

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Biomimicry-Inspired Engineering Solutions for Next-Generation Marine Aquaculture Cages



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Abstract

The rapid expansion of marine aquaculture is essential for meeting the growing global demand for seafood within the framework of the Blue Economy. However, conventional aquaculture cage systems face significant challenges in offshore environments, including strong hydrodynamic forces, biofouling, structural fatigue, predator interactions, and environmental impacts from nutrient accumulation. These challenges highlight the need for innovative engineering approaches that improve cage performance while maintaining environmental sustainability. Biomimicry, defined as the practice of emulating nature's time-tested strategies to solve human design challenges, offers promising solutions for developing resilient and efficient aquaculture infrastructure. This article explores how biological systems can inspire the design of next-generation marine aquaculture cages. Structural principles derived from deep-sea sponges (*Euplectella aspergillum*) demonstrate how hierarchical lattice architectures can enhance strength and stability under hydrodynamic loading. Shark skin dermal denticles provide insights for antifouling surfaces that reduce biofilm attachment and maintenance requirements. Flexible macroalgae such as kelp illustrate strategies for wave-resistant structures capable of adapting to dynamic ocean conditions. Hydrodynamic efficiency observed in schooling fish suggests optimized cage geometries that reduce drag and improve water circulation. Additionally, defensive mechanisms in porcupinefish inspire predator-resistant cage structures, while coral and mollusk biomineralization processes inform the development of self-healing materials for improved infrastructure durability. Beyond structural innovations, ecosystem-inspired approaches such as Integrated Multi-Trophic Aquaculture (IMTA) mimic coral reef nutrient cycling to reduce environmental impacts, while sensory systems like the fish lateral line inspire smart monitoring technologies for real-time cage management. Together, these biomimetic strategies highlight the potential of integrating biological principles with modern engineering, advanced materials, and artificial intelligence to enhance aquaculture system performance. By translating natural design strategies into aquaculture engineering solutions, biomimicry can contribute to the development of sustainable, resilient, and efficient offshore aquaculture systems, supporting global seafood production while minimizing environmental impacts. Such innovations are expected to play a critical role in advancing sustainable marine food systems and strengthening the long-term viability of the Blue Economy.

Introduction

Biomimicry is increasingly recognized as a transformative design philosophy that seeks to emulate nature's time-tested patterns, processes, and strategies to address complex human challenges. Rather than imposing purely mechanical solutions, biomimicry draws inspiration from biological systems that have evolved over millions of years to achieve remarkable efficiency, resilience, and adaptability [Benyus, 1997; Vincent et al., 2006]. In engineering and architecture, this discipline has led to innovations ranging from aerodynamic surfaces inspired by bird wings to self-cleaning materials modeled after plant leaves. Within marine engineering, biomimicry offers a promising pathway for developing aquaculture infrastructure that aligns with ecological principles while improving performance and durability.

The relevance of biomimicry is particularly significant within the framework of the **Blue Economy**, which promotes the sustainable use of ocean resources to support economic growth, food security, and environmental protection. Global demand for seafood continues to rise due to population growth and dietary shifts toward protein-rich foods. Consequently, aquaculture has become the fastest-growing sector of food production worldwide [FAO, 2022]. Offshore and marine aquaculture systems are increasingly viewed as essential components of future seafood supply. However, sustainable expansion requires technological innovation that

minimizes ecological impact while maximizing operational efficiency. In this context, Nature-based Solutions (NbS)—approaches that utilize natural processes and ecosystem functions to address societal challenges—are gaining attention as viable strategies for marine infrastructure design [Cohen-Shacham et al., 2016].

Over time, cage components also experience structural fatigue resulting from repeated mechanical loading and environmental stress, leading to material degradation and increased risk of infrastructure failure. Furthermore, predator interactions, including attacks by large fish, marine mammals, or sharks, can damage nets and result in fish escape or economic losses [Holmer, 2010].

Biomimicry offers a compelling approach for addressing these challenges by leveraging biological principles that have evolved specifically to cope with similar environmental pressures. Marine organisms exhibit extraordinary adaptations to withstand hydrodynamic forces, resist surface fouling, and maintain structural integrity in turbulent waters. By translating these biological strategies into engineering solutions, aquaculture cage designs can achieve improved hydrodynamic efficiency, enhanced durability, and reduced material consumption. For example, structural frameworks inspired by marine skeletal architectures may distribute stress more effectively, while microstructured surfaces modeled after shark skin can reduce fouling and drag. Such innovations not only enhance the functional performance of aquaculture systems but also contribute to broader sustainability goals by reducing energy demand, maintenance requirements, and environmental impact.

Integrating biomimicry into aquaculture engineering therefore represents a promising convergence of marine biology, materials science, and environmental engineering. By aligning technological design with ecological intelligence, biomimetic approaches have the potential to redefine the development of next-generation marine aquaculture cages, supporting resilient food production systems within the evolving Blue Economy.

Structural Strength and Stability Inspired by Deep-Sea Sponges

Biological Inspiration: *Euplectella aspergillum* (Venus Flower Basket Sponge)

The deep-sea sponge *Euplectella aspergillum*, commonly known as the Venus Flower Basket, exhibits a remarkable skeletal architecture composed of silica spicules arranged in a highly ordered hierarchical lattice structure. This lattice consists of longitudinal, transverse, and diagonal elements that create a cylindrical grid capable of distributing mechanical loads efficiently while maintaining structural rigidity. The hierarchical organization of the sponge skeleton enhances both stiffness and toughness by allowing stresses to be transferred across multiple structural levels, from nanoscale silica fibers to the macroscopic lattice framework [Aizenberg et al., 2005; Weaver et al., 2010]. Such structural strategies enable the sponge to maintain mechanical stability under deep-sea environmental forces, including water movement and mechanical loading.

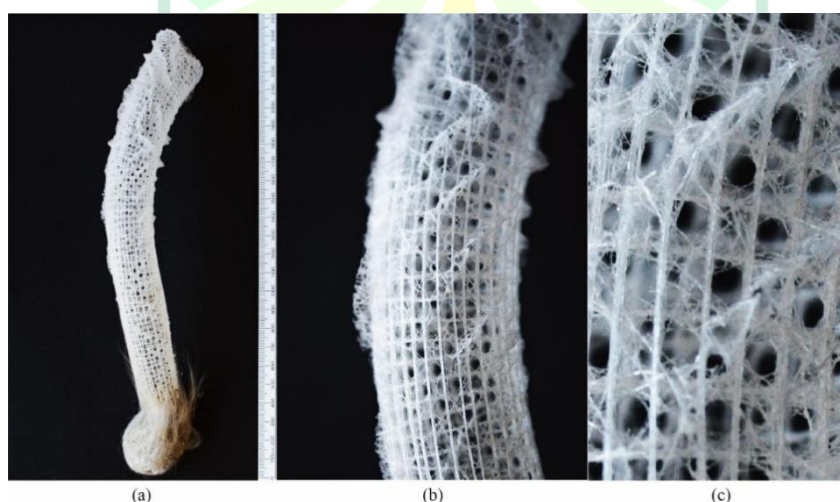


Fig. 1. The skeletal system of the *Euplectella aspergillum*, showing: (a) the entire skeletal tube, (b) a magnified view highlighting its regular lattice-like structure, and (c) the detailed pattern of alternating open and closed cells. Credit: *Composite Structures* (2024). Adapted from (Ramakrishna & Bala Murali, 2023).

Engineering Problem: Structural Stress in Offshore Aquaculture Cages

Marine aquaculture cages deployed in offshore environments are subjected to significant hydrodynamic forces from waves and currents, which can induce high stresses on cage frames and mooring systems. These forces can cause deformation, oscillation, and structural instability in cage structures, particularly during high-energy ocean conditions [Fredriksson et al., 2003]. In addition to instantaneous loading, repeated wave-induced motion results in cyclic mechanical loading, which contributes to structural fatigue and material degradation over time in aquaculture infrastructure [Lader et al., 2008]. Consequently, there is a growing need for structural designs that can effectively distribute loads and improve resilience in offshore aquaculture systems.

Biomimetic Engineering Solution: Sponge-Inspired Lattice Structures

The skeletal architecture of *Euplectella aspergillum* provides valuable design insights for developing lightweight yet mechanically robust structural frameworks. The sponge's lattice geometry demonstrates how hierarchical structural organization can enhance stiffness and load distribution while minimizing material usage [Aizenberg et al., 2005]. Engineers and materials scientists have increasingly studied such biological architectures to develop biomimetic lattice materials and frameworks capable of achieving high strength-to-weight ratios and improved mechanical performance [Fratzl & Barth, 2009].

Advances in manufacturing technologies, particularly additive manufacturing (3D printing) and composite material engineering, now enable the fabrication of complex lattice structures inspired by biological architectures. These technologies allow engineers to replicate hierarchical geometries similar to those observed in sponge skeletons, thereby creating structural frameworks with enhanced load distribution and structural stability [Meyers et al., 2008].

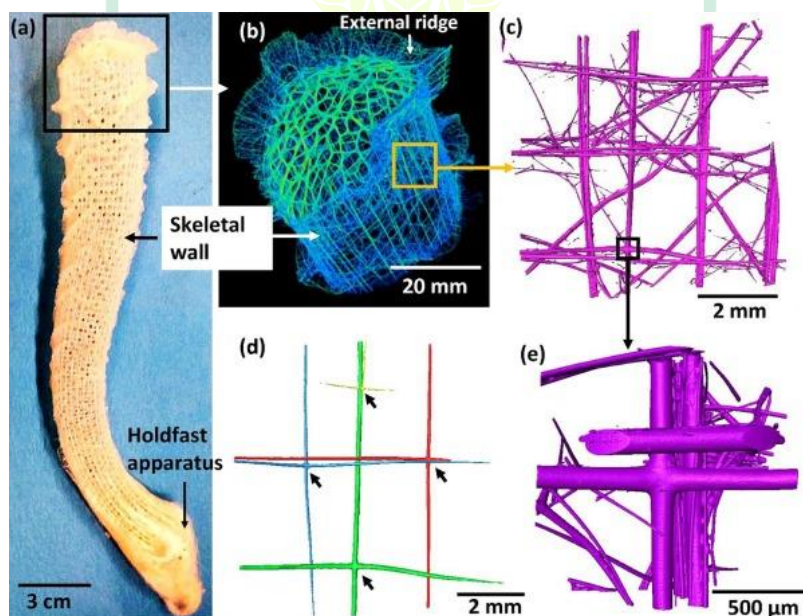


Fig. 2. Multiscale hierarchical structure of *E. aspergillum* investigated by x-ray microtomography- (a) photograph of *E. aspergillum*'s skeleton, (b) Volume rendering showing the upper section of *E. aspergillum*, (c) volume rendering showing a small portion of the skeletal wall, (d) cross-shaped spicules segmented and represented using different colors, arrows show nodes that contain axial center of spicules (e) volume rendering showing the axial center and cross shape (four rays) of spicule. Adapted from (Morankar et al., 2023).

Anti-Biofouling Surfaces Inspired by Shark Skin

Biological Inspiration: Shark Skin and Dermal Denticles

Sharks possess a unique skin structure composed of microscopic tooth-like scales known as dermal denticles. These denticles form riblet-like surface patterns aligned along the body of the shark, producing a textured microtopography that reduces hydrodynamic drag and inhibits the attachment of fouling organisms. The geometry of these riblets alters the boundary layer of water flow across the skin surface, thereby limiting the ability of microorganisms and larvae to settle and adhere [Bechert et al., 1997; Schumacher et al., 2007].

Research in biomimetic materials has demonstrated that the microstructured topography of shark skin can significantly reduce the attachment of bacteria, algae, and other fouling organisms. These natural antifouling properties have inspired the development of engineered surfaces that mimic dermal denticle patterns for applications in marine coatings and biomedical devices [Schumacher et al., 2007; Chung et al., 2007].

Engineering Problem: Biofouling in Marine Aquaculture Cages

Biofouling is one of the most persistent operational challenges in marine aquaculture systems. Cage nets submerged in seawater rapidly become colonized by fouling organisms such as barnacles, algae, hydroids, and mussels, forming dense biological layers on net surfaces. The accumulation of these organisms reduces net permeability and restricts water exchange within the cage, which can negatively affect oxygen availability and fish health [Fitridge et al., 2012].

In addition to reducing water flow, biofouling increases the hydrodynamic drag acting on cage structures, placing greater stress on cage frames and mooring systems. Fouled nets also require frequent cleaning or replacement, resulting in increased operational costs and labor requirements. Furthermore, conventional antifouling treatments often rely on chemical coatings that may release biocides into the marine environment, raising ecological concerns regarding their long-term sustainability [Fitridge et al., 2012; Schultz et al., 2011].

Biomimetic Engineering Solution: Shark-Skin-Inspired Riblet Surfaces

The antifouling properties of shark skin have inspired the development of microstructured riblet surfaces that replicate the geometry of dermal denticles. These surfaces function by disrupting microbial attachment and reducing the effective contact area available for settlement. Studies have shown that engineered surfaces mimicking shark skin microtopography can significantly inhibit bacterial colonization and biofilm formation without the use of toxic chemical coatings [Schumacher et al., 2007; Chung et al., 2007].

Advances in materials engineering now enable the fabrication of such microstructures using technologies such as laser etching, micro-molding, and advanced polymer manufacturing. These techniques allow the precise replication of riblet geometries that mimic shark skin patterns at micro- and nanoscale levels.

Flexible Wave-Resistant Structures Inspired by Seaweed

Biological Inspiration: Kelp Forests and Flexible Macroalgae

Large marine macroalgae, particularly kelp species such as *Macrocystis pyrifera* and *Laminaria* spp., exhibit remarkable flexibility that enables them to survive in highly energetic coastal environments. These organisms possess elongated, flexible stipes and blades that allow them to bend and reorient in response to water movement rather than resisting hydrodynamic forces. This mechanical strategy reduces the drag forces acting on the algae by allowing them to streamline with water flow, thereby minimizing structural stress and preventing breakage under strong wave action [Koehl, 1984; Denny & Gaylord, 2002].

The mechanical behavior of kelp is therefore a classic example of passive reconfiguration, where biological structures deform in response to fluid forces to reduce hydrodynamic loading. This adaptation allows kelp forests to persist in wave-exposed environments where rigid structures would experience significantly higher stress and potential failure.

Engineering Problem: Structural Damage to Rigid Aquaculture Cages

Marine aquaculture cages deployed in offshore or exposed coastal locations are frequently subjected to strong waves, currents, and storm events. Traditional cage systems constructed from rigid materials such as steel or high-density polyethylene (HDPE) frames can experience significant mechanical stress when exposed to these hydrodynamic forces. Under extreme conditions, rigid structures may deform, suffer structural fatigue, or even fail, resulting in equipment damage and fish escape events [Fredriksson et al., 2003; Lader et al., 2008].

As aquaculture operations expand into more energetic offshore environments, there is increasing interest in developing cage structures that can adapt dynamically to water movement, thereby reducing the structural loads imposed by waves and currents.

Biomimetic Engineering Solution: Flexibility-Based Structural Design

The mechanical strategy observed in kelp provides an important design principle for marine engineering: structures that can flex and reorient in response to fluid forces experience lower hydrodynamic loads compared

to rigid structures. By allowing controlled deformation, flexible systems can dissipate wave energy and reduce stress concentrations within structural components [Denny & Gaylord, 2002].

Applying this principle to aquaculture cage design suggests the development of flexible or semi-flexible cage systems capable of adapting to dynamic ocean conditions. Instead of resisting wave forces entirely, these biomimetic systems would partially move with the surrounding water, thereby lowering mechanical stress.

Hydrodynamic Efficiency Inspired by Fish Schools

Biological Inspiration: Hydrodynamics of Schooling Fish

Many fish species exhibit schooling behavior, where individuals swim in coordinated groups that maintain specific spatial arrangements. This behavior provides hydrodynamic advantages because the vortices generated by one fish can be exploited by neighboring fish, reducing the energy required for swimming. Research has shown that fish swimming in organized schools can experience improved propulsion efficiency and reduced drag compared with solitary swimming [Weihs, 1973; Liao, 2007].

In such formations, the spacing and orientation between individuals allow fish to take advantage of the wake structures generated by others, a mechanism often referred to as hydrodynamic drafting. By optimizing their position relative to surrounding individuals, fish can reduce the energetic cost of locomotion while maintaining stability in moving water [Weihs, 1973]. These fluid dynamic interactions have attracted considerable interest in engineering because they demonstrate how spatial arrangement and flow alignment can improve hydrodynamic efficiency.

Engineering Problem: Drag Forces on Aquaculture Cage Systems

Aquaculture cages deployed in marine environments are constantly exposed to water currents and wave-induced flows, which generate hydrodynamic drag on cage structures and nets. Increased drag forces can lead to deformation of nets, increased tension on mooring systems, and higher structural loads on cage frames. These forces may also increase the energy required to maintain cage stability and positioning in offshore environments [Lader et al., 2008].

In addition, poorly designed cage geometries can disrupt natural water flow patterns around the structure, increasing turbulence and resistance. Such inefficiencies may reduce water exchange within the cage and increase mechanical stress on infrastructure components [Fredriksson et al., 2003].

Biomimetic Engineering Solution: Schooling-Inspired Spatial Optimization

The hydrodynamic advantages observed in schooling fish provide an important design principle for marine infrastructure: efficient spatial arrangement and streamlined shapes can reduce drag forces in fluid environments. Engineers can apply this concept to aquaculture cage design by optimizing the geometry and layout of cage structures to interact more efficiently with surrounding water flow.

Hydrodynamic modeling studies have demonstrated that streamlined structures experience significantly lower drag compared with blunt or irregular shapes, suggesting that cage geometry plays a critical role in determining flow behavior around aquaculture systems [Lader et al., 2008].

Predator Protection Inspired by Porcupine Fish Defense

Biological Inspiration: Defensive Structures of Porcupinefish

Porcupinefishes belonging to the family Diodontidae possess a highly effective defense mechanism against predators. When threatened, these fish rapidly inflate their bodies by ingesting water or air, causing their bodies to expand and exposing numerous rigid dermal spines that cover their skin. This inflation transforms the fish into a larger, spiny structure that is difficult for predators to grasp or swallow. The spines function as a mechanical deterrent, discouraging attacks from predators such as large fishes and marine mammals [Leis, 2006; Randall et al., 1997].

Engineering Problem: Predator Interactions with Aquaculture Cages

Predator interactions are a significant challenge in marine aquaculture operations. Large marine predators such as sharks, seals, and sea lions may attempt to access cultured fish within cage systems. These interactions often involve biting, tearing, or deforming cage nets, which can lead to structural damage, fish escape events, and economic losses for aquaculture producers [Nash et al., 2005; Sanchez-Jerez et al., 2016].

In addition to direct structural damage, predator attacks can also induce stress responses in cultured fish, negatively affecting growth, health, and overall production performance. Consequently, the development of cage designs that provide effective predator deterrence and structural protection remains an important engineering objective in aquaculture infrastructure.

Biomimetic Engineering Solution: Spine-Inspired Protective Systems

The defensive strategy of porcupinefish suggests a biomimetic approach to predator protection based on physical deterrence through structural protrusions. By creating cage systems that incorporate external protective elements analogous to the spines of porcupinefish, aquaculture infrastructure can reduce the likelihood of predator attacks and net damage.

Biomimetic design principles emphasize the use of passive mechanical barriers that discourage predator interaction without harming wildlife or relying on active deterrent systems.

Self-Healing Materials Inspired by Coral and Shell Repair

Biological Inspiration: Coral Skeleton Repair and Mollusk Shell Regeneration

Many marine organisms possess the ability to repair structural damage through biological mineralization processes. Reef-building corals can regenerate damaged skeletal structures by depositing calcium carbonate through specialized cells that rebuild the skeletal matrix following injury [Allemand et al., 2011]. Similarly, mollusks such as oysters and mussels can repair damaged shells through biomineralization processes in which the mantle secretes calcium carbonate layers to restore structural integrity [Mount et al., 2004].

These natural repair mechanisms demonstrate how biological systems maintain durability in physically demanding marine environments through continuous self-maintenance and regeneration, offering inspiration for the development of self-healing materials in engineering applications.

Engineering Problem: Structural Degradation in Aquaculture Cage Materials

Aquaculture cage systems are continuously exposed to mechanical stress, corrosion, and environmental wear caused by waves, currents, and operational handling. Over time, cage nets and structural components can develop micro-cracks, abrasion damage, and material fatigue, which may reduce structural strength and increase the risk of failure [Lader et al., 2008]. Maintenance and replacement of damaged nets represent significant operational costs in aquaculture systems.

Biomimetic Engineering Solution: Self-Healing Materials

Inspired by biological repair processes, materials scientists have developed self-healing polymers that can automatically repair micro-scale damage. These materials typically incorporate microcapsules or reversible chemical bonds that activate when cracks form, allowing the material to restore its mechanical integrity [White et al., 2001; Hager et al., 2010].

Eco-Integrated Cage Systems Inspired by Coral Reef Ecosystems

Biological Inspiration: Coral Reef Ecosystems

- Coral reefs represent one of the most efficient nutrient-cycling ecosystems in the marine environment. Despite existing in nutrient-poor waters, reef ecosystems maintain high productivity through complex biological interactions among multiple trophic levels, including corals, algae, mollusks, and microorganisms [Moberg & Folke, 1999]. These organisms form interconnected systems where nutrients are continuously recycled, supporting ecosystem stability and productivity.

Engineering Problem: Nutrient Pollution from Aquaculture

- Intensive aquaculture systems can release excess nutrients such as nitrogen and phosphorus into surrounding waters through uneaten feed and fish waste. These nutrient inputs may lead to localized eutrophication, algal blooms, and environmental degradation if not properly managed [Troell et al., 2009].

Conclusion

Biomimicry provides powerful solutions for designing next-generation marine aquaculture cages. By learning from marine organisms such as sponges, sharks, seaweed, fish, and corals, engineers can create systems that are stronger, more efficient, and environmentally sustainable. Integrating these nature-inspired innovations will play a crucial role in advancing the Blue Economy and sustainable aquaculture development.

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Smart Pest Control: How AI and Drones are protecting Crops



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Abstract

Smart pest control is transforming modern agriculture through the integration of artificial intelligence (AI) and drone technology. These advanced systems enable real-time monitoring of crop health, early detection of pest infestations, and precise application of pesticides. AI-powered image recognition can identify pest species and assess damage levels, while drones equipped with sensors and cameras efficiently scan large agricultural areas. This targeted approach reduces excessive pesticide use, minimizes environmental impact, and lowers costs for farmers. Additionally, predictive analytics helps forecast pest outbreaks based on weather patterns and historical data, allowing proactive intervention. By improving accuracy and efficiency, AI-driven pest management enhances crop yield and sustainability. As global food demand rises, smart pest control offers an innovative solution to protect crops while promoting eco-friendly farming practices and resource optimization, ultimately contributing to more resilient and productive agricultural systems.

Keywords: AI in agriculture, drone technology, pest detection, precision farming, crop protection

Introduction:

For millennia, agriculture has waged a relentless war against pests. From biblical locust swarms to the microscopic fungi that decimate vineyards, the battle to protect crops has traditionally been reactive, imprecise, and chemically intensive. The standard operating procedure, blanket spraying of pesticides has led to a trifecta of problems: resistant super-bugs, environmental contamination, and the decimation of beneficial pollinators. Today, that paradigm is being dismantled. AI drone technology integrates artificial intelligence, computer vision, and edge computing to enable unmanned aerial vehicles (UAVs) to operate autonomously, make real-time decisions, and navigate complex environments without constant human control (Zhang and Kovacs, 2012). The integration of Artificial Intelligence (AI) and drone technology is ushering in the era of precision pest control. This isn't about futuristic speculation; it is an operational reality that is reducing chemical usage by up to 90% while increasing crop yields (Agrawal and Arafat, 2024). By combining high-resolution aerial imagery with machine learning models, farmers can now identify, predict, and neutralize threats at a per-plant level. AI-enabled drones equipped with high-resolution cameras and multispectral sensors can capture real-time data from crop fields, enabling early detection of pests and diseases. These systems use machine learning and deep learning algorithms to analyse visual and environmental data, allowing farmers to make informed decisions about targeted pesticide application and crop protection strategies. The combination of AI and drones represents a shift toward precision agriculture, where inputs such as pesticides and water are applied only where needed (Ramesh, 2025). This not only increases crop yield and reduces costs but also minimizes environmental impact, making agriculture more sustainable.

The Architecture of Autonomous Scouting

The modern smart pest control system operates on a closed-loop architecture: Scout, Analyze, and Act. Drones serve as the sensory organs, while AI functions as the cognitive processor.

The Hardware: Multispectral Drones

Standard RGB cameras (red-green-blue) are insufficient for detecting plant stress before it becomes visible to the naked eye. Modern agricultural drones are equipped with multispectral and hyperspectral sensors. These sensors capture reflected light across specific bands of the electromagnetic spectrum, particularly the near-infrared (NIR) and red-edge bands. Healthy plants reflect a significant amount of near-infrared light; stressed plants whether from aphid infestation, fungal infection, or water scarcity, absorb more NIR and reflect less. By capturing this

data, drones generate Normalized Difference Vegetation Index (NDVI) maps (Fig 1). These maps act as a heatmap of crop health, allowing farmers to see pest hotspots before a single leaf turns yellow.



Fig 1. NDVI map view via multispectral drone

The AI Models Driving Detection

The raw data captured by drones is useless without interpretation. This is where specialized AI models come into play. Unlike generic computer vision, agricultural models are trained to distinguish between abiotic stress (drought, nutrient deficiency) and biotic stress (insects, fungi). Here are the models associated with the image interpretation.

a. Convolutional Neural Networks (CNNs) for Image Segmentation

The backbone of pest detection is the Convolutional Neural Network. Specifically, U-Net architectures and Mask R-CNN are the industry standards for semantic and instance segmentation.

- U-Net is used to classify every single pixel in an orthomosaic (a large, geometrically corrected image of the field). It excels at identifying the boundaries of blighted areas, such as the circular patches left by *Fusarium* wilt or the irregular scorching caused by spider mites.
- Mask R-CNN (Region-based Convolutional Neural Network) is employed when the goal is to identify individual pests or specific plants. If a farmer needs to know whether a specific corn stalk is harboring a European corn borer, Mask R-CNN can analyse high-resolution drone imagery to detect the characteristic entry holes or frass (insect debris) with an accuracy rate exceeding 95%.

b. You Only Look Once (YOLO)

For flying insects or rapid mobile pests, real-time detection is critical. YOLOv8 and its subsequent iterations are widely deployed in edge-computing drones. Unlike models that require uploading images to the cloud for processing, YOLO models run locally on the drone's on-board computer. As the drone flies over a field, it can identify and count pests like locusts, stink bugs, or Colorado potato beetles in real-time, allowing the spray system to activate within milliseconds of detection. These enhancements allow the model to achieve higher accuracy while maintaining real-time processing speeds, even on resource-constrained hardware. These advancements will further enhance the capability of autonomous drone systems in precision agriculture, making pest control more efficient, sustainable, and scalable.

c. Support Vector Machines (SVMs)

Support Vector Machines (SVMs) play a critical role in smart pest control, particularly in scenarios where labelled training data is limited, a common constraint in agricultural settings where disease outbreaks may be rare or ground-trothing is labour-intensive. Unlike neural networks that require vast datasets to generalize effectively, SVMs excel at binary and multi-class classification by finding the optimal hyper plane that maximizes the margin between distinct classes, such as healthy versus infected crops, or distinguishing between different pest species. In practice, SVMs are fed feature vectors extracted from drone or satellite imagery, these features may include spectral reflectance values from multispectral bands, texture metrics like entropy and contrast from the infected

leaf surfaces, or morphological parameters of pest shapes. For example, an SVM model can be trained to separate *Phytophthora infestans* (late blight) from early blight by analysing the statistical distribution of pixel intensities in the red-edge and near-infrared bands, where the two diseases exhibit subtle but quantifiable differences (Mohanty *et al.*, 2016). This makes SVMs particularly valuable for edge-deployment scenarios where computational resources are constrained, enabling rapid, on-drone classification of pest pressure with high precision and interpretability, farmers can understand exactly which spectral or textural features triggered an alert, fostering trust in automated decision-making.

d. Random Forest & Decision Trees

Random Forest and Decision Trees are powerful predictive models for forecasting pest outbreaks based on environmental conditions. Decision Trees function as flowchart-like structures that split data through sequential binary questions such as "Is temperature above 24°C?" or "Has humidity exceeded 80%?" leading to a risk prediction. While interpretable, single trees often over fit. Random Forest overcomes this by constructing an ensemble of hundreds of decision trees, each trained on random data subsets, with final predictions aggregated through majority voting. These models excel at processing tabular data including temperature, rainfall, humidity, and historical pest pressure. Their key advantage is feature importance ranking, which identifies the most influential environmental variables driving outbreaks. Computationally efficient and interpretable, Random Forest enables farmers to shift from reactive spraying to proactive, condition-based interventions, reducing chemical inputs while improving timing accuracy.

e. Transfer Learning Models

Transfer learning leverages pre-trained models like ResNet (Residual Networks) and VGG (Visual Geometry Group) that have been trained on massive general-purpose datasets such as ImageNet. These models have already learned to detect fundamental visual features edges, textures, shapes, and patterns that are transferable to agricultural applications. Rather than training a deep neural network from scratch (which requires vast labeled datasets and significant computational resources), researchers fine-tune these pre-trained models on smaller, domain-specific agricultural datasets of pests, diseases, and crop damage. This approach dramatically reduces training time, often from weeks to hours, while achieving superior accuracy. For instance, a ResNet-50 model pre-trained on ImageNet can be fine-tuned on just a few thousand images of Fall Armyworm damage to achieve over 95% classification accuracy. Transfer learning enables rapid deployment of high-performance pest detection systems even in data-scarce agricultural contexts.

f. Variable Rate Technology (VRT) Integration

VRT is the actuation component of precision pest control, enabling site-specific application of pesticides, fungicides, or fertilizers based on AI-generated prescription maps. After AI models (CNNs, YOLO, Random Forest) process drone imagery, the output is exported as a **shapefile** or **GeoJSON** containing geofenced polygons. Each polygon is tagged with a specific application rate e.g., "Zone A: 2.5 L/ha chlorantraniliprole," "Zone B: 0 L/ha." This file is uploaded to the sprayer's onboard **section control system**. VRT-equipped sprayers, whether tractor-mounted or autonomous drones, read these maps and automatically adjust application rates in real-time as they traverse the field. Instead of uniform blanket spraying, VRT delivers high rates only to infested zones, reduced rates to buffer areas, and zero application to healthy zones. This precision reduces chemical usage by 30–90%, minimizes environmental runoff, preserves beneficial insects, and lowers input costs. VRT transforms AI-driven detection into targeted, economical action, closing the loop from scouting to treatment with surgical accuracy.

g. TinyML Model

In smart pest control, TinyML enables on-device inference without internet connectivity. Instead of sending drone or camera imagery to the cloud for processing, lightweight models such as quantized versions of MobileNet, TensorFlow Lite Micro, or pruned Random Forests, run directly on sensors, traps, or small drones. These models are compressed through quantization (reducing 32-bit floats to 8-bit integers), pruning (removing redundant neural connections), and knowledge distillation (training small models to mimic larger ones). Applications include smart pheromone traps that use camera-equipped microcontrollers to identify and count specific pests (e.g., codling moth) in real-time, triggering alerts only when thresholds are crossed. TinyML enables continuous,

real-time pest monitoring with battery life exceeding one year, democratizing AI for remote, off-grid agricultural settings.

Implications of AI and Drone-Based Pest Control

a. Economic Implications

- Reduced input costs: Farmers save 30–90% on pesticides, fungicides, and labour through targeted application
- Increased crop yields: Early detection and precise intervention minimize crop loss from pest outbreaks
- Lower barriers to entry: TinyML and Transfer Learning enable small holder farmers in developing regions to access advanced pest management without expensive infrastructure

b. Environmental Implications

- Drastic chemical reduction: Targeted spraying minimizes pesticide runoff into soil, groundwater, and adjacent ecosystems
- Protection of beneficial insects: Preserves pollinators (bees, butterflies) and natural pest predators by avoiding blanket applications
- Soil health preservation: Less chemical accumulation maintains microbial diversity and long-term soil fertility

c. Agricultural Practice Implications

- Shift from reactive to proactive management: Predictive models enable intervention before visible symptoms appear
- Scalability: One operator can manage thousands of acres through autonomous drone fleets.

d. Social Implications

- Reduced chemical exposure: Farmers and farmworkers face lower health risks from handling and inhaling pesticides
- Food safety: Consumers benefit from produce with significantly lower chemical residues
- Food security: More resilient crop production helps stabilize food supply chains against pest-driven shortages

Conclusion:

The integration of artificial intelligence and drone technology represents a fundamental departure from traditional pest control methods. Blanket spraying reactive, imprecise, and environmentally damaging is being replaced by a closed-loop system where every action is informed by data. Multispectral drones scout fields; Convolutional Neural Networks interpret visual data with superhuman accuracy; YOLO enables real-time detection; Random Forest models forecast outbreaks; and Variable Rate Technology ensures chemical applications are delivered with surgical precision only where and when needed. The implications are profound. Farmers benefit from reduced input costs and higher yields. Consumers receive food with lower chemical residues. The environment gains from minimized pesticide runoff and preserved pollinator populations. As TinyML extends intelligence to remote fields and Transfer Learning accelerates deployment in data-scarce regions, this technology becomes increasingly accessible. This is not merely incremental improvement but a reimagining of agriculture, one that prioritizes precision over volume, intelligence over brute force, and sustainability over short-term expediency.

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Spent Mushroom Substrate: A Sustainable Agricultural Resource



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Abstract

Spent Mushroom Substrate (SMS) is the residual biomass left after mushroom cultivation, which has gained increasing attention as a valuable agricultural by-product. Traditionally considered waste, SMS is now recognized for its potential applications in soil fertility enhancement, organic farming, composting, animal feed supplementation, and environmental sustainability. Rich in organic matter, nutrients, and beneficial microorganisms, SMS serves as an eco-friendly alternative to chemical fertilizers. This article explores the composition, benefits, and diverse applications of SMS, emphasizing its role in sustainable agriculture and waste management. The utilization of SMS not only improves soil health but also contributes to circular economy practices, reducing environmental pollution. The study highlights innovative uses and future prospects of SMS, making it an essential resource for modern agriculture.

Introduction

Mushroom cultivation has emerged as a profitable agro-based industry due to its high nutritional value and growing demand. However, large quantities of waste are generated after the harvest cycle, commonly referred to as Spent Mushroom Substrate (SMS). For every kilogram of mushrooms produced, approximately 5–6 kilograms of SMS are generated, creating disposal challenges.

Traditionally, SMS was discarded or burned, leading to environmental concerns such as air pollution and nutrient loss. With increasing awareness about sustainable agriculture, SMS is now being recognized as a valuable organic resource. Its rich composition of partially decomposed organic materials, microbial biomass, and residual nutrients makes it highly beneficial for agricultural and environmental applications.

This article aims to provide a comprehensive understanding of SMS, including its composition, benefits, applications, and future scope in sustainable farming systems.

Nutritional status of SMS

SMS is regarded as being quite nutrient-dense since it includes (button mushroom SMS) N-P-K in the ratio of 1.9-0.4-2.4% when it is fresh and 1.9-0.6-1.0 after 8–16 months of decomposition. In contrast to SMS of button mushrooms, Oysters, milky, and paddy straw SMS are nutritionally Lacking.



Composition of Spent Mushroom Substrate

SMS consists of the leftover growing medium used for mushroom cultivation, typically composed of materials such as straw, sawdust, poultry manure, gypsum, and other organic supplements. During mushroom growth, only a portion of nutrients is utilized, leaving behind a nutrient-rich residue.

The major components of SMS include:

- Organic matter (high carbon content)
- Nitrogen, phosphorus, and potassium (NPK)
- Calcium and magnesium
- Beneficial microorganisms (bacteria and fungi)
- Enzymes and bioactive compounds
- The presence of these elements enhances soil fertility and supports plant growth, making SMS a valuable organic amendment.

Benefits of Spent Mushroom Substrate

1. Soil Fertility Improvement

SMS improves soil structure, aeration, and water-holding capacity. It enhances microbial activity, which plays a crucial role in nutrient cycling and soil health.

2. Organic Fertilizer

Due to its nutrient content, SMS can be used as a natural fertilizer, reducing dependence on chemical inputs and promoting sustainable farming.

3. Waste Management Solution

Utilizing SMS helps in reducing agricultural waste and minimizes environmental pollution. It supports eco-friendly waste recycling practices.

4. Cost-Effective Resource

Farmers can use SMS as a low-cost alternative to commercial fertilizers and soil conditioners, reducing production costs.

5. Carbon Sequestration

SMS contributes to carbon storage in soil, helping mitigate climate change by reducing greenhouse gas emissions.



Applications of Spent Mushroom Substrate

1. Soil Amendment

SMS is widely used to improve soil quality. It enhances soil fertility and supports crop growth in both field crops and horticultural systems.

2. Compost Production

SMS can be composted alone or mixed with other organic wastes to produce high-quality compost, rich in nutrients and beneficial microbes.

3. Vermicomposting

Earthworms can convert SMS into nutrient-rich vermicompost, which is highly beneficial for plant growth.

4. Animal Feed Supplement

In some cases, SMS can be used as a supplementary feed for livestock due to its fiber and nutrient content, after proper treatment.

5. Biogas Production

SMS can be used as a substrate for biogas production, contributing to renewable energy generation.

6. Mulching Material

SMS acts as an effective mulch, helping retain soil moisture, suppress weeds, and regulate soil temperature.

7. Nursery and Potting Mix

- SMS is used in potting mixtures for nursery plants, improving plant growth and root development.
- Challenges in Utilization of SMS
- Despite its benefits, the use of SMS faces certain challenges:
- High moisture content makes transportation difficult
- Presence of pathogens if not properly treated
- Variability in nutrient composition
- Limited awareness among farmers
- Lack of proper storage and processing facilities

Disadvantages of spent mushroom substrate

- Despite its advantages, SMS also has certain limitations:
- High Moisture Content: Fresh SMS is heavy and difficult to transport due to its high water content.
- Risk of Pathogens: If not properly processed, it may contain harmful microbes, pests, or weed seeds.
- Variable Nutrient Composition: Nutrient levels may vary depending on the substrate used, making it less consistent.
- Salinity Problems: Some SMS may contain excess salts, which can negatively affect sensitive crops.
- Bulky Nature: Its large volume and low density make storage and transportation challenging.
- Slow Nutrient Release: Nutrients are released gradually, which may not meet immediate crop requirements.
- Odor Issues: Improper decomposition can lead to unpleasant smells.
- Limited Awareness: Lack of knowledge among farmers restricts its effective utilization.

Conclusion

Spent Mushroom Substrate (SMS) has transformed from a waste by-product of mushroom cultivation into a valuable resource for sustainable agriculture. Its rich composition of organic matter, essential nutrients, and beneficial microorganisms makes it highly effective in improving soil fertility, enhancing crop productivity, and supporting eco-friendly farming practices. The utilization of SMS contributes significantly to waste management by recycling agricultural residues and reducing environmental pollution.

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From Soil to Startup: Revolutionizing Indian Agriculture through Innovation and Technology



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Abstract:

Agriculture, once seen as a traditional and labor-intensive occupation rooted in age-old practices, is now witnessing a powerful transformation driven by innovation and technology. The shift from “soil to startup” represents a new era where farming is not just about growing crops but about integrating science, data, and entrepreneurship.

It reflects how modern agri-startups are revolutionizing every stage of agriculture, from production to market delivery. This evolution



is making agriculture more efficient, profitable, and sustainable, especially in a country where millions depend on farming for their livelihood. In India, agriculture contributes about 15–18% to the Gross Domestic Product (GDP) and supports nearly 45–50% of the population for employment. Moreover, the country has witnessed the emergence of over 7,000+ agri-startups in recent years, highlighting rapid technological adoption in the sector. Technologies such as precision farming, drones, and digital marketplaces have been shown to improve productivity by 15–25% while reducing input costs significantly.

The Need for Transformation

The transformation is not just an option; it is a necessity because agriculture has long faced structural challenges such as:

1. Small and fragmented landholdings (over 85–86% of farmers in India are small and marginal, owning less than 2 hectares, with the average landholding reduced to about 1.08 ha)
2. Unpredictable weather due to climate change (agriculture remains highly dependent on monsoon, while India has only about 4% of global water resources despite supporting a large population)
3. Limited access to markets and price fluctuations (post-harvest losses account for nearly 20–22% of total produce in some sectors due to weak supply chains)
4. Heavy dependence on traditional marketing
5. Low productivity and income instability (around 40–46% of the workforce depends on agriculture, but it contributes only about 17–18% to GDP, reflecting low productivity and income levels)

These issues highlight the urgent need for a modern, technology-driven approach to farming.

Table 1: Structure of Indian Agriculture

Parameter	Value	Significance
Share in GDP	15–18%	Indicates moderate economic contribution
Workforce Dependence	45–50%	High dependency vs low GDP share
Small & Marginal Farmers	85–86%	Dominance of fragmented holdings
Average Landholding Size	~1.08 ha	Limits scalability and mechanization
Irrigated Area	~50% of net sown area	High dependence on monsoon
Post-Harvest Losses	20–25% (F&V)	Major inefficiency in supply chain

Rise of Agri-Startups in India

In the last decade, India has witnessed a surge in agri-startups led by young entrepreneurs, engineers, and rural innovators. These startups are leveraging digital tools, scientific techniques, and business models to solve real-world agricultural problems. As of recent estimates, India has more than 7,000–8,000 agri-startups, a significant rise from fewer than 1,000 a decade ago, supported by government initiatives and increasing venture capital investments (Table 2).

They are transforming agriculture into a scalable and profitable enterprise, attracting youth and investors alike. The sector has attracted significant funding, with areas like precision agriculture, supply chain, and agri-fintech witnessing rapid growth.

Table 2: Growth of Agri-Startup Ecosystem in India

Indicator	2013–14	2024–25 (Est.)	Growth Trend
Number of Agri-Startups	<1,000	7,000–8,000+	Rapid expansion (7–8x growth)
Investment in Agri-Tech	Limited	₹6,000+ crore (cumulative)	Increasing VC interest
Key Focus Areas	Basic advisory	AI, drones, fintech, supply chain	Tech diversification
Government Support	Minimal	Multiple schemes (RKVY, Startup India)	Strong policy push
Farmer Reach	Limited	Millions via apps/platforms	High scalability

Key Areas of Innovation and Transformation

The transformation of Indian agriculture from traditional practices to a technology-driven startup ecosystem is taking place across several key areas:

1. Smart and Precision Farming

One of the most significant innovations is the adoption of precision farming techniques. Sensors, drones, and data analytics help farmers monitor:

- Soil health
- Growth of crops
- Moisture levels
- Irrigation needs

Precision farming technologies have been shown to increase crop productivity by 15–25% while reducing input costs by nearly 20–30%. The use of agricultural drones in India is also expanding rapidly under government support such as the Kisan Drone initiative. This allows efficient use of water, fertilizers, and pesticides, reducing waste and increasing crop yield.

2. Digital Platforms and Market Linkages

Agri-startups are developing online platforms and mobile applications that directly connect farmers with buyers, retailers, and consumers. This:

- Eliminates middlemen
- Ensures fair pricing
- Provides transparency in transactions

Platforms like e-NAM (National Agriculture Market) have integrated over 1,000+ mandis across India, enabling farmers to access real-time price information and wider markets. Digital platforms are helping improve price realization by 10–15% in many cases. Farmers can now access real-time market prices and choose the best place to sell their produce.

3. Supply Chain and Logistics Management

Improving the agricultural supply chain is a major focus. Startups are introducing:

- Cold storage facilities
- Efficient transportation systems
- Smart warehousing

India faces post-harvest losses estimated at ₹90,000–1,00,000 crore annually, especially in fruits and vegetables (up to 20–25%). Improved logistics and cold chain solutions are significantly reducing these losses. These innovations help reduce post-harvest losses and ensure timely delivery of fresh produce.

4. Agri-Finance and Digital Services

Startups are offering:

- Easy access to loans and insurance
- Digital payment systems
- Crop insurance

Only about 30–35% of small farmers have access to formal credit. Agri-fintech startups are bridging this gap through digital lending, while crop insurance schemes are expanding financial security. Farmers are also receiving advisory services through apps and helplines, helping them make informed decisions.

5. Farm Mechanization and Equipment Access

Startups are making modern machinery accessible through rental platforms, allowing small farmers to use:

- Tractors
- Harvesters
- Advanced tools

Farm mechanization in India is around 45–50%, compared to over 90% in developed countries, indicating significant scope for growth. This reduces labor dependency and increases efficiency.

6. Sustainable and Climate-Smart Agriculture

Technology is promoting eco-friendly practices with a focus on sustainability. Startups promote:

- Organic and natural farming
- Water-saving irrigation methods
- Climate-resilient crops

Micro-irrigation has the potential to save 30–50% water while increasing productivity by 20–40%. Climate-smart practices are becoming essential due to rising temperature variability. This ensures long-term environmental protection and soil health.

7. Research, Biotechnology, and Input Innovation

Advancements in biotechnology and agricultural research are leading to:

- Improved seed varieties
- Pest-resistant crops
- Better fertilizers and inputs

Improved seed varieties can enhance yields by 20–30%, while precision inputs help reduce costs. These innovations increase productivity and reduce risks.

Impact on Indian Agriculture

The transformation “from soil to startup” is creating a positive impact on Indian agriculture by making it more productive, profitable, and sustainable (Table 3).

- Increased farmer income through better pricing and productivity (income gains of 20–40% reported in tech-enabled farming models)
- Data-driven decision-making reducing uncertainty and risk
- Sustainability through eco-friendly practices
- Youth engagement, attracting young talent to agriculture
- Economic growth, strengthening the rural economy



Table 3: Impact of Technology in Agriculture

Technology / Innovation	Impact on Productivity	Cost Reduction	Additional Benefits
Precision Farming	+15–25% yield	20–30% input saving	Efficient resource use
Drones (Kisan Drone)	Faster operations	15–20% labor saving	Uniform spraying
Digital Market Platforms	10–15% better price	Reduced intermediaries	Transparency
Cold Chain Logistics	Reduced 20–25% losses	Improved profit margins	Better quality
Micro-Irrigation	+20–40% productivity	30–50% water saving	Climate resilience
Improved Seeds	+20–30% yield	Lower risk	Pest resistance

Challenges in the Transformation

The shift is revolutionizing Indian agriculture, but it is not without obstacles (Table 4).

- Many small farmers are unable to benefit from digital platforms, creating a gap between advanced and traditional communities
- Lack of digital literacy slows the adoption of modern farming practices (only about 25–30% of farmers are digitally literate)
- High initial investment in technologies makes them unaffordable for small farmers
- Trust deficit between farmers and startups
- Limited access to finance restricts adoption of new technologies
- Fragmented landholdings reduce efficiency and scalability

Table 4: Key Challenges in Agri-Tech Adoption

Challenge	Current Status	Impact
Digital Literacy	~25–30% farmers digitally aware	Slows adoption
Access to Credit	Only 30–35% farmers covered	Limits investment
Technology Cost	High initial investment	Excludes small farmers
Land Fragmentation	85% small holdings	Reduces scalability
Trust Gap	Moderate	Slows startup adoption

Future Prospects

This transformation is shaping the future of Indian agriculture. Agri-startups are expected to:

- Build smart farming ecosystems
- Enhance global competitiveness of Indian produce
- Strengthen food security
- Promote inclusive and sustainable growth

Conclusion

The journey “from soil to startup” reflects a transformation of Indian agriculture from traditional practices to a modern, technology-driven, and entrepreneurial sector. This transformation is shaping a sustainable and prosperous future for millions of farmers in India.

Application of Drone Technology in Agricultural Management for Sustainable Productivity



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Abstract

Drone Technology or Unmanned Aerial Vehicles (UAVs), has emerged as a transformative tool in modern agriculture, enabling precision-based management for sustainable productivity. This article synthesizes current advancements in UAV applications for crop monitoring, including crop health assessment, irrigation management, soil and field analysis, yield estimation, and crop damage assessment. Equipped with advanced sensors such as multispectral, hyperspectral, thermal, and LiDAR systems, drones facilitate real-time, high-resolution data acquisition, allowing early detection of biotic and abiotic stresses and enabling site-specific interventions. These capabilities significantly enhance resource-use efficiency by optimizing the application of water, fertilizers, and pesticides, thereby reducing production costs and environmental impacts. The review further highlights key advantages of UAV integration, including improved accuracy, time and labour savings, and support for smart farming through integration with Geographic Information System (GIS), IoT (Internet of Things), and decision-support systems. However, challenges such as high initial investment, technical skill requirements, regulatory constraints, and infrastructural limitations remain critical barriers to widespread adoption. Future prospects emphasize the integration of UAVs with artificial intelligence, development of low-cost scalable solutions, and their role in climate-smart agriculture and digital crop insurance systems. Overall, UAV technology holds significant potential to revolutionize agricultural management and contribute to sustainable and climate-resilient food production systems.

Keywords: Drone Technology, Precision Agriculture, Unmanned Aerial Vehicles (UAVs), Remote Sensing, Sustainable Agriculture

1. Introduction

Agriculture is undergoing a rapid technological transformation to cope with the challenges of global food security, climate change, resource depletion, and the need for sustainable intensification of crop production (Sarkar and Sarkar, 2025a). Among the emerging tools, drone technology or Unmanned Aerial Vehicles (UAVs), coupled with remote sensing systems has become one of the most significant innovations for precision agriculture (Zhang & Kovacs, 2012). These technologies are revolutionizing how farmers monitor, manage, and optimize crop production by providing timely, cost-effective, and highly accurate field information. Traditionally, crop health assessment, soil condition monitoring, and pest or disease monitoring relied on manual field visits, which are labour-intensive, time-consuming, and often limited in spatial coverage. In contrast, UAVs integrated with advanced sensors such as multispectral, hyperspectral, LiDAR, and thermal imaging enable the collection of real-time, high-resolution data over large agricultural landscapes (Huang et al., 2013; Awais et al., 2023). This information allows for early detection of biotic and abiotic stresses, mapping of variability in crop growth, and assessment of soil-water-plant interactions. The integration of UAV-based remote sensing into precision agriculture facilitates site-specific management strategies (Sarkar and Sarkar, 2025b). For example, drones equipped with thermal sensors can detect plant water stress, guiding irrigation scheduling to conserve water while maximizing yields (Bendig et al., 2013). Similarly, multispectral and hyperspectral imaging support nutrient management by identifying deficiencies in nitrogen and other essential elements, enabling farmers to apply

fertilizers only where needed, thus reducing costs and environmental pollution (Mogili & Deepak, 2018). In pest and disease management, drones provide rapid surveillance, offering early warnings that allow for targeted application of pesticides, minimizing chemical use and ecological harm. Beyond operational efficiency, the adoption of UAVs contributes significantly to sustainable agricultural productivity. By reducing the overuse of inputs such as water, fertilizers, and pesticides, drone-assisted decision-making enhances resource-use efficiency, lowers production costs, and mitigates negative environmental impacts (Tsouros et al., 2019). This aligns with global sustainability goals by promoting climate-smart farming practices and resilient food production systems.

2. Applications in Crop Monitoring

2.1. Crop Health Assessment

Drone-based crop health assessment represents a major advancement in agricultural diagnostics. By utilizing multispectral and hyperspectral imaging systems, drones can detect subtle physiological changes in crops that are not visible to the naked eye (Barbedo, 2019). These sensors capture variations in reflectance across different wavelengths, which can be processed to generate vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Enhanced Vegetation Index (EVI), Soil-Adjusted Vegetation Index (SAVI). These indices provide insights into chlorophyll content, photosynthetic activity, and overall plant vigour. Early detection of stress caused by pests, diseases, or nutrient deficiencies allows for timely intervention, thereby preventing yield losses and reducing unnecessary input application (Ajith et al., 2025). Moreover, continuous monitoring throughout the crop growth cycle enables farmers to track plant development and assess the effectiveness of management practices. This proactive approach shifts agriculture from reactive to predictive management, significantly improving crop performance and economic returns.

2.2. Irrigation Management

Efficient water management is critical in agriculture, particularly in regions facing water scarcity and erratic rainfall patterns. Drone-mounted thermal sensors play a crucial role in identifying spatial variability in crop water stress by detecting differences in canopy temperature (Dong et al., 2024). Plants experiencing water stress typically exhibit higher leaf temperatures due to reduced transpiration, which can be captured through thermal imaging. This information enables farmers to implement precision irrigation strategies, delivering water only to areas that require it. Such targeted irrigation not only conserves water resources but also reduces energy consumption associated with pumping and distribution. Additionally, optimized irrigation improves root development, nutrient uptake, and overall crop productivity, contributing to sustainable water-use efficiency in agriculture.

2.3. Soil and Field Analysis

Understanding soil variability is fundamental to effective agricultural management, and drones provide a powerful tool for detailed soil and field analysis. By capturing high-resolution aerial imagery, UAVs can generate digital elevation models and three-dimensional maps that reveal field topography, drainage patterns, and areas prone to erosion (Pineux et al., 2017). Remote sensing data can also be used to estimate soil moisture content, organic matter distribution, and variability in soil properties across the field. This information is essential for precision land preparation, optimized seeding, and site-specific nutrient management. Furthermore, identifying erosion-prone zones enables farmers to implement conservation practices such as contour farming, cover cropping, and reduced tillage, thereby enhancing soil health and long-term productivity.

2.4. Yield Estimation

Accurate yield estimation is essential for effective farm planning, market forecasting, and supply chain management. Drones provide valuable data on crop canopy structure, biomass accumulation, and growth stages, which can be analyzed using advanced algorithms to predict yield with high precision (Wang et al., 2021). At a larger scale, yield estimation data supports policymakers and agribusiness stakeholders in assessing regional production trends, ensuring food security, and stabilizing market dynamics. The integration of UAV data with machine learning models further enhances the accuracy and reliability of yield predictions.

2.5. Crop Insurance and Damage Assessment

Natural disasters such as floods, droughts, cyclones, and hailstorms can cause significant agricultural losses, making timely and accurate damage assessment crucial. Drones enable rapid aerial surveys of affected areas, capturing high-resolution images that provide objective and verifiable evidence of crop damage. This technology facilitates quicker processing of insurance claims by providing transparent and unbiased data, reducing disputes between farmers and insurance providers. Moreover, government agencies can utilize drone data for efficient disaster response planning, compensation distribution, and policy formulation. The use of UAVs in crop insurance thus enhances accountability, efficiency, and trust in agricultural risk management systems.

3. Advantages of Drone technology in Agriculture

3.1. Precision in Crop Health Monitoring

One of the most significant advantages of drone technology is its ability to provide precise and detailed insights into crop health. Advanced imaging sensors detect minute variations in plant growth and vigor, enabling accurate assessment at the micro-level. This precision allows farmers to address specific issues within a field rather than applying uniform treatments, thereby improving efficiency and reducing input wastage.

3.2. Time and Cost Savings

Drones significantly reduce the time and labor required for field monitoring compared to traditional methods. Large agricultural areas can be surveyed within minutes, providing real-time data that supports immediate decision-making. This reduction in manual labor translates into cost savings, while the availability of timely information enhances operational efficiency and productivity.

3.3. Early Detection of Stress, Pests, and Diseases

Early detection is critical for effective crop management, and drones excel in identifying stress factors at their initial stages. Multispectral and hyperspectral imaging technologies can detect physiological changes before visible symptoms appear, allowing farmers to take preventive measures. This early intervention minimizes yield losses, reduces chemical usage, and promotes environmentally sustainable practices.

3.4. Optimized Resource Use

Drone-based precision agriculture enables the targeted application of inputs such as water, fertilizers, and pesticides. By identifying specific areas requiring intervention, farmers can avoid over-application, thereby conserve resources and reducing environmental pollution. This optimization not only lowers production costs but also enhances the sustainability of farming systems.

3.5. Support for Precision Agriculture and Smart Farming

The integration of drones with digital technologies such as Geographic Information Systems (GIS), Internet of Things (IoT), and decision-support systems represents a major advancement in smart farming. These integrated systems enable real-time monitoring, data analytics, and automated decision-making, improving overall farm management. As a result, farmers can achieve higher productivity, profitability, and resilience against climatic uncertainties.

4. Challenges in Adopting Drone Technology in Agriculture

4.1. High Initial Investment

Despite its benefits, the adoption of drone technology is often constrained by high initial costs associated with purchasing UAVs, sensors, and data processing software. For small and marginal farmers, these costs can be prohibitive, limiting widespread adoption. Financial support mechanisms such as subsidies, cooperative ownership models, and rental services are essential to overcome this barrier.

4.2. Need for Skilled Manpower

Operating drones and interpreting remote sensing data require technical expertise and specialized training. The lack of skilled personnel, particularly in rural areas, poses a significant challenge to effective implementation. Capacity-building initiatives, training programs, and extension services are crucial to bridge this knowledge gap and promote technology adoption.

4.3. Policy and Regulatory Barriers

Drone operations in agriculture are subject to regulatory frameworks that govern airspace usage, licensing, and safety protocols. In India, evolving regulations can create uncertainties and delays in adoption. Simplifying

procedures and developing farmer-friendly policies are necessary to facilitate the widespread use of UAV technology in agriculture.

4.4 Connectivity and Data Processing Issues

Effective utilization of drone data requires reliable internet connectivity and advanced data processing infrastructure. In many rural areas, limited connectivity and lack of access to analytical tools hinder real-time data transmission and analysis. Addressing these infrastructural challenges is essential for maximizing the benefits of drone technology.

4.5 Maintenance and Operational Challenges

Drones are sensitive to environmental conditions such as wind, rain, and extreme temperatures, which can affect their performance and reliability. Regular maintenance, battery management, and operational complexities further add to the challenges faced by farmers. Developing robust and user-friendly drone systems is essential to ensure long-term sustainability.

5. Future Directions

5.1. Synergy with AI and IoT

The integration of drone technology with Artificial Intelligence (AI) and Internet of Things (IoT) is expected to revolutionize agricultural management. AI-driven analytics can process large volumes of drone data to generate actionable insights, while IoT devices enable continuous monitoring of field conditions. This synergy will support real-time decision-making for irrigation, fertilization, and pest control.

5.2. Low-Cost and Scalable Solutions

Developing affordable drone technologies and scalable deployment models is critical for ensuring accessibility to smallholder farmers. Innovations such as drone rental services, community-based ownership, and government-supported initiatives can significantly enhance adoption rates and democratize access to advanced agricultural tools.

5.3. Climate-Smart Agriculture

As climate change continues to impact agricultural systems, drones will play a vital role in monitoring crop stress, assessing climate risks, and supporting adaptive management strategies. By providing timely data on environmental conditions, UAVs enable farmers to respond effectively to climate variability and enhance resilience.

5.4. Digital Crop Insurance and Monitoring

The use of drones in digital crop insurance systems is expected to increase significantly, improving transparency and efficiency in claim settlements. UAV-based monitoring also supports government programs in agricultural planning, resource allocation, and disaster management, contributing to more effective policy implementation.

5.5. Public-Private Partnerships

Collaboration between government agencies, research institutions, and private sector organizations is essential for accelerating innovation and adoption of drone technology. Public-private partnerships can facilitate research, funding, training, and infrastructure development, ensuring that the benefits of UAV technology reach farmers at all levels.

6. Conclusion

Drone and remote sensing technologies are transforming modern agriculture by enabling precise, efficient, and data-driven crop management. These tools significantly reduce reliance on traditional manual methods, enhance resource-use efficiency, and support sustainable farming practices. By providing timely and actionable insights, drones empower farmers to make informed decisions, optimize inputs, and mitigate risks associated with climate variability and market uncertainties.

With supportive policies, affordable technologies, and effective capacity-building initiatives, drone technology has the potential to become an integral component of agricultural systems. In the coming years, UAVs will not only serve as monitoring tools but will also play a central role in the development of smart, climate-resilient, and sustainable agriculture, particularly in countries like India where the need for innovation in farming is critical.

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The Mechanics of Soil Carbon Sequestration: Building the Terrestrial Carbon Sponge



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Introduction

The global carbon cycle is often discussed in terms of atmospheric concentrations and oceanic absorption, yet one of the most immediate levers for climate stabilization lies beneath our feet. The "Carbon Sponge" refers to a soil ecosystem that has been biologically optimized to capture, infiltrate, and store carbon and water. In a healthy state, soil is not a solid mass of weathered rock; it is a porous, living infrastructure.

Historically, industrial agricultural practices have treated soil as a physical substrate for chemical inputs, a perspective that has led to the widespread degradation of soil structure. When soil loses its organic carbon, it loses its ability to hold water, transitioning from a porous sponge to a compacted "brick." However, recent advancements in soil microbiology reveal that this process is reversible. By understanding the pathways through which plants transfer carbon into the earth, we can rebuild the soil's physical architecture.

The Architecture of the Sponge: Porosity and Aggregation

To understand the carbon sponge, one must first understand soil aggregation. Soil is a mixture of mineral particles including sand, silt, and clay. In a degraded system, these particles remain independent or are crushed together into a dense mass. In a "spongy" system, these particles are bound together into clusters called aggregates.

Aggregation is a biological feat driven by the production of biotic glues, most notably glomalin. This sticky glycoprotein, secreted by arbuscular mycorrhizal fungi (AMF), acts as a long-term adhesive that coats soil particles and fungal hyphae to create a stable framework.

This framework creates two types of essential spaces:

1. **Macropores:** Large channels created by roots and earthworms that allow for rapid water infiltration and gas exchange.
2. **Micropores:** Tiny spaces within aggregates that hold water against the pull of gravity through capillary action.

A soil rich in carbon is a soil rich in volume. Every 1% increase in soil organic matter (SOM) can increase the soil's water-holding capacity by approximately 20,000 to 25,000 gallons per acre. This transformation is the primary mechanism of terrestrial drought resilience.

The Liquid Carbon Pathway: The Primary Engine

For decades, the consensus was that soil carbon was built primarily through the decomposition of "above-ground" biomass, such as fallen leaves. While this contributes to the surface mulch, it is not the most efficient way to store carbon deep in the soil profile.

The more significant driver is the Liquid Carbon Pathway (LCP). Through photosynthesis, plants convert solar energy and CO² into glucose. A substantial portion of this up to 40% in some species is transported to the roots and excreted into the rhizosphere as exudates.

This is a strategic trade: the plant provides high-energy carbon to microbes, and in return, the microbes "mine" minerals like phosphorus and nitrogen from the soil that the plant cannot access alone. Because this carbon is delivered directly into the soil matrix in a dissolved form, it is more likely to be processed by microbes and converted into stable organic compounds rather than being oxidized and released as CO².

Carbon Stability: POM vs. MAOM

A critical distinction in soil science is the difference between temporary carbon and long-term storage. Scientists categorize soil organic carbon into two primary pools:

- **Particulate Organic Matter (POM):** This consists of relatively fresh bits of plant debris. It is "labile," meaning it cycles quickly (within months or years). While essential for fertility, POM is vulnerable to management changes like tillage.
- **Mineral-Associated Organic Matter (MAOM):** This is the "gold standard" of sequestration. MAOM occurs when small organic molecules form chemical bonds with the surfaces of silt and clay particles. Once "associated" with minerals, carbon is protected from decomposition for centuries. Building a carbon sponge is the process of maximizing the conversion of carbon into this stable MAOM pool.

Case Study: The Brown Ranch Transformation

The transition of the Brown Ranch in North Dakota provides a documented example of these principles in action. In the early 1990s, the land was characterized by low organic matter (1.7%) and high compaction.

The Intervention:

The management shifted to "soil health principles": zero-till to protect fungal networks, high-diversity cover cropping to provide a varied microbial diet, and integrated livestock grazing to stimulate the nutrient cycle.

The Scientific Outcomes:

1. **Carbon Accumulation:** Over 20 years, SOM increased to over 6%. This represents a massive net drawdown of atmospheric carbon into the mineral-associated pool.
2. **Infiltration Rate:** The change in hydrology was a "phase-shift." In 1991, the soil absorbed 0.5 inches of water per hour. By 2011, the infiltration rate exceeded 30 inches per hour.
3. **Thermodynamics:** By maintaining moisture, the ranch used solar energy for **evapotranspiration** (latent heat) rather than re-radiating it as **sensible heat**, effectively cooling the local microclimate.

Challenges in Scaling

Despite the clear benefits, scaling the carbon sponge requires addressing significant hurdles:

- **Spatial Variability:** Carbon levels vary significantly across a single field, making verification for carbon markets difficult.
- **Saturation Points:** Soils have a finite capacity to hold MAOM, determined by their specific clay and silt content.
- **Economics:** Farmers require financial incentives to move away from high-yield, extractive monocultures toward regenerative systems.

Conclusion

The carbon sponge represents a synthesis of biology, physics, and hydrology. It shifts our understanding of climate mitigation from a purely atmospheric problem to one of terrestrial health. By fostering the Liquid Carbon Pathway and protecting soil aggregates, we restore the soil's fundamental ability to manage water and temperature. The solution to atmospheric instability is found in the billions of microscopic "glues" and fungal threads that hold our world together.

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Simplified Precision Irrigation Planning Using CropWat Model



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Introduction

CROPWAT, a decision support tool developed by Land and Water Development Division of FAO. It is a computer-based tool designed to estimate reference evapotranspiration, crop water requirements, irrigation needs, and scheme-level water supply for different cropping patterns using soil, climatic, and crop data. The program also supports the preparation of irrigation schedules under various management conditions. The latest available version of CropWat is “CropWat 8.0”. CROPWAT 8.0 is a Windows program based on the previous DOS versions. CROPWAT 8.0 can also be used to evaluate farmers irrigation practices and to estimate crop performance under both rainfed and irrigated conditions. All calculation procedures used in CropWat 8.0 are based on the two FAO publications of the Irrigation and Drainage Series, namely, No. 56 “Crop Evapotranspiration - Guidelines for computing crop water requirements” and No. 33 titled “Yield response to water”. In this article, it is clearly explained how to calculate ET_c and how to schedule irrigation using ET_c at farmers point of view.

Data collection and arrangement:

1. Weather/climatic data (daily/decade/monthly data)

Step 1: Collect the given below weather data from any official website or from nearby weather stations.

Step 2: Arrange the below mentioned data in separate excel sheet of on monthly basis as shown in figure 1.

Minimum air temperature ($^{\circ}\text{C}$)
Maximum air temperature ($^{\circ}\text{C}$)
Relative humidity (%)
Sunshine hours (hrs)
Windspeed (km/day)

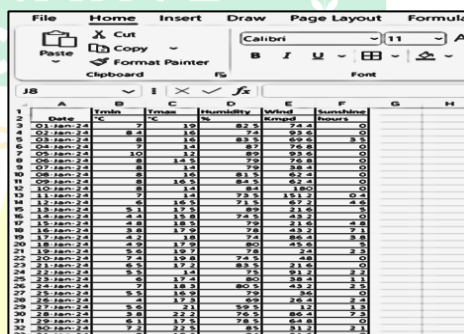


Figure 1: Arranging the Minimum and maximum temperature, RH, Sunshine hours, Windspeed data

Step 3: Arrange the rainfall data in separate excel sheet of on monthly basis as shown in figure 2.

Rainfall (mm)

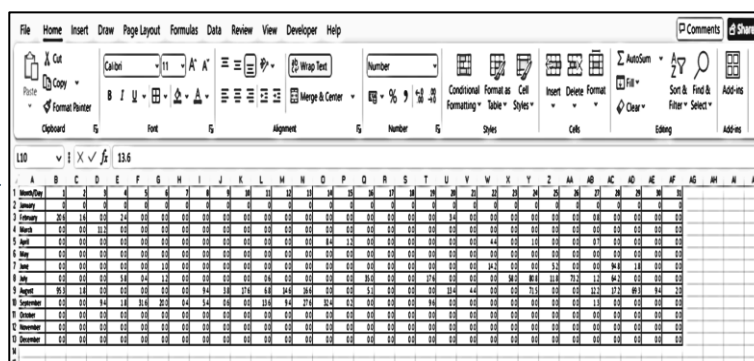


Figure 2: Arranging the rainfall data

2. Crop Data

If the crop specific data is not available, use the data are available in Cropwat software by clicking open tool bar in the model for many crops as shown in *figure 3*. Eg: Rice, sorghum, cotton, groundnut, sorghum, etc. This data is changed based on our respective crops and location specific.

The crop data required are given below

- Crop name
- Sowing/Planting date
- Stage days (initial, development, mid-season and late season)
- Crop coefficient (Kc) values at different stages
- Rooting depth (m)
- Critical depletion (fraction)
- Yield response function
- Crop height (m)

Crop	K _c (ini)	K _c (mid)	K _c (end)
Barley	0.3	1.15	0.4
Wheat	0.3	1.15	0.25-0.4
Maize	0.3	1.2	0.6
Rice	1.05	1.3	0.90-0.60
Cotton	0.35	1.15-1.2	0.7-0.5
Legumes	0.4	1.15	0.55
Broccoli	0.7	1.05	0.95
Potato	0.5	1.15	0.75
Broccoli	0.7	1.05	0.95
Tomato	0.7	0.9	0.85
Mustard	0.35	1.15	0.35

Table 1: Kc values of different crops with different stages

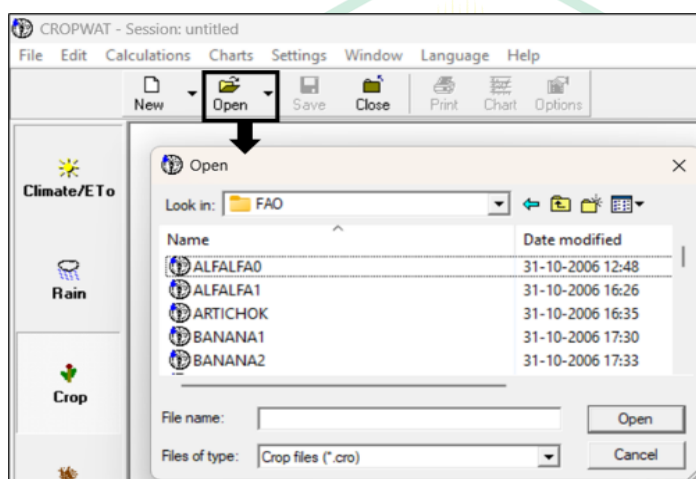


Figure 3: Crop data

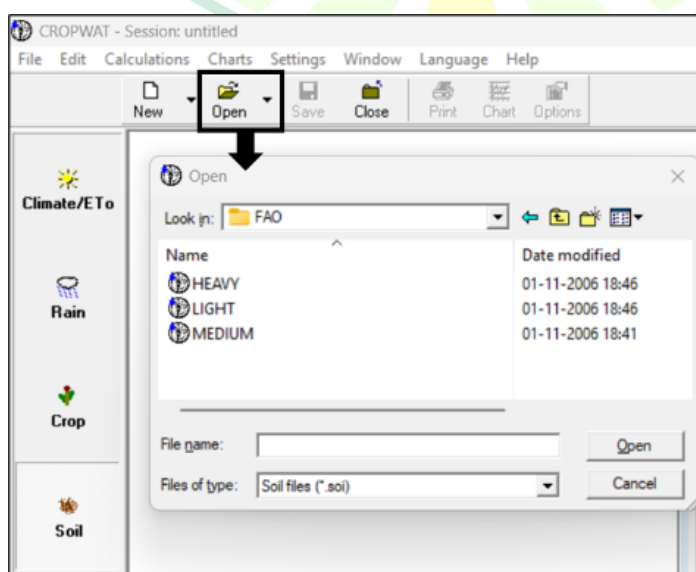


Figure 4: Soil data

3. Soil

Same as crop data, if the soil data is not available, use the data are available in Cropwat software as shown in figure 4 for different soil which is similar to your location. Eg: Heavy, medium and light soil, black clay soil, red loamy soil, red sandy soil, red sandy loam soil, etc.

The soil data required are given below

- Soil type
- Total available soil moisture (Field Capacity–Wilting Point)
- Maximum soil infiltration rate
- Maximum rooting depth
- Initial soil moisture depletion (as % of total available moisture)

Procedure:

Step 1: Download the software using the link <https://www.fao.org/land-water/databases-and-software/cropwat/en/> by clicking download option and install the software.

Step 1: Collect the required data (Weather data, soil data and crop data).

Step 2: Arrange the data as mentioned above in data collection and arrangement section.

Step 3: Open the climate/ET₀ toolbar at left corner and paste the arranged weather data as mentioned above for each month. If it is a June month, paste the data upto June month of that year, the remaining July to December month data of previous year data was pasted in the remaining data.

Step 4: Open the Rain toolbar at left corner and paste the arranged monthwise rainfall data as mentioned above for each month same like in step 2.

Step 5: Next, open the crop toolbar and give crop data or open FAO data based on your location as mentioned above in data collection and arrangement section.

Step 6: Next, open the soil toolbar and give soil data or open FAO soil data based on your location same as step 5.

Step 7: Now open CWR toolbar after feeding of all data, it will show the required daily and decadal ET_c.

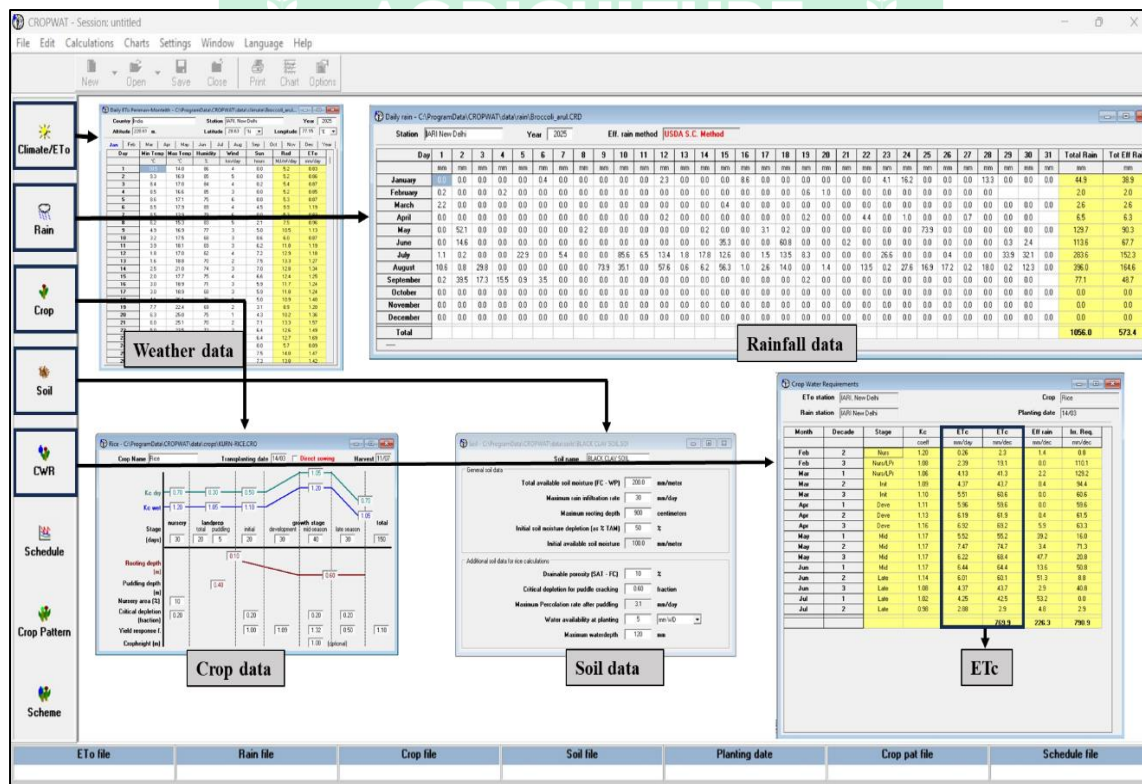


Figure 5: step by step Procedure to calculate ET_c.

Irrigation scheduling:

From the above steps, we calculated the ET_c of the particular crop in mm/day. From this add the application losses such as for drip irrigation – 10%, sprinkler irrigation- 15%, Flood irrigation- 50% and flood with pipe irrigation- 30% for irrigation. From the calculated ET_c along with losses, if we multiply with area, we can calculate the volume of water required for irrigation.

Eg:

If daily ET_c calculated from CropWat= 5mm/day

For drip irrigation = 10% application losses = 10 % x 5mm/day = 0.05 mm/day.

Total Daily ET_c = 5+0.05 = 5.05 mm/day = 5.05/1000 m/day.

If the area is 1 ha = 10,000 m²

Therefore, total volume of irrigation water required per day for 1 ha = 10,000 x 5.05/1000 m³
= 50.5 m³/day of irrigation water is required.

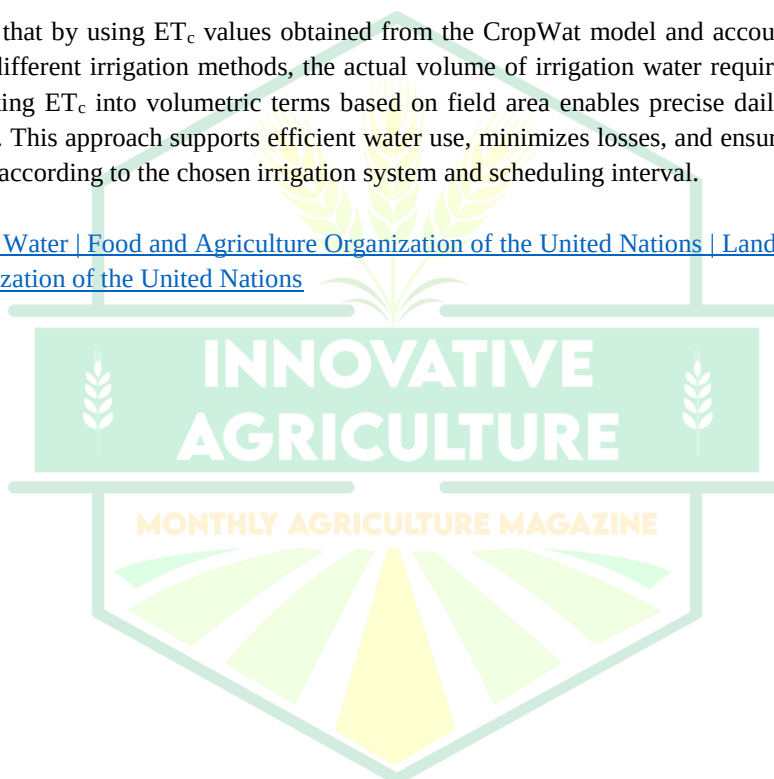
Based on this, we can add the volume of irrigation water as per irrigation interval.

Conclusion:

This demonstrates that by using ET_c values obtained from the CropWat model and accounting for application losses specific to different irrigation methods, the actual volume of irrigation water required can be accurately estimated. Converting ET_c into volumetric terms based on field area enables precise daily and interval-based irrigation planning. This approach supports efficient water use, minimizes losses, and ensures that crops receive adequate moisture according to the chosen irrigation system and scheduling interval.

Reference:

[CropWat | Land & Water | Food and Agriculture Organization of the United Nations | Land & Water | Food and Agriculture Organization of the United Nations](#)



Mitigating the Effects of High Temperature Stress during Grain Filling Stage of Wheat to Enhance Yield and Productivity



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Wheat (*Triticum aestivum* L.) is one of the most important staple cereal crops in the world, contributing substantially to global food and nutritional security by supplying a major share of calories and protein to the human diet. Globally, wheat is cultivated on approximately **215–220 million hectares**, with an annual production of around **780–800 million tonnes**, making it the most widely grown temperate cereal crop. India is the second-largest producer of wheat after China, cultivating the crop on about **31–32 million hectares** with a production exceeding **110 million tonnes**, and it forms the backbone of food security during the rabi (winter) season in the Indo-Gangetic Plains.

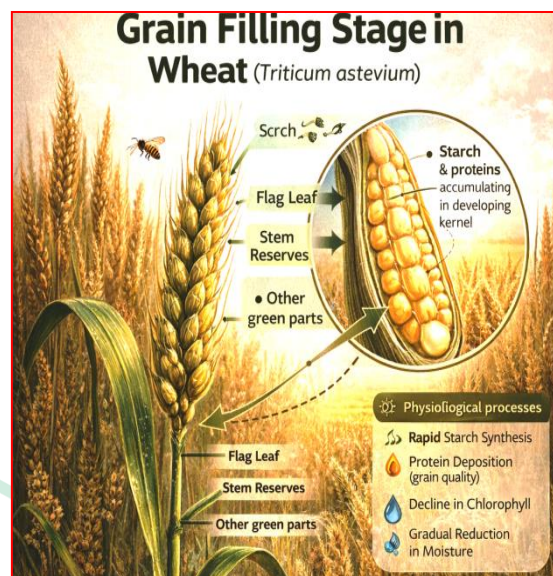


The grain filling stage of wheat, extending from anthesis to physiological maturity, is considered the most sensitive and critical phase of crop growth, as assimilates synthesized through photosynthesis in leaves and stems are translocated and accumulated in the developing grains, ultimately determining grain size, test weight, and final yield. However, rising temperatures associated with climate change, particularly the occurrence of terminal heat stress during the grain filling period, have emerged as a serious threat to wheat productivity in both tropical and subtropical regions. Exposure to high temperatures exceeding **30–35°C** during this stage accelerates leaf senescence, reduces chlorophyll content and photosynthetic efficiency, shortens the duration of grain filling, disrupts assimilate translocation, and results in shriveled grains with reduced thousand-grain weight and inferior quality. Traditionally, wheat has been well adapted to cool temperatures during vegetative growth and moderately warm conditions during reproductive development, but in recent decades, delayed sowing, shortened winter seasons, and sudden temperature spikes during March and April have increased the frequency and severity of terminal heat stress. Consequently, both yield potential and grain quality are significantly compromised, highlighting the urgent need to understand the physiological impacts of high temperature stress during grain filling and to develop and adopt effective agronomic, varietal, nutritional, and water management strategies to mitigate its adverse effects and sustain wheat productivity under changing climatic conditions.

Grain Filling Stage in Wheat: An Overview

The grain filling stage in wheat begins immediately after fertilization and continues until physiological maturity and represents the most critical period for determining final grain yield and quality. This stage involves the transfer of photosynthetically produced assimilates from source tissues, mainly leaves and stems, to the developing grains. Based on physiological and biochemical changes, the grain filling process is broadly divided into three distinct phases.

1. **Cell division phase:** This is the initial phase of grain development, occurring soon after fertilization, and is characterized by rapid cell division within the endosperm. During this period, the number of endosperm cells increases significantly, establishing the potential storage capacity of the grain. Adequate temperature, moisture, and nutrient availability during this phase are essential, as stress can limit cell number and irreversibly reduce the sink size, ultimately affecting grain weight.
 2. **Grain enlargement phase:** This is the most active phase of grain filling, during which there is rapid accumulation of starch and storage proteins in the endosperm. The grain increases substantially in size and dry weight as carbohydrates synthesized in the leaves are translocated to the grains. Efficient photosynthesis, enzyme activity, and assimilate transport are critical during this phase, and any stress, particularly high temperature, can reduce starch synthesis and shorten the duration of grain filling.
 3. **Desiccation phase:** In the final phase, grain moisture content gradually declines, metabolic activity slows down, and grains approach physiological maturity. Although dry matter accumulation is minimal during this stage, proper completion of desiccation is important for achieving good grain quality and test weight.
- Overall, the duration and efficiency of these three phases largely determine grain size, thousand-grain weight, and final yield. Optimal temperatures ranging from 18–24°C are ideal for normal grain filling, while higher temperatures adversely affect metabolic processes and grain development.



High Temperature Stress and Its Occurrence in Wheat

A. Definition of Terminal Heat Stress

Terminal heat stress in wheat refers to the exposure of the crop to **high temperatures, generally above 30–35°C**, during the reproductive phase, particularly from flowering to grain filling. This type of heat stress is considered more damaging than early-season heat stress because it coincides with the most sensitive stage of yield formation. During this period, the developing grains depend heavily on current photosynthesis and stored assimilates, and any thermal disturbance directly affects grain growth, weight, and quality. Terminal heat stress accelerates physiological processes, forcing the crop to mature earlier than normal, thereby reducing the effective grain filling duration and final yield.

B. Causes of Terminal Heat Stress

The occurrence of terminal heat stress has increased significantly in recent years due to several interacting factors. **Climate change and global warming** have resulted in a steady rise in mean temperatures and more frequent heat waves during the wheat-growing season. **Delayed sowing of wheat**, often due to late harvesting of preceding crops such as rice, exposes the crop to higher temperatures during grain filling. Additionally, a **shortened winter season** reduces the availability of cool temperatures required for normal crop development. The **cultivation of long-duration wheat varieties** further increases the likelihood of exposure to high temperatures at later growth stages. Poor or **inadequate irrigation scheduling** also aggravates heat stress by reducing transpirational cooling and increasing canopy temperature.

Physiological Effects of High Temperature during Grain Filling

High temperature stress during the grain filling stage affects wheat plants at physiological, biochemical, and molecular levels, leading to significant yield losses.

1. **Accelerated leaf senescence:** Elevated temperatures hasten chlorophyll degradation, resulting in premature yellowing and drying of leaves. This reduces the photosynthetically active leaf area and limits the supply of assimilates to developing grains.
2. **Reduction in photosynthesis:** High temperatures adversely affect the activity and stability of photosynthetic enzymes, particularly Rubisco. Heat stress also induces partial stomatal closure, restricting carbon dioxide uptake and further reducing photosynthetic efficiency.
3. **Shortened grain filling duration:** Heat stress accelerates crop phenology and leads to early maturity. The reduced duration of grain filling limits the time available for assimilate accumulation, resulting in smaller and lighter grains.
4. **Impaired assimilate translocation:** High temperature disrupts the transport of photosynthates from source tissues such as leaves and stems to sink organs, i.e., the grains. This imbalance between source and sink weakens grain development.
5. **Reduced starch and protein synthesis:** Heat stress inhibits key enzymes involved in starch biosynthesis, leading to lower starch deposition in grains. It may also alter protein composition, negatively affecting grain quality and end-use characteristics.

Impact of High Temperature Stress on Yield and Yield Components

High temperature stress during critical growth stages, particularly anthesis and grain filling, exerts severe adverse effects on wheat physiology. These effects ultimately translate into reduced yield and deterioration of grain quality. Elevated temperatures accelerate plant developmental processes, disrupt assimilate partitioning, and impair starch accumulation in grains, leading to inferior yield components (Table 1).

Table1. Effect of High Temperature on Wheat Yield Components

Yield Parameter	Normal Temperature	High Temperature (>30–35 °C)
Grain filling duration	Longer	Shortened
Grain size	Bold and uniform	Shriveled grains with reduced endosperm content
1000-grain weight	Higher	Reduced
Test weight	Optimal	Lower
Total yield	Higher	Significantly reduced

Agronomic Strategies to Mitigate High Temperature Stress

High temperature stress, particularly during the reproductive and grain filling stages, can severely reduce wheat productivity. Adoption of appropriate agronomic practices plays a crucial role in minimizing the adverse effects of heat stress and stabilizing yield.

1. **Timely Sowing:** Timely sowing is the most effective strategy to escape terminal heat stress. Early sowing allows sensitive growth stages such as flowering and grain filling to occur under relatively favorable temperature conditions. In North India, the recommended sowing window for wheat is the **first fortnight of November**. Delayed sowing exposes the crop to elevated temperatures during grain filling, leading to shortened grain filling duration, reduced grain weight, and lower yield.
2. **Selection of Suitable Varieties:** The use of heat-tolerant and early-maturing varieties is another important strategy for managing high temperature stress. Such varieties can either escape heat stress by completing their life cycle earlier or tolerate high temperatures through adaptive traits. Key characteristics of heat-tolerant varieties include the **stay-green trait**, **efficient photosynthesis at elevated temperatures**, and **maintenance of longer grain filling duration under stress conditions**.
3. **Optimal Plant Density:** Maintaining the recommended seed rate and plant population helps in developing an optimal canopy structure. Proper plant density improves light interception, enhances photosynthetic efficiency, and reduces competition for water and nutrients, thereby improving the crop's resilience to high temperature stress.

Water Management Practices

Efficient water management plays a vital role in mitigating the adverse effects of high temperature stress in wheat. Adequate soil moisture helps regulate canopy temperature through transpiration cooling, maintains cell turgidity, and supports physiological processes during critical growth stages.

1. **Critical Irrigation at Grain Filling Stage:** Timely irrigation at sensitive phenological stages is essential to minimize yield losses under heat stress. The critical irrigation stages in wheat include crown root initiation, booting, flowering, and grain filling. Among these stages, irrigation at the grain filling stage is the most crucial under high temperature conditions, as moisture availability during this phase supports assimilate translocation, prolongs grain filling duration, and improves grain weight.
2. **Light and Frequent Irrigation:** During periods of high temperature, light but frequent irrigations are more effective than heavy irrigation. This practice helps in maintaining optimum soil moisture in the root zone and regulates canopy temperature through enhanced transpiration. Frequent irrigation prevents moisture stress, reduces heat-induced injury to plant tissues, and supports normal physiological processes. As a result, crop resilience is improved and yield losses due to thermal stress are minimized.

Nutrient Management to Reduce Heat Stress Effects

Proper nutrient management is essential for improving plant vigor and enhancing tolerance to high temperature stress. Balanced nutrition ensures efficient metabolic activity and strengthens the plant's defense mechanisms under stress conditions.

1. **Nitrogen Management:** Adequate nitrogen supply delays leaf senescence and helps in maintaining photosynthetic activity for a longer duration, particularly during grain filling. However, excessive application of nitrogen should be avoided, as it can lead to lush vegetative growth, increased susceptibility to lodging, and greater sensitivity to heat stress.
2. **Potassium Role in Heat Stress Tolerance:** Potassium plays an important role in osmotic regulation, enzyme activation, and stomatal regulation. Adequate potassium nutrition improves water use efficiency, maintains cellular integrity, and enhances tolerance to high temperature stress.
3. **Micronutrients:** Micronutrients such as zinc and boron contribute to improved enzyme activity, pollen viability, and reproductive success, thereby reducing the adverse effects of heat stress on crop growth and yield.

Role of Foliar Application in Heat Stress Mitigation

Foliar application is an effective short-term strategy for mitigating the adverse effects of sudden heat waves in wheat. Foliar sprays supply nutrients and growth-regulating compounds directly to the leaves, ensuring quick absorption and immediate physiological response. These treatments help in maintaining photosynthetic activity, delaying leaf senescence, improving antioxidant defense, and supporting grain filling under high temperature stress. Foliar sprays are particularly useful during reproductive and grain filling stages when heat stress can cause severe yield losses (Table 2).

Table 2: Foliar Sprays for Mitigating Heat Stress in Wheat

Foliar treatment	Concentration	Benefit
Potassium nitrate (KNO ₃)	1–2%	Improves grain filling
Urea	2%	Delays senescence
Thiourea	500 ppm	Enhances stress tolerance
Salicylic acid	100–200 ppm	Improves antioxidant activity

Mulching and Residue Management

Crop residue retention and mulching play an important role in mitigating the adverse effects of high temperature stress in wheat. Retention of crop residues on the soil surface helps in conserving soil moisture by reducing evaporation losses. It also lowers soil and canopy temperature by moderating heat flux and improves soil organic matter content, which enhances soil structure and water-holding capacity. Zero tillage combined with residue retention has shown promising results in reducing terminal heat stress, improving root growth, and sustaining wheat yield under warmer conditions.

Use of Plant Growth Regulators and Biostimulants

Plant growth regulators and biostimulants serve as effective tools for improving plant tolerance to heat stress. Growth regulators such as cytokinins delay leaf senescence by maintaining chlorophyll content and photosynthetic activity. Biostimulants, including seaweed extracts, enhance stress tolerance by activating antioxidant defense mechanisms and improving metabolic efficiency. Their application helps wheat plants better withstand high temperature stress during critical growth stages.

Breeding and Genetic Approaches

Long-term mitigation of heat stress depends on the development of heat-resilient wheat varieties. Breeding programs focus on traits such as heat tolerance at the reproductive stage, stay-green phenotype, high grain filling rate, and an efficient antioxidant defense system. Modern breeding tools, including marker-assisted selection and genomic selection, are increasingly being used to accelerate the incorporation of heat tolerance traits into high-yielding wheat cultivars.

Climate-Smart Wheat Production

Climate-smart wheat production requires the integration of agronomic, genetic, and resource management practices to enhance resilience against rising temperatures. Climate-smart strategies include adjusted sowing dates, cultivation of stress-tolerant varieties, precision irrigation, and integrated nutrient management. Adoption of these practices helps reduce climate-related risks and improves sustainability of wheat production systems.

Future Perspectives

With climate change intensifying, terminal heat stress is expected to become more frequent and severe. Strengthening research, extension, and farmer linkages, along with the promotion of adaptive technologies, will be essential for sustaining wheat productivity under changing climatic conditions.

Conclusion

The grain filling stage of wheat is the most sensitive phase for yield determination, and exposure to high temperature during this period significantly reduces grain weight, yield, and quality. Terminal heat stress, driven by climate change and delayed sowing, poses a major challenge to wheat production. However, timely sowing, selection of heat-tolerant varieties, efficient water and nutrient management, foliar sprays, and residue management can effectively mitigate the adverse effects of high temperature stress. A holistic climate-smart approach that combines short-term agronomic interventions with long-term genetic improvement is essential for ensuring sustainable wheat production under rising temperature scenarios.

Influence of Soil Thermal Properties on Crop Growth and Development under Varying Climatic Conditions



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1. Introduction

The soil environment is basically an intricate, muddled porous medium in which solid material, water and air all coexist. Temperature is the emperor in this blend, it almost all in the soil (physical, chemical, biological) is influenced by it. Soil temperature changes gradually unlike air temperature that can jump around within seconds and this combination of slow change is what gives soil temperature a fairly unique little climate provided to plant roots and soil microbes to spend their days.

Thermal properties of the soil are all about the ability of the soil to absorb, store and conduct heat. Those properties inform us about the rate at which the root zone warms in the spring, the extent of frost in the winter and the severity of heat stress in the hot summer. Understanding soil thermal processes is overly important since despite the presence of adequate water and nutrients, both excessive or insufficient temperatures are still the primary source of yield restraint.

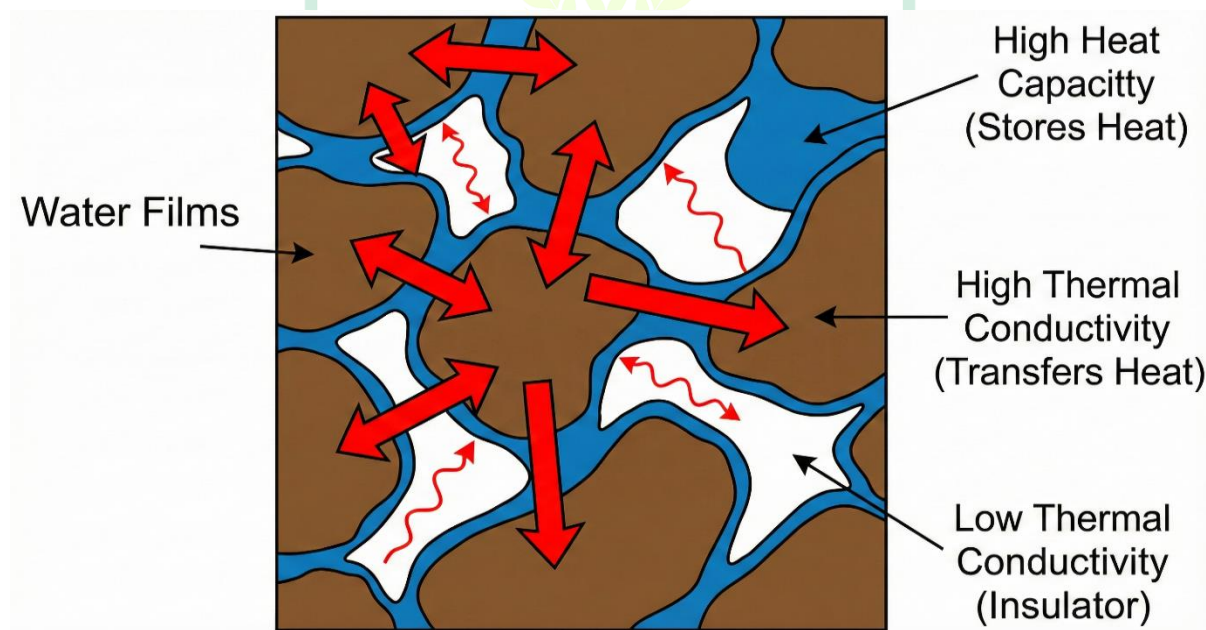


Figure 1. Microscale Thermal Interactions in a Soil Aggregate

2. Fundamental Soil Thermal Properties

2.1 Volumetric Heat Capacity (C_v)

The volumetric heat capacity is the amount of energy (Joules) required to raise one cubic meter of soil mass by one Kelvin ($\text{Jm}^{-3}\text{K}^{-1}$). It demonstrates the level of heat retention by soil. The big factor then on C_v is our soil water since the heat capacity of water is greater than that of minerals and air. In air, there is hardly any heat storage. It would require a lot more energy to warm up wet soil than dry soil, but it retains it longer as well, providing it with greater stability.

2.2 Thermal Conductivity (λ)

Thermal conductivity is the capability of soil to transfer heat, or the number of watts per meter per Kelvin ($\text{Wm}^{-1}\text{K}^{-1}$). In essence, conduction is the movement of heat between adjacent molecules and is based on the kinetic energy transfer of the bulk density of water. Air pockets in a dry airy soil serve the purpose of insulation, reducing. With increased water content of the soil, water films fill the spaces between the particles increasing contact and lifting up to saturation. Hard-packed soil contains a larger portion of solid-to-solid contact therefore it has a greater λ compared to a loose tilled soil.

2.3 Thermal Diffusivity (D)

The product of thermal conductivity over volumetric heat capacity is called thermo-diffusivity (D). The greater D is, the greater the speed with which the temperature changes spread through the profile. D in $\text{m}^2 \text{s}^{-1}$ is a measure of the rate at which a soil will heat or cool at depth in response to changes in surface temperature. A dry soil is one with low λ , but it is also characterized by low C_v , resulting in a large D--heat rises very fast but only at the surface. The wet soil contains a high λ and a high C_v , so the lower D -heat will take longer to reach deeper levels:

$$D = \frac{\lambda}{C_v}$$

3. Physiological Impacts of Soil Temperature on Crops

The thermal state of the rhizosphere (the root zone) directly regulates plant metabolic processes. Every enzyme-catalyzed reaction has a minimum, optimum, and maximum temperature range.

3.1 Germination and Emergence

The most sensitive thing in the development of a crop is seed germination. The metabolism of soil is induced to go into dormancy and start-up by soil temperature. Cool soil retards emergence and increases seedlings susceptibility to soil pests and insects. Hot soil will even kill seedlings or induce thermoinhibition.

3.2 Root Growth and Morphology

When the soil temperature reaches the optimum point of each species, the growth of roots becomes accelerated. The viscous effect is caused by cold soils, which make water less permeable and less permeable cell membranes, so physiological drought may arise despite the presence of an abundance of moisture. Warm soil will promote side root development, although higher than 35°C temperatures in the top layer have been found to kill roots in most crops of moderate climates, restricting root penetration and access to closer nutrients such as phosphorus.

3.3 Nutrient Cycling and Microbial Activity

The degradation of nitrogen in organic matter is done by microbes- this is the principal nutrient-cycling process. Their rates increase about 2 times per 10°C (Q_{10}) up to an optimum. Early spring cold soil inhibits microbes, and this can cause temporary nutrient deficiencies even insofar as the overall fertility is good.

Table 10. Cardinal Soil Temperatures for Selected Agronomic Crops

Crop	Minimum Germination Temp ($^\circ\text{C}$)	Optimum Growth Temp Range ($^\circ\text{C}$)	Maximum Survival Temp ($^\circ\text{C}$)
Wheat (<i>Triticum aestivum</i>)	3 - 5	15 - 25	35 - 38
Maize (<i>Zea mays</i>)	8 - 10	25 - 30	40 - 42
Soybean (<i>Glycine max</i>)	8 - 10	25 - 32	38 - 40
Cotton (<i>Gossypium hirsutum</i>)	14 - 16	28 - 34	42 - 45
Potato (<i>Solanum tuberosum</i>)	7 - 9	15 - 20	28 - 30
Note: Potato tuberization is severely inhibited above $20\text{-}22^\circ\text{C}$.			

4. Interactions with Varying Climatic Conditions

The interaction between inherent soil thermal properties and external climatic forcing creates distinct soil thermal regimes across different agro-ecological zones.

4.1 Arid and Semi-Arid Climates

These regions are characterized by high solar irradiance and low precipitation. Soils are typically dry with low organic matter.

- Thermal Behaviour:** C_v decreases with low moisture hence these soils vary widely on their daily temperatures. During the day, surface can heat quickly, up to 50-60°C and this temperature can kill seedling stems. During the night the retention of heat is poor thus leading to a sudden decrease in temperature.
- Crop Challenges:** The primary complaint is heating stress in the upper root zone and evanescence. High temperature difference between the hot surface and colder subsoil results in a high upward vapor flux, which pulls out more water in the soil.

4.2 Temperate and Cold Climates

These regions are defined by distinct seasons, with significant periods where air temperatures are below freezing.

- Thermal Behaviour:** Soils in spring are often wet due to snowmelt and seasonal rainfall. This high-water content increases volumetric heat capacity, meaning the soil requires substantial energy inputs to warm up.
- Crop Challenges:** It is not about hot weather, it is that the continuous heat accelerates the process of decomposing organic matter (carbon sequestration becomes difficult), and that there is a high pressure on soil-dwelling pests and pathogens which survive best in hot and wet soil.

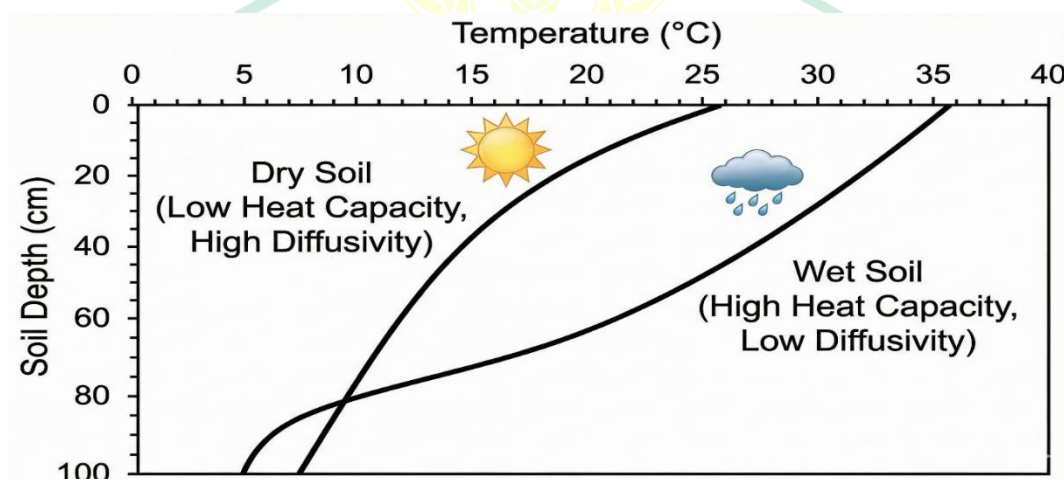


Figure 2. Soil Temperature Profiles under Varying Moisture Conditions

5. Management Strategies to Modify Soil Thermal Regimes

Farmers and agronomists can influence soil thermal properties through various management practices to mitigate adverse climatic impacts. The primary levers for manipulation are soil water content, surface cover (residue or mulch), and soil bulk density (tillage).

5.1 Mulching and Residue Management

Surface cover is the most effective tool for modifying the soil energy balance.

- Organic Mulches:** Straw or stover is like insulation- it is not very thermal conductive. In the hot climates they reflect the sunlight and make the surface of the soil cooler reducing the evaporation. Packed residue in the spring of cool climates may actually cause the soil to warm faster thus preventing the early-season crops to begin growing.
- Plastic Mulches:** Extremely widespread in the production of veggies. Crystalline plastic allows the shortwave light to pass through but blocks the longwave radiation (greenhouse effect), and thus the soil is heated quickly. Black plastic captures heat after which it is transferred to the soil through conduction, as well as it prevents weeds.

5.2 Tillage Practices

Tillage alters soil structure, bulk density, and surface roughness, all of which affect thermal properties.

- Conventional Tillage:** This is what loosens the soil, lowers bulk density, and produces air pores. It permeabilizes initially and desiccates surfaces, and dissects thermal conductivity. A dry and rough surface absorbs heat rapidly during the day then falls rapidly at night.
- No-Tillage (Conservation Tillage):** Leaves a greater amount of bulk density and residue on the surface. Un-tilled soils tend to be damper and colder during spring since the leftovers provide insulation and the added moisture enhances thermal capacity.

5.3 Irrigation Management

Since water is the principal factor governing both soil heat capacity and conductivity, irrigation is a powerful thermal regulator.

- Pre-planting Irrigation:** To keep the heat levels in hot areas reduced with a higher capacity to withstand heat, watering the soil prior to planting makes the soils less prone to temperature changes and provide the seedlings with a cooler and more stable environment to sprout.
- Frost Protection:** In areas with a temperate climate, humans irrigate in the lead-up to a forecasted freeze. Wet soil is more effective in retaining heat than dry soil and releases latent heat of freezing, which may save roots or crowns of lethal cold.

Table 11. Impact of Agronomic Practices on Soil Thermal Properties and Regimes

Agronomic Practice	Effect on Bulk Density	Effect on Soil Moisture	Net Thermal Impact on Soil	Best Application
Conventional Tillage	Decreases	Decreases (surface)	Faster surface warming in spring; greater diurnal fluctuation.	Cool climates needing rapid spring warmup.
No-Tillage with Residue	Maintains/Slight Increase	Increases	Slower spring warming; cooler summer temperatures; reduced diurnal fluctuation (insulation).	Hot/Arid zones to reduce heat stress; erosion-prone areas.
Clear Plastic Mulch	No direct effect	Conserves	Rapid soil heating via greenhouse effect.	High-value crops in cool regions requiring early harvest.
Organic Straw Mulch	No direct effect	Conserves	Insulation: keeps soil cooler in day, warmer at night.	Hot climates to prevent root zone heat stress.
Irrigation	Increases (transiently)	Increases	Increases heat capacity and conductivity; buffers temperature extremes.	Universal regulator for both heat stress and frost risk.

6. Conclusion and Future Perspectives

The important physical objects that determine the climatic conditions of energy around the roots are soil thermal characteristics. They are not merely passive constants, but they positively contribute to the ability of crops to grow. The interplay between the soil texture, moisture and sunlight concept makes the soil either welcoming or unfriendly towards plants.

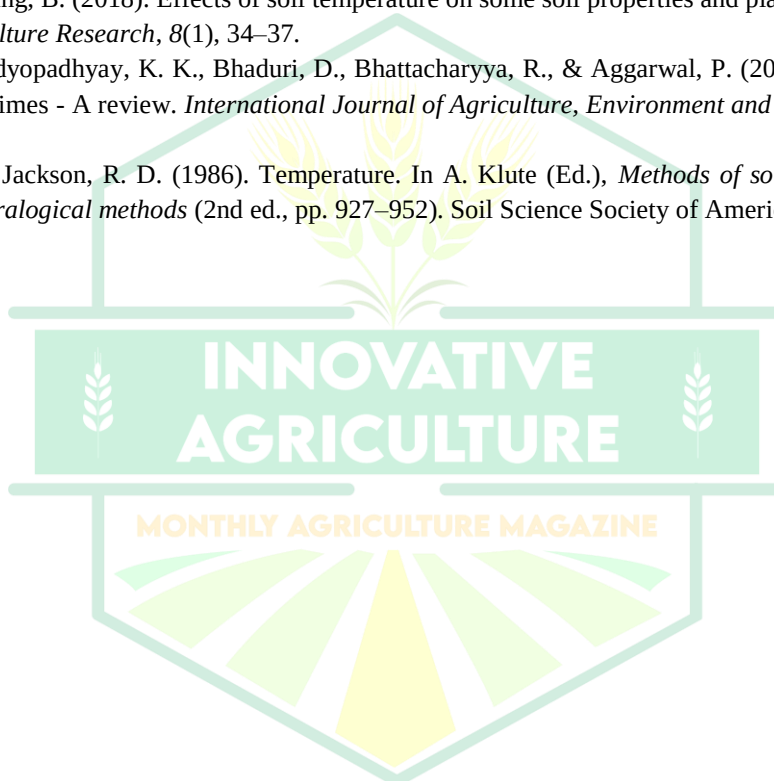
Trying to keep the one-size-fits-all suggestions old school because of the increasing unpredictability of weather due to climate change. We should have subtlety in the perception of the process of soil heating. As an example, no-till may be excellent at soil health during cool, wet springs, but may slow down the production of yields because it slows the soil warming, which is required to have dry land to plant. In hot dry regions, it is not

just the issue of preventing erosion that is of concern regarding management of residues, but it is rather a key to ensuring that the soil does not overheat.

The future studies need to develop elaborate and location-explicit soil thermal models incorporating weather forecast and real-time soil information to provide farmers with current information. They should also breed plants that have the capacity to withstand heat stress at the root level as opposed to the leaves. Finally, strong farming implies sustaining soils are not simply nutrient-containing containers, but rather fluid physical systems in which temperature and water cannot be separated.

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Assessment of Soil Fertility Status Using GIS and Remote Sensing Techniques for Precision Agriculture



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1. Introduction

Agricultural land use relies heavily on soil fertility for optimal production of plants and crop yields. The use of fertilizer applications historically has been based upon a composite sample taken across an entire field (the field) that represents an overall or average nutritional status of that field. An application of fertilizer is then made uniformly across the field. This method is very easy to implement; however, it completely neglects the inherent heterogeneity found in agricultural fields. These differences include variations in field topography, parent materials, past management techniques and past crops grown. As a result, there will be significant variation in the levels of some of the most critical indicators of soil fertility (e.g., pH, SOM, NPK).

Precision agriculture (PA), reconciles this paradox, by providing the "right" inputs in the "right" quantities; delivered in the "right" place; at the "right" time. For PA to be successful, it requires a spatial dataset that is both highly accurate and highly resolved. It is here that the integration of remote sensing (RS) with geographic information systems (GIS) can provide the necessary tools to obtain large datasets quickly; and to utilize a spatial analytical tool set to collect, analyze and present the spatial data to support decision making. This article reviews the methods used to evaluate spatial levels of soil fertility using these integrated technologies.

2. The Imperative of Spatial Soil Fertility Assessment

Based on what we discussed during lecture, soil fertility is not a fixed property, but rather a constantly evolving property in both time and space. The big three macro-nutrients (N, P, K), the secondary actors (Ca, Mg, S), and the microns that we do need to pay attention to (such as Zn, Fe, B) are the primary determinants of it. Next is the response of the soil (pH), the extent of organic matter that is in it (SOM) and the electric conductivity (EC) that indicates the amount of dissolved salts present.

These spatial variations in these values actually strike crop yield due to the Law of the Minimum: the increase in yield can only be as great as the increase in the scarcest nutrient. As an example, the phosphorus in a field may not be able to be absorbed by plants because even though the overall phosphorus level in the field is decent, there may be some areas with low pH. These areas of constraint are lost in the mean numbers unless a fine spatial evaluation is performed.

3. Remote Sensing Applications in Soil Analysis

The whole idea of remote sensing is to seize information on the surface of the Earth, but not to touch it, typically by detecting reflected or emitted light in various parts of the light spectrum. In the case of soil fertility, RS tends to operate in two fashions where by one either looks at the soil directly, or assumes information based on the plants that require the soil.

3.1 Direct Soil Observation

The physical and chemical makeup of a bare soil is much to be determined by the manner in which it reflects light. When the sun is exposed to the soil, not all the wavelengths are absorbed and others are reflected.

- a) **Soil Organic Matter (SOM):** Generally, soils with a higher organic matter appear darker and are less reflective in the visible and near-infrared (NIR) regions of the spectrum.
- b) **Soil Moisture:** As with SOM, increased moisture is likely to reduce the reflectance of the soil.
- c) **Soil Texture and Iron Oxides:** Clay and iron oxides and their presence bring about certain characteristics of absorption that we can see using hyperspectral sensors.

By this, however, we are typically restricted by the vegetation covering the ground and any remnants of the crop, thus direct observation is most effective when the area is fallow or when we are about to plant it.

3.2 Indirect Assessment

In most cases RS determines the soil fertility through observation of the state of crops. The spectral signature will be a healthy crop with sufficient nutrients: low reflectance in the visible red (due to the chlorophyll absorbing that light) and high reflectance in the NIR (due to the scattering light off the leaf structure).

By calculating Vegetation Indices (VIs) such as the Normalized Difference Vegetation Index (NDVI) the researchers can make guesses as to what the soil is actually doing under the plants. The low NDVI of a crop is likely to indicate that the crop is lacking nitrogen or is otherwise stressed in that area.

Courtesy: Shutterstock

THE ELECTROMAGNETIC SPECTRUM

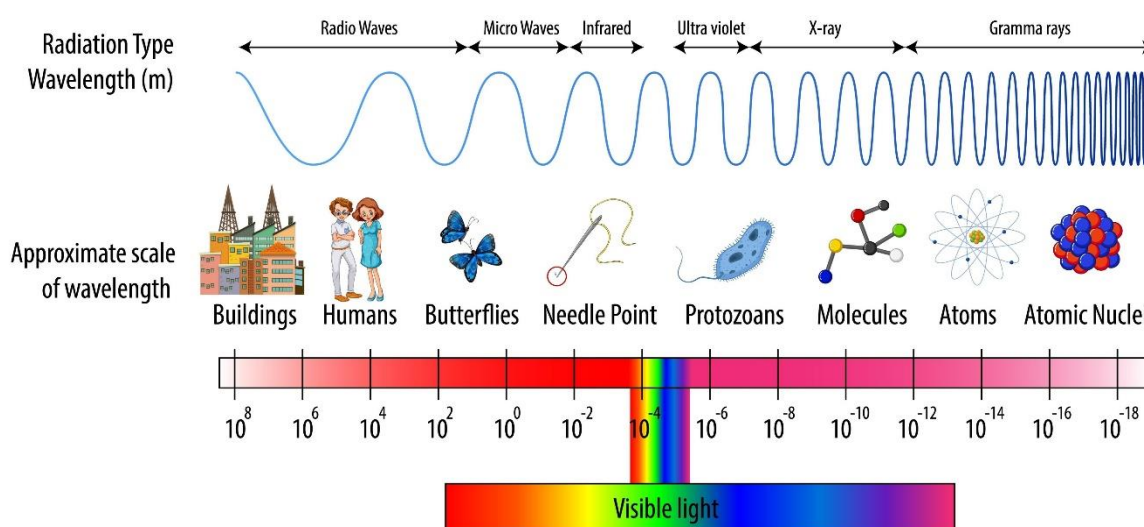


Figure 8. Generalized spectral reflectance curves illustrating the difference between healthy vegetation (high NIR, low red reflectance) and bare soil, which shows a more linear increase in reflectance. Variations in soil composition shift the soil curve vertical

In modern RS, a combination of tools, including freely available satellite data (such as Sentinel 2 and Landsat 8), which might be used to map time-consuming areas, to expensive high-resolution satellites, and even drones (UAVs) with multispectral cameras that can be used to study the farm on an incredibly local level.

4. Geographic Information Systems (GIS): The Analytical Engine

Remote sensing provides user with raw images but GIS provides processing power. GIS is a computer platform that is aimed at gathering, storing, editing, analysing, managing, and visualizing geographical information. GIS is the centre in which all the various layers of information combine in soil fertility work.

4.1 Data Integration and Management

A GIS allows user to overlay a collection of data that determines the fertility of the soil. When we have a common precision-ag project user might have the following layers:

- Digital Elevation Models (DEM) to determine the topography and slope, which influence the movement and runoff of water and nutrients.
- Soil type maps from legacy surveys.
- Remote sensing imagery (e.g., NDVI maps over several seasons).
- Previous yield monitor information.
- Point data from geo-referenced soil sampling.

GEODATA LAYERS

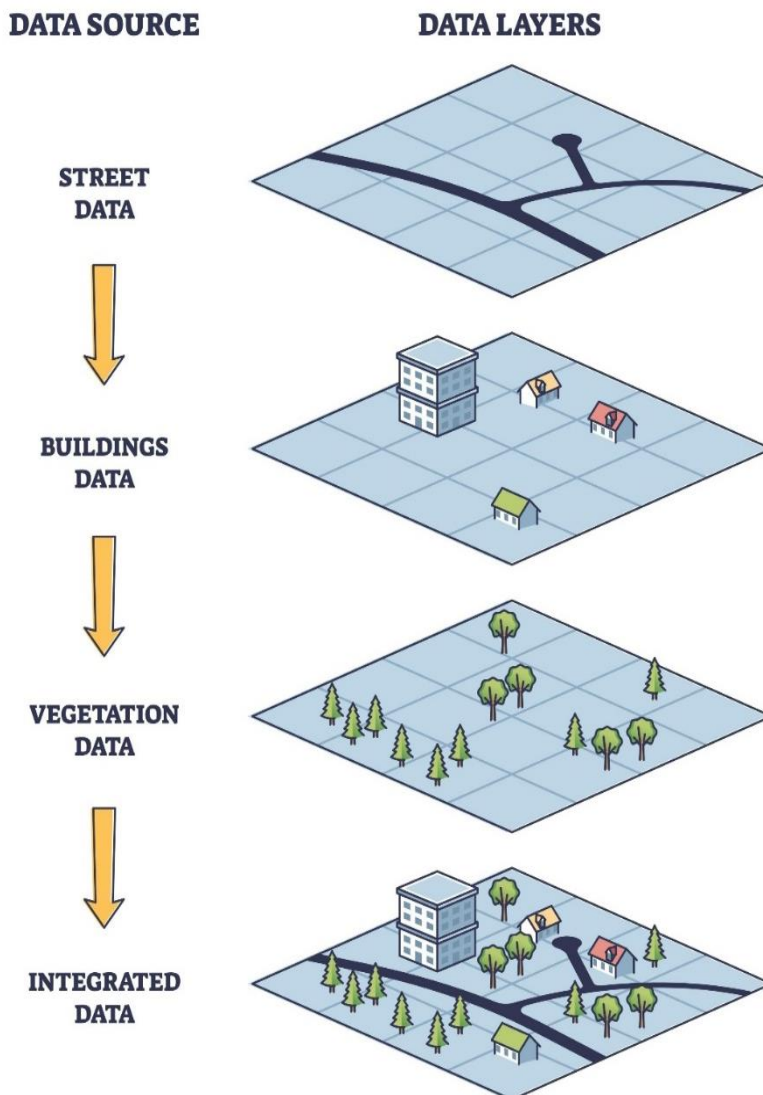


Figure 9. The GIS Layering Concept. Data from various sources satellite imagery, soil samples, topography, and yield data are stacked geographically to reveal relationships and patterns influencing soil fertility. (Source: Shutterstock)

4.2. Geostatistics and Interpolation

The primary contribution of GIS to the fertility analysis is the fact that discrete point data, which consists of soil samples collected at particular locations, becomes smoothed and continuous surfaces (maps). It is simply not feasible to sample out each square meter. This is why we apply geostatistical interpolation.

Other methods like Kriging or Inverse Distance Weighting (IDW) are used to estimate quantities at unmeasured points using the local known ones. The reason why kriging is particularly helpful is that it takes into consideration the spatial aspect of autocorrelation: similarity between soil properties located closer together than the ones located more distant. The final product is a raster map of each nutrient concentration.

5. Integrated Methodology for Fertility Assessment

Table 12. A Structured Workflow for GIS and RS-Based Soil Fertility Assessment

Phase	Step	Description	Technology Involved
1. Planning	Preliminary Survey	Collection of boundary data, historical cropping records, and existing maps.	GPS
	Sampling Design	Designing a geo-referenced sampling scheme (grid-based or zone-based) to ensure representative coverage.	GIS
2. Data Acquisition	Soil Sampling	Physical collection of soil samples at pre-determined GPS coordinates.	GPS, Field Tools
	Remote Sensing	Acquisition of satellite or UAV imagery (preferably multi-temporal).	Satellite/UAV Sensors
	Ancillary Data	Obtaining DEMs, yield data, etc.	Various Sources
3. Laboratory Analysis	Chemical Analysis	Analyzing soil samples for pH, EC, OC, N, P, K, and micronutrients using standard protocols.	Soil Testing Lab
4. Geospatial Analysis	Data Processing	Pre-processing RS imagery (atmospheric correction) and organizing lab data into databases.	Image Processing Software
	Spatial Interpolation	Using geostatistical models (e.g., Kriging) to create continuous maps from soil sample points.	GIS (Geostatistical Analyst)
	Data Integration	Overlaying interpolated soil maps with RS indices (NDVI) and topography to identify correlations.	GIS
5. Output & Application	Map Generation	Creating thematic fertility maps showing spatial distribution of nutrients.	GIS
	Zonation	Delineating Management Zones comprising areas with similar fertility characteristics.	GIS (Clustering Algorithms)
	VRA Prescription	Generating prescription maps for Variable Rate Application equipment.	Farm Management Software

6. Moving from Maps to Management Zones

The actual purpose of mapping spatial fertility is not merely to make a map beautiful but to cut out actionable Management Zones (MZs). MZs are minor sub-units of a field with relatively homogeneous combinations of yield-limiting factors and need management in the same way.

Instead of managing a 50-hectare field as one unit, GIS analysis might reveal three distinct zones:

- Zone A:** Large native fertility, large historical productivity. Strategy: Maintenance fertilizer.
- Zone B:** Moderate fertility, pH limitation. Strategy: Lime application and moderate fertilizer rates.
- Zone C:** infertile, sandy, low water-holding capacity. Strategy: Reduce the target yield and reduce input in order to maximise ROI.

These areas form the basis of Variable Rate Technology (VRT) whereby based on the GPS position of the tractor in relation to the GIS prescription map, smart spreaders are capable of adjusting the quantity of fertiliser (or lime) on a case-by-case basis.

Table 13. Comparison of Conventional vs. GIS/RS-Based Precision Approach

Feature	Conventional Agriculture	Precision Agriculture (GIS/RS Based)
Sampling Method	Composite sampling (random or zig-zag) providing one average value.	Grid or Zone sampling providing spatially referenced data points.
Data Resolution	Field-level average (low spatial resolution).	High spatial resolution, mapping variability within the field.
Input Application	Uniform, blanket application based on average needs.	Variable Rate Application (VRA) matched to local soil needs.
Efficiency	Low. Over-application in high-fertility areas; under-application in low-fertility areas.	High. Inputs go only where needed, optimizing crop response.
Environmental Impact	Higher risk of nutrient runoff and leaching from over-fertilized zones.	Reduced risk. Targeted application minimizes excess nutrients in the environment.
Economic Model	Focus on maximizing gross yield across the whole area.	Focus on maximizing profit per unit area (optimizing ROI).

7. Challenges and Future Directions

7.1. Limitations and Challenges

- a) **Cost and Complexity:** It is prohibitively expensive to the small-holder farmers in the form of high-resolution imagery, specialised software and the technical expertise required.
- b) **Ground Truthing Dependency:** Remote sensing is difficult to use unilaterally in regards to soil fertility. It primarily identifies spectral stand-ins (such as crop colour). A lot of soil sampling is required to calibrate RS data and confirm geostatistical models.
- c) **Temporal Variability:** A soil-fertility map is simply a snapshot. Nutrient concentrations, notably, nitrogen, change rapidly depending on weather and uptake of crops.

7.2. Future Directions

- a) **Hyperspectral Sensing:** Compared to multispectral sensors, which operate over 4-10 broad bands, hyperspectral sensors emit hundreds of narrow bands, and it allows us to identify particular biochemical imprints in the soil depending on the finesse absorption trends.
- b) **Proximal Soil Sensing:** Tractor mounted real time sensors that look at EC, pH, or NIR reflectance at any point in the field are now becoming common, reducing the amount of lab work required.
- c) **Machine Learning (ML) Integration:** ML algorithms are beginning to enter GIS to sort through large numbers of data (weather, multi-year satellite data, past yield) and forecast soil-fertility patterns more accurately than pure geostatistics.

8. Conclusion

The analysis of the soil fertility situation through the GIS and Remote Sensing methods is a breakthrough in the contemporary agronomy. These techs enable us to view the actual spatial variations within the farmland by abandoning the old field-average model. To map, monitor, and control nutrients at a pixel-level implies that we are now able to actually apply Precision Agriculture and perform Variable Rate Application as opposed to merely spraying all the things.

Certainly, the financial and technological sophistication still sting. However, the trend is obvious, there is a declining price of sensors, an increased ease of software, and it will not take long before spatial fertility assessment is considered normal. This focus is critical to increasing on-farm profits by reducing input waste, and also to facing the vast international demand of sustainable farming by reducing that ugly footprint of fertilizers.

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Impact of Climate Change on Soil Physico-Chemical Properties and Agricultural Sustainability



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1. Introduction

The soil health is completely related to the sustainability of world agriculture. Soil is not merely dirt; it is a kind of living ecosystem, which recycles nutrients, filters water, and stores carbon. And when we disregard that over the time-periods with which we are concerned, we are really wasting a non-renewable resource. The current climate change is the ultimate multiplier to soil degradation. Agricultural ecosystems continue to be extremely vulnerable as claimed by the IPCC. It is a two-way street: climate over geologic time changed soil, but at present climate is changing so rapidly that processes in soil are unable to keep up. Besides, whatever we do to the soil is actually returning to the climate through GHG fluxes.

It is important to know how climate change is playing around with the physical and chemical characteristics of soil in order to create resilient farms. The thing is: it is not a choice but a necessity of the future food security, proactive soil management.

2. Primary Climatic Drivers Affecting the Edaphic Environment

While atmospheric carbon dioxide (CO₂) enrichment directly affects plant physiology, the primary climatic drivers influencing soil properties physically and chemically are:

- Elevated Temperature:** Increases surface and subsurface temperature, accelerates reactions, microbes and evapotranspiration.
- Altered Precipitation Patterns:** Alters in the total precipitation, intensity and seasonality, that is, more drought and more flood.
- Extreme Weather Events:** More intense storms of a high frequency devastate soil surface energy structures.

3. Impact on Soil Physical Properties

These properties determine the mechanical behaviour of soil, water and air behaviour of the soil. Kinetic energy of water and heat is enormous determiners.

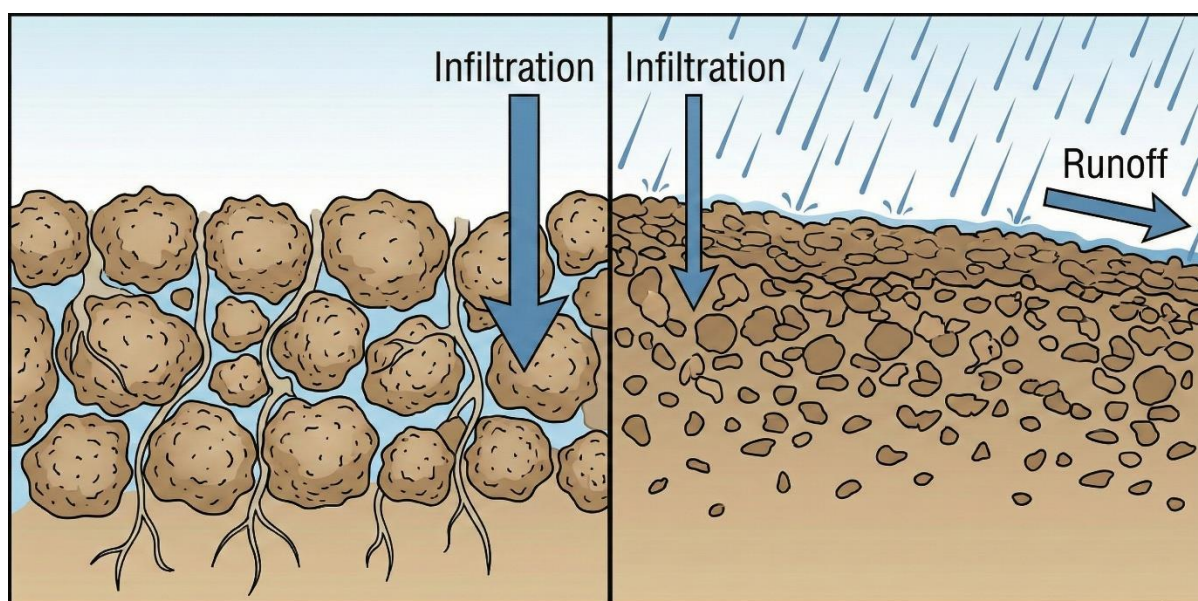
3.1 Soil Structure and Aggregation

Soil structure the arrangement of soil particles into aggregates is central to pore space distribution, root penetration, and aeration.

- Intense Precipitation:** Agglut fracture of aggregates due to kinetic energy deposited on the surface resulting in slaking. The small particles block pores, coat the surface, slow down infiltration, and increase runoff and erosion.
- Drought Conditions:** Extensive dry periods reduce the size of some clay lattices (Vertisols). A little cracking is good to allow the water to infiltrate as the soil again gets rained, and excessive drying causes the soil to become too hard resulting in tilling that is hard and the roots are constrained.

3.2 Soil Water Dynamics

- Reduced Water Holding Capacity (WHC):** Heat increases evapotranspiration; unless it is replenished by rain, water moisture is lost quickly, and deteriorated structure closes off macropores, thus the soil becomes unable to hold plant-available water.
- Waterlogging and Anaerobiosis:** Intensive rains flood the drainage, kill aerobic root respiration, and increase denitrifying bacteria, which expel nitrous oxide (N₂O) which is a gaseous of high emission.



Before Rainfall

After Intense Rainfall

Figure 1. Conceptual diagram illustrating the impact of high-intensity rainfall raindrops hitting soil aggregates, causing disintegration (slaking) and subsequent surface sealing, which reduces water infiltration

3.3 Soil Texture

While soil texture is generally considered a stable property over human timescales, climate change-induced erosion can alter topsoil texture selectively. Intense rainfall events preferentially transport finer particles (silt and clay) and organic matter downslope, leaving coarser, less fertile material behind in the upper horizons.

4. Impact on Soil Chemical Properties

The chemical environment of the soil dictates nutrient bioavailability and toxic element mobility. Temperature and moisture are master variables controlling these chemical and bio-chemical processes.

4.1 Soil Organic Carbon (SOC) Dynamics

The main measure of soil health is the SOC, balancing structure and nutrients. Climate forces the balance of carbon inputs (litter, root exudates) and outputs (microbial burn-down).

- **The Temperature Effect:** According to Arrhenius kinetics, hotter the temperature, the faster the enzymes increase; therefore, microbes can chew SOM at a quicker rate emitting CO₂ and in turn, there is a loop of feedback, which further warms the planet.
- **The Moisture Effect:** Microbes require water, excessively wet (anaerobic) depersonalizes them, excessively dry halts them as well. The largest SOC losses occur in zones that become both warmer and retain sufficient moisture permafrost thaw zones, and warming temperate locations.

4.2 Soil pH and Salinization

Changes in hydrology directly impact soil reaction (pH) and salt concentrations.

- **Acidification:** During the heavy rains in moist areas, the basic cations (Ca, Mg, K, Na) are washed away, reducing the base saturation and acidifying the soil. These fractures open toxic elements such as Al and Mn leaving them easier to plant tissues.
- **Salinization:** The drier the place, the higher the amount of evaporation is. That draws salty groundwater up, spills to the surface, evaporates and the salts accumulate forming osmotic stress, sodicity and deteriorating structure. Besides, the rising of the sea level transports the saltwater to the inland areas.

4.3 Nutrient Cycling and Bioavailability

Climate regulates the biogeochemical cycles of major plant nutrients like Nitrogen (N) and Phosphorus (P).

- **Nitrogen Mineralization:** Warming has an accelerating effect on the rate at which microbes convert organic N to plant-available forms. That works well in the short term, but when crops fail to absorb it at a rate that matches that of the crop, it may be washed away in water or be fixed in GHGs.
- **Phosphorus Availability:** P depends on the pH. It is bound by acidification to iron and alumina phosphates, such that when the total P is large, the plants are unable to access it.

Table 14. Matrix of Climatic Drivers and their Impact on Key Soil Chemical Properties

Climatic Driver	Soil Property Affected	Primary Mechanism	Consequence for Agriculture
Increased Temperature	Soil Organic Carbon (SOC)	Accelerated microbial respiration (decomposition).	Net loss of SOC; reduced fertility and water holding capacity.
	Nitrogen (N) Availability	Increased rate of N mineralization.	Potential short-term N boost, but high risk of nitrate leaching if not synchronized with crop uptake.
Increased Precipitation Intensity /	Soil pH (Humid Regions)	Leaching of basic cations (Ca^{2+} , Mg^{2+} , K^{+}).	Soil acidification; aluminium toxicity risk.
	Nutrient Status (General)	Physical removal of nutrients via runoff and deep leaching.	Nutrient depletion; increased fertilizer requirement; eutrophication downstream.
	Redox Potential (Waterlogging)	Anaerobic conditions promoting denitrification.	Loss of plant-available N; increased emissions of N_2O (greenhouse gas).
Decreased Precipitation / High Evaporation	Soil Salinity (Arid Regions)	Capillary rise of saline groundwater and surface evaporation.	Osmotic stress on crops; ion toxicity; soil structure degradation (sodicity).

5. The Nexus: Soil Health and Agricultural Sustainability

The degradation of soil physico-chemical properties under climate change is not an isolated environmental concern but a direct threat to the pillars of agricultural sustainability: productivity, economic viability, and environmental soundness.

5.1 Yield Penalties and Food Security: Soil unable to retain water loses nutrients and roots can no longer grow through it and this results in huge yield gaps. Plants on eroded soil are less resistant to climatic shocks. An example is a low SOC and bad soil structure will also attain permanent wilting point much quicker than a healthy one in case of drought event. That is a true threat to world food security particularly in the developing nations relying on rainfed agriculture.

5.2 Economic Implications When soil is degraded this implies that farmers will incur additional costs in inputs. The loss of natural fertility causes the increased utilization of synthetic fertilizers to maintain the yields and the increase of the amounts of energy-intensive tillage operations to prepare seedbeds. Besides, erosion will forever destroy the top soil, the hottest land capital, and this will reduce land value with time.

5.3 Ecosystem Service Disruption Other than food, agricultural soils also offer important ecosystem services. Poor quality soils do not absorb as well the pollutants of water and cannot control its floods as well and may even transform to net carbon sources. That is a risky feedback in the global climatic system.

6. Mitigation and Adaptation Strategies: Building Soil Resilience

The agri-systems must change with climate smart soil practices since the climate change is intractable. The objectives of these are to reduce GHG emissions and increase the resilience of the soil to climate stress. The main premise is the protection and improvement of Soil Organic Carbon (SOC).

6.1 Conservation Agriculture (CA)

CA is based on three principles: minimum soil disturbance (no-till or reduced till), permanent soil organic cover (crop residues or cover crops), and species diversification (rotations).

- **Mechanism:** Reduced tilling preserves soil aggregates and inhibits the oxidation of SOC. The retention of residues evenly the soil temperature, minimizes the evaporation process, and also protects the surface against the impact of rainfall, which reduces crusting and erosion.

6.2 Integrated Nutrient Management (INM) and Organic Amendments

Moving beyond sole reliance on synthetic fertilizers to include organic sources like manure, compost, and biosolids.

- **Mechanism:** Organic amendments increase the amount of carbon directly, enhance the stabilization of aggregates and enhance the water-holding capacity. They also increase the biomass of the microbes which are critical in the cycle of nutrients.

6.3 Biochar Application

Biochar is a stable, carbon-rich product of biomass pyrolysis (heating in low oxygen).

- **Mechanism:** Long-term carbon sequestration is provided by its great resistance to decomposition. Its porous nature enhances aeration and water retention and its big surface area and charge density have the potential to improve cation-exchange capacity (CEC) trapping nutrients and buffering acidification.

6.4 Agroforestry and Perennial Systems

Integrating trees into agricultural landscapes.

- **Mechanism:** Deep roots fix the soil layers and reach deep nutrient pools. Leaf litter adds a lot to SOC. The canopy reduces temperatures of the microclimate and decreases the surface temperatures on soil and the evaporation.

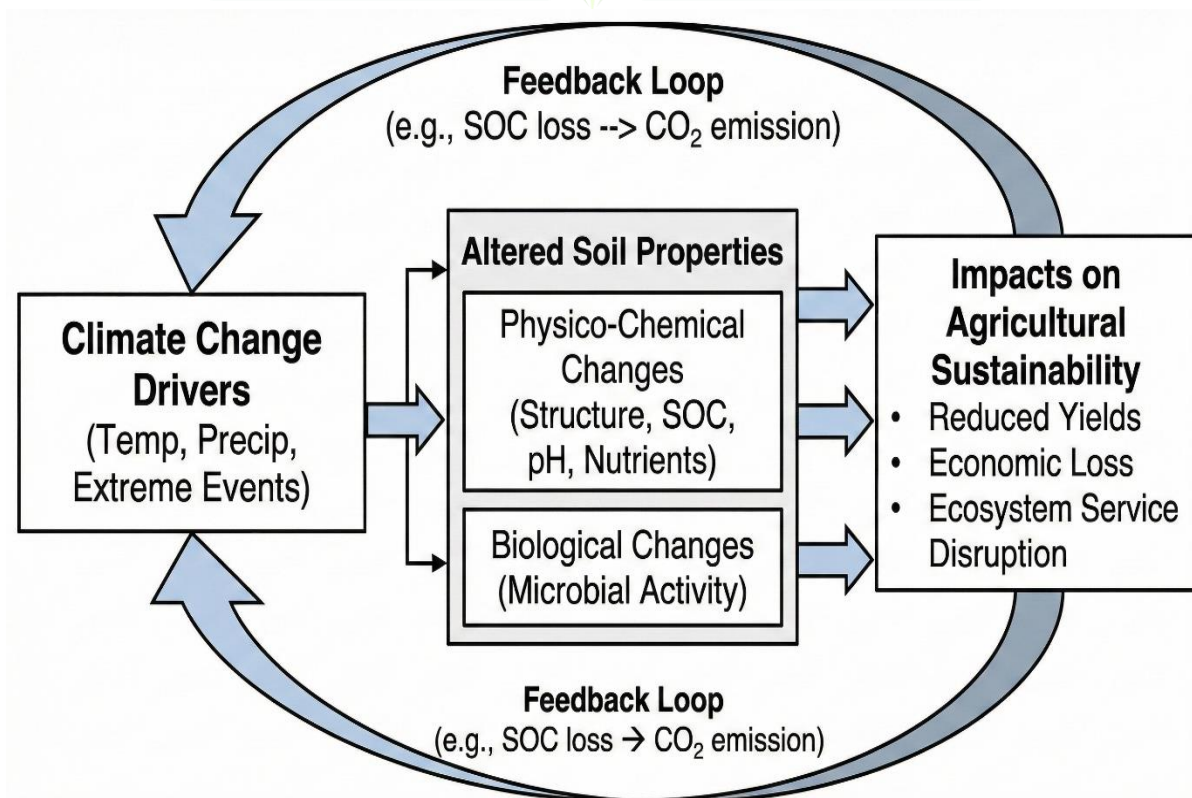


Figure 2. Conceptual framework illustrating the feedback loops between climate change drivers, alterations in soil physico-chemical properties, and the subsequent impacts on agricultural sustainability and ecosystem services.

Table 15. Adaptation Strategies for Enhancing Soil Resilience to Climate Change

Adaptation Strategy	Primary Target Soil Property Improvement	Secondary Benefits
Conservation Tillage (No-Till/Strip-Till)	Physical: Improved structure, reduced erosion, increased water infiltration.	Chemical: Slower SOC oxidation; Economic: Reduced fuel/labour costs.
Cover Cropping/Residue Management	Physical/Hydrological: Increased surface protection, reduced evaporation, better aggregation from root exudates.	Chemical: Addition of biomass Carbon; Nitrogen fixation (if legumes used).
Organic Amendments (Compost/Manure)	Chemical/Biological: Increased SOC, enhanced microbial activity and nutrient cycling.	Physical: Increased Water Holding Capacity (WHC) and lower bulk density.
Biochar Application	Chemical: Long-term C sequestration, increased Cation Exchange Capacity (CEC).	Physical: Improved porosity and water retention in sandy soils.
Improved Drainage/Irrigation Efficiency	Hydrological/Chemical: Prevention of waterlogging (reducing N ₂ O emissions) and salinization.	Physical: Maintenance of aerobic soil conditions for root health.

7. Conclusion

One of the issues facing the 21st century is climate change and soil resources. The fact is obvious: changes in climate are destroying the basic physical and chemical characteristics of soil, which underpin agriculture. An increase in temperature poses risks to the stocks of carbon contained in the soil and distorted rainfall interferes with soil structure and chemistry.

Maintaining the status quo of business, which is farming that worsens the soil, will increase the effects of climate, compromising food security and ecosystem security. A real way to go is to switch to regenerative, climate- smart practices which prioritize soil health first. Knowing the way the soils respond physically and chemically to the drivers of climate, agronomists and policymakers are able to develop systems that not only adapt to the changing world, but also contribute to alleviating the crisis by increasing the extent of carbon sequestration in the soils. The future of agriculture is literally beneath us in the strength of the pedosphere.

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ROLES AND RESPONSIBILITIES OF FARM WOMEN AND SCHEMES TO EMPOWER FARM WOMEN



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Abstract:

Rural women are the major stakeholder in agricultural sector Indian economy. Acknowledgement of rural women in access to resource, technology, education, health facilities, ownership rights improve Agricultural productivity and helps in building empowered nations. Ensuring gender equality in agriculture can help build a more sustainable foundation for future generations. Women's economic and educational empowerment can help improve food security, nutritional outcomes, and agricultural output. Strengthening women's land rights can increase their participation and access to resources. Women play a vital role in agriculture, especially in developing countries, where they produce a large portion of the world's food. Since Independence, several government flagship schemes and programs are initiated to improve rural women's stature in society by creating livelihood opportunities and engagements in paid employments. An estimated 52-75% of Indian women engaged in agriculture are illiterate, which is a significant education barrier that prevents women from access to agricultural information. On the fields and construction sites of Tamil Nadu women work restlessly, yet they are paid much less than what men earn for the same tasks. Providing education and training in agricultural practices, financial management, and entrepreneurship can help women become more confident and active in farming. Wage disparity persists, driven by deep seated social and economic biases. Whether planting paddy, mixing concrete, or working in shops, women consistently earn less, even when performing the same tasks as men. Further to support farm women's development, governments, organizations, and communities must provide accessible training and capacity-building programs. Promote gender-sensitive policies and legislation. We can improve rural areas by investing on farm women's development.

Key words : Farm women, MKSP, NRCWA, disparity in wages.

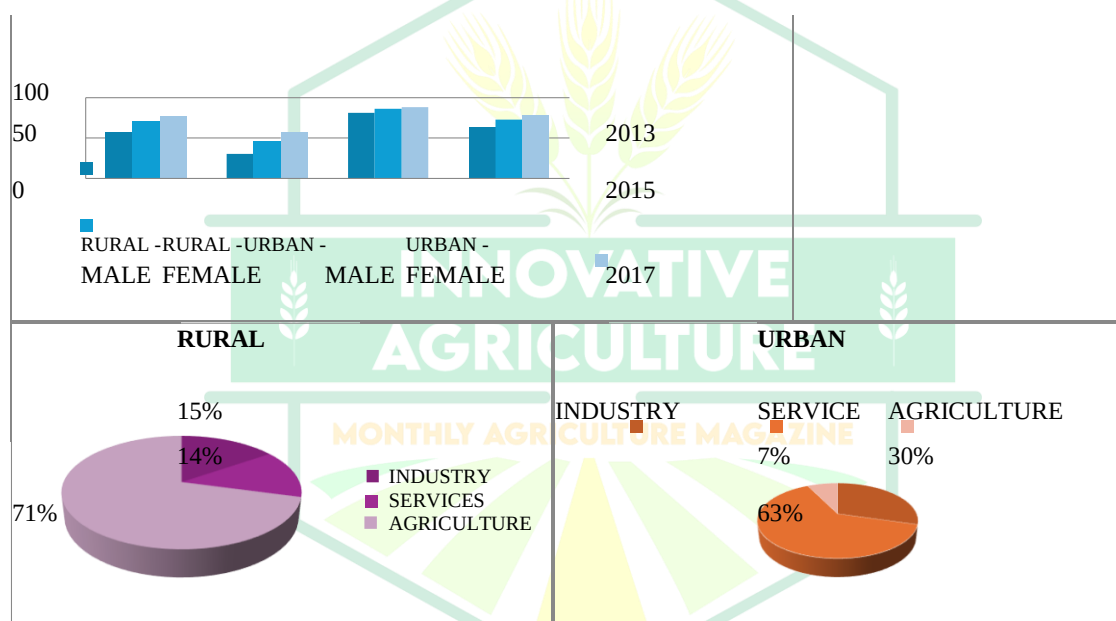
Introduction

As per the Annual Periodic Labour Force Survey (PLFS) Report 2021-22, the estimated percentage distribution of workers at All-India level in usual status by broad industry division as per National Industrial Classification (NIC) 2008 women contributes 62.9 % and male contributes 38.1 %. Women's are extensively engaged in the activities pertaining to agriculture and allied sectors. The work participation rate for rural females is significantly higher at 41.8 % against urban women participation rate of 35.31 %. Labour is a crucial input for many agriculture industries. For some farm operations like planting, weeding, pruning and harvesting require access to seasonal and migrant farmworkers. Women play vital role in agriculture, responsible for nearly half of the world's food production. In 2019, women made up 38% of Agricultural workers in primary production around the world. The national policy on farmers 2007 accorded high priority to Recognition and mainstreaming of women's role in agriculture and highlighted incorporation of 'Gender issues' in agriculture development agenda. In India, reforms are underlined for Holistic development of women, enabling socio economic and health security. Since Independence, several government flagship schemes and programs are initiated to improve rural women's stature in society by creating livelihood opportunities and engagements in paid employments.

Status of women in India

Women constitute half of the world's population and produce half of the agricultural products according to a UN report. This indicates the contribution of women in the economic prosperity of the nations, whose lifeblood is agriculture, through their participation in agriculture as cultivators, agricultural labourers and casual helpers. In spite of this, women suffer from womb to tomb in the male dominated society. It is known that 78 % of India's employed women work in agriculture. As per the Annual Periodic Labour Force Survey, 2021-2022, agriculture has the highest estimated female labour force participation of 62.9 %. The rural women in India are contributing to this sector for many years, but mostly as labourers in their own farms and not "farmers". Though they work hard for long hours, they get very less money leading to indebtedness. Yet they continue to depend on the landowners for employment and loans. Farmers, particularly women, face a high degree of economic, legal, and institutional uncertainties when investing in their land and other resources. Three quarter of women all over to world live in rural areas and work in agricultural sector and a wide range of related activities. World farmers day is celebrated on May 14th. National farmers day is celebrated during 12th of October. Participation of women in the workforce is only 13.9% in the urban sector. Women's wage rates are, on an average only 75 per cent of men's wage rates constitute only 25 per cent of the family income. In no Indian State women and men earn equal wages.

Literacy rate in India



Sectoral distribution of workforce of women 2018- 19

Source : iw wage.org

From the given data the women's in both rural and urban are lower than the male community in literacy rate due to less awareness. Considerably in urban more or less equal education is given to female. In India rural areas are mainly dependent on agriculture and allied activities. Urban areas mainly concentrate on service sector and contribute of nearly 75%.

Multi-dimensional works of farm women

Agriculture: Sowing, transplanting, weeding, irrigation fertilizer application, plant protection, harvesting, winnowing, storing etc.

Horticulture: In south India, women are involved in nursery technology, including nursery raising, irrigation, and application of manures and fertilizers. In north India, women are involved in fruit processing and kitchen gardening.

Domestic: Women are more likely than men to perform most household tasks, such as laundry, cleaning, cooking etc.,. Women are often responsible for caring for children and providing informal care to family members who are ill. Women's roles in the home are influenced by societal and cultural norms. They are also shaped by the need to acquire information on various aspects, such as child development, health care, diet, and nutrition.

Allied activities: Women perform many manual, labour- intensive tasks in agriculture, such as milking, cattle management, fodder collection. Women are responsible for more than 90% of fish marketing. Women perform unpaid allied activities, such as collecting vegetables, roots, firewood, and cattle feed, as well as sewing, tailoring, and weaving. Women perform tasks such as bathing and cleaning cattle, milking, cutting fodder, and collecting dung. Women perform tasks such as collecting and carrying fuel, fetching water, and preparing and storing dung cakes. Women maintain kitchen gardens. Women collect agricultural products for family consumption. Women market agricultural goods. Women play a key role in food security as food producers and providers. Sowing, Nursery management, Transplanting, Weeding, Irrigation, Fertilizer application, Plant protection ,Harvesting, winnowing, storing etc. are agricultural works taken by women.

Importance of women in agriculture

In order to eradicating poverty to ensure food security to increase their stake in agriculture to increase economic contribution ownership in land, livestock, etc. Women are a vital part of the global food production system, making up 41% of the world's agricultural workforce. Women perform many of the most labour- intensive tasks in agriculture, such as cattle management, milking, and threshing. Empowering women in agriculture can lead to economic growth. Women are key to social, economic, and environmental transformation. The World Food Programme estimates if women farmers had the same resources and opportunities as men, agricultural production could increase between 2.5 and 4% and the number of malnourished people would decrease 12 to 17%, lifting as many as 150 million people out of hunger and poverty. Ending hunger and poverty begins with supporting rural women. Women are often the main custodians of crop diversity, selecting, planting, and harvesting crops that are resilient to local climatic conditions. They are powerful community organizers who can drive impact at the farm and community levels. They play an essential role in the development of agriculture and rural sectors. Women play an important role in agricultural decision-making and the adoption of agricultural technologies. Agricultural diversification creates jobs for many women who can engage themselves in a productive manner.

Problems faced by farm women

Women often have limited access to land, finance, technology, education, training, and markets. They may also have difficulty accessing agricultural inputs like improved seedlings, fertilizers, pesticides, and machinery. Women in agriculture face gender-based violence. Women generally own less property than men, and their property rights are often less secure. This can lead to women making farming decisions that negatively impact their land productivity. Women often have major gaps in their agricultural education, such as a lack of education on equipment maintenance. These challenges include low self-confidence, lack of knowledge, limited access to information and technology, illiteracy, male dominance, no knowledge about improved technology, and lack of education. Women's agricultural work, both in the fields and at home, is often unpaid or undervalued. Women in India spend an average of 6 hours a day on unpaid work, compared to 52 minutes a day for men. This unpaid labour is not counted in economic statistics, leading to a skewed perception of their contributions to agriculture. An estimated 52-75% of Indian women engaged in agriculture are illiterate, which is a significant education barrier that prevents women from access to agricultural information. This lack of education and access to information limits their ability to invest in modern farming techniques, equipment, and inputs that can improve their yields and quality. It also limits their ability to obtain institutional loans from banks that usually consider land as collateral.

Opportunities for farm women

Education: Providing education and training in agricultural practices, financial management, and entrepreneurship can help women become more confident and active in farming. Although women make up the majority of rural smallholder farmers globally, they often face discrimination in terms of access to land, credit, inputs, and markets. Education can significantly contribute to empowering women to overcome these challenges and reach their full potential in the food system.

Land rights: Providing secure land tenure and legal protection for women's land rights can help empower women in agriculture. Women with secure land rights can increase crop yields, which can lead to better nutrition for the whole household. Women with land rights can invest more in their children's education, health, and welfare. They can stand up for their rights.

Financial services: Providing financial services tailored to women's needs can help empower women in agriculture. In India, a Reserve Bank of India study found that women with financial education were more likely to obtain loans from formal institutions, enabling them to invest in their farms and boost productivity.

Market access: Promoting access to markets and market information can help empower women in agriculture.

Gender equity: Promoting gender equity and addressing gender-based violence in agricultural settings can help empower women in agriculture. Women farmers can increase their yields by 20–30% if they have equal access to resources and opportunities. Gender equality can help reduce poverty and hunger. They can have more secure livelihoods.

Leadership: Empowering women as leaders and decision-makers in farming communities can make positive impacts for those communities. Social and economic networking can help women connect with each other, share knowledge, and develop skills. Equitable access to land, credit, technology, and markets can help women expand their agricultural enterprises and increase productivity.

Agricultural diversification: Agricultural diversification can create jobs for women and help them make a living. Diversification can improve the availability and accessibility of food for female-headed households. It can improve income from agricultural activities. It can reduce financial risk and mitigate price risk and fluctuations in outputs.

Marketing: There are opportunities in the marketing of agricultural produce. Farmers markets can help women farmers build confidence and leadership skills by interacting with customers and showcasing their products. Markets are a place for women farmers to build local connections with other vendors and consumers.

Climate resilience: Research shows that empowering women as leaders and decision-makers in farming communities can advance more climate-resilient agriculture. Climate-resilient farming models, like the Women-led Climate Resilient Farming (WCRF) model, help women make informed decisions about what to grow, consume, and sell. This can help them ensure their households have enough food and income.

Initiatives by government to empower farm women

The research efforts at the ICAR Institute have been made to relieve her of the drudgery by providing time and Labour saving tools. Vocational trainings are also being conducted, to impart skills to Undertake different avocations. In extension activities the woman is now the centre point and activities are being planned keeping her in view. Her enlightenment will change the face of rural India several programs started at the National Centre for women in agriculture and Krishi Vigyan Kendra are the right steps in this direction.

NRCWA

The National Research Centre for Women in Agriculture (NRCWA) has been functioning at Bhubaneswar, Orissa, for developing methodologies, for identification of gender implications in farming systems approach and to develop women specific technologies under different production systems. There are 16 ongoing research projects in the areas of gender study on agriculture and household economy, management of coastal agro-eco system, extension methods for farm women, standardization of women specific field practices, occupational health hazards, reducing drudgery of women in agricultural operations, improvement of farming system suited to farm women, eco-friendly pest management technologies for vegetables among farm women, evaluation of interactive learning modules, technological needs in empowering women in rural aquaculture, and improvement in storage practices of seeds and grains.

Mandate

- Research on gender issues in agriculture and allied fields.
- Gender-equitable agricultural policies/ programmes and gender-sensitive agricultural-sector responses
- Co-ordinate research on Women in Agriculture.

The guidelines of the various beneficiary oriented schemes of the Department of Agriculture & Cooperation and Farmers Welfare (DAC&FW), Ministry of Agriculture & Farmers Welfare provide that States and other

Implementing Agencies to incur atleast 30% expenditure on women farmers. These schemes include Support to State Extension Programmes for Extension Reforms, National Food Security Mission, National Mission on Oilseed & Oil Palm, National Mission on Sustainable Agriculture, Sub Mission for Seed and Planting Material, Sub-Mission on Agricultural Mechanization and Mission for Integrated Development of Horticulture.

Mahila Kisan Sashaktikaran Pariyojana (MKSP)

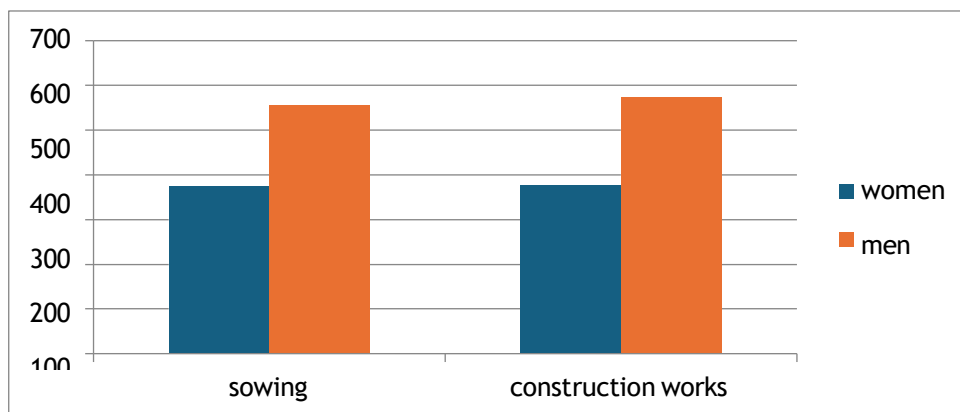
The Department of Rural Development, Ministry of Rural Development launched a specific scheme namely 'Mahila Kisan Sashaktikaran Pariyojana (MKSP)', as a subcomponent of DAY-NRLM (Deendayal Antyodaya Yojana — National Rural Livelihoods Mission). This scheme is being implemented since 2011 with the objective to empower women by making systematic investments to enhance their participation and productivity, as also create sustainable livelihoods for rural women. The program is implemented in project mode through State Rural Livelihoods Mission (SRLM) as Project Implementing Agencies. In order to familiarize women with the latest techniques in agriculture and allied sectors, trainings are being imparted to women farmers under schemes of DA&FW and DAY-NRLM. These include Support to State Extension Programmes for Extension Reforms (ATMA) under Sub-Mission on Agriculture Extension (SMAE). Skill training courses in agriculture and allied areas (of minimum 200 hours duration) are also being conducted for farmers including women farmers through National Training Institutes, State Agricultural Management & Extension Training (SAMETIs), Krishi Vigyan Kendras (KVKs) and State Agricultural Universities (SAUs), across the country. Under DAY-NRLM, the trainings on the agro-ecological practices are being provided through the community resource persons. KVKs established by Indian Council Agricultural Research (ICAR) impart training to farmers including women farmers on various aspects of agriculture and allied sectors. Government is taking various measures to increase the participation of women farmers in agriculture sector. This includes providing additional support and assistance to women farmers, over and above the male farmers under few schemes; provision of 30% of funds for women under various beneficiary oriented schemes/programmes.

State wise list for fund allocation by Mahila Kisan Sashaktikaran Pariyojana 2022-23

S.no	States	Target FY 2022-23	Achievement	18	Himachal Pradesh	25,000	68,819
1	Andhra Pradesh	9,00,000	6,23,934	19	Jammu & Kashmir	1,06,870	1,59,807
2	Assam	6,50,000	8,16,100	20	Punjab	35,940	41,726
3	Bihar	3,50,000	1,05,184	21	Uttarkhand	60,000	62,994
4	Chattisgarh	1,50,000	1,97,498	22	Arunachal Pradesh	50,000	24,566
5	Gujarat	4,00,000	5,24,298	23	Manipur	16,750	653
6	Jharkhand	1,25,000	1,86,198	24	Meghalaya	55,000	28,659
7	Karnataka	47,500	4,31,284	25	Mizoram	8,590	10,318
8	Kerala	83,500	39,032	26	Nagaland	27,000	16,674
9	Madhya Pradesh	3,40,000	4,04,111	27	Sikkim	4,000	5,225
10	Maharastra	8,00,000	8,92,972	28	Tripura	45,000	49,150
11	Odisha	1,20,000	6,71,682	29	Andaman & Nicobar	1,500	1,500
12	Rajasthan	2,00,000	2,19,441	30	Goa	600	2,081
13	Tamil nadu	3,00,000	3,00,000	31	Ladakh	1,000	0
14	Telungana	30,000	3,49,206	32	Lakshadweep	50	0
15	Uttar Pradesh	6,38,175	4,72,313	33	Puducherry	15,000	8,444
16	West Bengal	3,00,000	3,70,287	34	Daman DIU & NH	0	NA
17	Haryana	5,000	7,214	TOTAL		69,71,475	70,91,370

Source : Ministry of rural development.

Case study on disparity in wages in Tamil Nadu



Gender wages gap in Tamil Nadu 2023-24

On the fields and construction sites of Tamil Nadu women work restlessly, yet they are paid much less than what men earn for the same tasks. Wage disparity persists, driven by deep seated social and economic biases. Whether planting paddy, mixing concrete , or working in shops , women consistently earn less , even when performing the same tasks as men. Their contributions are undervalued and they are underpaid across sectors , discovers . The data from the State as well as Union governments highlight a clear gender pay gap, even when men and women perform similar tasks. Though Tamil Nadu has been a pioneer in introducing laws, including the Tamil Nadu Manual Workers (Regulation of Employment and Conditions of Work) Act, 1982, it has done little to address the gender pay gap. Sources in the Labour Department acknowledge that while district-level data on welfare measures for construction and agriculture k workers exist, reliable data on unorganised workers are lacking. The Equal Remuneration Act addresses gender pay equality in the organised sector, but there are no regulations for the unorganised sector. International rural women day is celebrated on October 15.

		MENS (in rupees)	WOMENS (in rupees)
Sowers and Pluckers of seedlings	Highest	₹853 (Chengapattu)	₹583 (Kancheepuram)
	Average	₹620	₹341
	Lowest	₹306 (Ranipet)	₹254 (Pudukottai)
Transplanters and weeders	Highest	₹711(Madurai)	₹496 (Kanyakumari)
	Average	₹545	₹328
	Lowest	₹335 (Theni)	₹254 (Pudukottai)
Reapersand harvesters	Highest	₹1034 (Tenkasi)	₹438 (Kanyakumari)
	Average	₹708	₹331
	Lowest	₹549 (Thiruvallur)	₹257 (Dharmapuri)
Other agricultural operations	Highest	₹867 (Chengalpattu)	₹600 (Kanyakumari)
	Average	₹656	₹350
	Lowest	₹510 (Dharmapuri)	₹249 (Dharmapuri)

Conclusion

Rural women are the major stakeholder in agricultural sector Indian economy. Acknowledgement of rural women in access to resource, technology , education , health facilities, ownership rights improve Agricultural productivity and helps in building empowered nations. The development of farm women is crucial for the growth and sustainability of rural communities. Empowering farm women through education, training, and access to resources has far-reaching benefits, includes Improved agricultural productivity and food security. Enhanced economic stability and independence. Better healthcare and nutrition for families. Increased participation in decision-making processes. Role modelling for future generations. To further support farm women's development, governments, organizations, and communities must: Provide accessible training and capacity-

building programs. Promote gender-sensitive policies and legislation. Enhance access to credit, markets, and technology. Foster supportive networks and mentorship opportunities. Celebrate and recognize farm women's contributions. By investing in farm women's development, we can unlock their potential, transform rural landscapes, and ensure a brighter future for generations to come.

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