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Beyond the myth: Why more organic matter isn't always better?



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In the quest for sustainable farming and climate mitigation, we often treat soil organic matter (SOM) like a universal bank account the more you deposit, the wealthier the soil becomes. However, the soil is not a passive storage locker; it is a living, breathing digestive system. Adding massive amounts of organic material to a field can sometimes act more like a sugar rush than a balanced meal, triggering a metabolic frenzy that actually burns through the soil's long-term carbon reserves.

To build a truly climate-resilient future, we must move past the "more is better" mantra and embrace the science of precision carbon management. This article explores why the volume of organic inputs is less important than the biochemical context in which they are applied.

1. The Metabolic Trap: When Fresh Inputs Burn Old Carbon

One of the most counterintuitive realities in soil science is the **Priming Effect**. When we add fresh, "tasty" organic matter such as green manures, compost, or crop residues it provides an immediate energy boost to soil microbes. However, this "kickstart" can be a double-edged sword.

- **Microbial Mining:** If the new organic matter is high in carbon but low in essential nutrients like nitrogen or phosphorus, microbes will produce extracellular enzymes to decompose the existing, high-quality humus to find the nutrients they need to process the new material.
- **Net Carbon Loss:** In certain conditions, this metabolic spike leads to a net loss of total carbon. Essentially, you are "mining" the soil's original fertility to handle the new additions.
- **Short-term vs. Long-term:** While the soil looks "active" in the short term due to high microbial respiration, the long-term stable carbon structures are being eroded.

2. The Ceiling of Sequestration: The Carbon Saturation Limit

Every soil type has a physical "ceiling" for how much carbon it can truly protect, known as its **Saturation Capacity**. This capacity is largely dictated by the soil's mineral architecture specifically its clay and silt particles.

- **Mineral-Associated Organic Matter (MAOM):** The most stable form of carbon occurs when organic molecules are chemically bonded to mineral surfaces. These bonds shield carbon from microbial decay for centuries.
- **Particulate Organic Matter (POM):** Once the mineral "docking sites" (clays) are fully occupied, any additional organic matter remains as "labile" or particulate carbon.
- **The Overload Risk:** Unprotected POM is highly vulnerable to rapid decomposition. Overloading the soil beyond its saturation point results in a massive spike of CO₂ emissions through respiration rather than a permanent increase in soil health. It is the difference between building a stone wall (MAOM) and piling up loose straw (POM); the latter may look substantial at first, but it vanishes with the first signs of microbial activity or temperature shifts.

3. The Microbial Carbon Pump and Efficiency

The transition from plant waste to stable soil is governed by **Microbial Carbon Use Efficiency (CUE)**. This is the ratio of carbon used for growth (building biomass) versus carbon lost to the atmosphere through respiration.

- **Anabolism vs. Catabolism:** Ideally, we want a "Microbial Carbon Pump" that is anabolic meaning microbes turn organic matter into their own cell walls and structures (necromass). This necromass eventually becomes a major component of stable soil carbon.

- **Respiration Spikes:** When soil is overloaded with poor-quality organic matter, microbes become "inefficient." They shift their metabolism toward catabolism (breaking things down for energy) to survive the nutrient imbalance, wasting carbon as greenhouse gas.
- **Community Shifts:** Consistent over-application can suppress beneficial, slow-growing microbes (like *Acidobacteria*) and favor fast-growing "opportunistic" bacteria that rapidly deplete soil nutrients and respire carbon quickly.

4. The Stoichiometric Constraint: The C:N:P Nexus

Soil health is governed by the laws of chemistry, specifically the **stoichiometric ratio** of Carbon, Nitrogen, and Phosphorus. Microbes require these elements in specific proportions (roughly 100:10:1) to function.

- **Nitrogen Immobilization:** Adding too much high-carbon material (like straw or wood chips) causes microbes to "steal" nitrogen from the soil to balance their diet, making it unavailable for crops.
- **Carbon-to-Nitrogen (C:N) Ratio:** If the C:N ratio of the input is too high, mineralization slows down, but the priming effect increases as microbes hunt for nitrogen.
- **The Balance:** Precision management ensures that organic amendments are "balanced" with the right nutrients to prevent the microbial community from depleting the soil's native reserves.

5. Physical Protection and the Role of Aggregates

Organic matter acts as the "glue" that holds soil particles together into aggregates. However, the "more is better" logic often ignores the stability of these aggregates.

- **Macro vs. Micro Aggregates:** Carbon is physically "hidden" inside small micro-aggregates where microbes cannot reach it.
- **The Disturbance Factor:** In intensively tilled systems, these aggregates are physically broken. If you add organic matter to a tilled field, the lack of physical protection means the carbon is exposed to oxygen and microbes, leading to rapid CO₂ release rather than sequestration.
- **Aggregate Stability:** The goal is to build "resilient" soil where the added organic matter facilitates the formation of water-stable aggregates that can withstand heavy rainfall and erosion.

6. The Temperature Sensitivity Paradox (Q10)

As global temperatures rise, the "more organic matter" strategy becomes even more complex.

- **The Q10 Factor:** This is the rate at which soil respiration increases with a 10°C rise in temperature. Soils with high amounts of labile organic matter (POM) often show higher temperature sensitivity.
- **The Warming Feedback:** If we pack soils with labile carbon that isn't mineral-protected, a slight increase in global temperature could trigger a massive "burp" of CO₂ from the soil back into the atmosphere, creating a dangerous warming feedback loop.
- **Focus on Stability:** Climate-resilient agriculture must focus on building stable, mineral-associated carbon that is less sensitive to temperature fluctuations.

7. Precision Solutions: Moving Toward Pedometric Modeling

Because the relationship between organic inputs and carbon storage is so site-specific, modern agriculture is shifting toward **Pedometric Mapping**.

- **Predictive Mapping:** By leveraging machine learning models, researchers can now predict a soil's current health and its future capacity for carbon sequestration with high accuracy.
- **Environmental Covariates:** These models use data like topography, rainfall, and historical land-use to create fine-resolution maps.
- **Surgical Application:** This allows land managers to identify which areas are "carbon-hungry" (low saturation) and which are "carbon-saturated." Instead of broadcasting compost across a whole farm, we can apply it where it will actually be sequestered, saving money and reducing emissions.

8. Conclusion: Quality over Quantity:

1. **Context is King:** Adding organic matter without considering the nutrient balance (C:N ratio) triggers the priming effect.
2. **Saturation is Real:** Soil has a limited number of mineral "docking sites" for stable carbon storage.

3. **Stability over Volume:** The goal of climate-resilient farming should be to build Mineral-Associated Organic Matter (MAOM), not just pile up labile waste.
4. **Digital Tools:** Machine learning and pedometrics are essential to guide precision applications and avoid carbon "waste."

By shifting our focus from quantity to **biochemical stability**, we can ensure that our efforts to "feed the soil" don't inadvertently fuel the climate crisis. True sustainability lies in the precision of the input, the health of the microbial community, and the physical protection of the carbon we strive to save.

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The Biological Engines: The Critical Role of Soil Enzymes in Soil Health



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In the silent, dark world beneath our feet, a high-speed chemical factory is constantly at work. While we often measure soil health through physical traits like texture or chemical traits like pH, the true heartbeat of the soil is biological. At the center of this biological vitality are soil enzymes the molecular "engines" that drive the recycling of nutrients, the decomposition of organic matter, and the overall resilience of the ecosystem.

Without these enzymes, the Earth would be buried under a mountain of undecomposed plant litter, and the nutrients required for plant growth would remain "locked" in complex molecular chains, inaccessible to the crops that feed the world.

1. What are Soil Enzymes?

Soil enzymes are biological catalysts, primarily produced by soil microorganisms (bacteria and fungi) and, to a lesser extent, by plant roots and soil animals. Unlike the microbes themselves, which can be sensitive to rapid environmental shifts, enzymes can sometimes persist in the soil matrix long after the organism that produced them has perished. They are often "stabilized" by attaching to clay particles or humic substances, allowing them to continue functioning as a legacy of the soil's biological history.

2. The Gatekeepers of Nutrient Cycling

The primary function of soil enzymes is to break down complex organic polymers into smaller, soluble units that plants and microbes can actually absorb. Each enzyme has a specific "lock and key" relationship with its substrate:

- **Carbon Cycling (Cellulase and β -Glucosidase):** These enzymes break down cellulose the most abundant organic compound on Earth into simple sugars. This process is the fundamental step in the "Microbial Carbon Pump," determining how much carbon is stored in the soil versus how much is released as CO₂.
- **Nitrogen Cycling (Urease and Protease):** These enzymes convert organic nitrogen (from proteins and urea) into inorganic forms like ammonium. This is a critical service for agriculture, as it dictates the "nitrogen availability" for crops without the need for excessive synthetic fertilizers.
- **Phosphorus Cycling (Phosphatase):** Phosphorus is often "stuck" in organic forms in the soil. Phosphatase enzymes clip the phosphate groups off organic molecules, making this vital nutrient available for plant energy transfer and DNA synthesis.

3. Enzymes as "Early Warning Systems"

One of the most valuable aspects of soil enzymes is their role as sensitive indicators of soil health. Because enzymes respond much faster to land-management changes than total organic matter does, they serve as an "early warning system" for soil degradation or recovery.

- **Impact of Tillage:** Intensive plowing physically disrupts the soil niches where enzymes are stabilized, often leading to a sharp decline in enzyme activity and a subsequent "starvation" of the soil food web.
- **Chemical Stress:** The over-application of pesticides or heavy metals can inhibit enzyme functions. For example, high levels of copper or lead can "denature" enzymes, effectively shutting down the nutrient factory.
- **Restoration Success:** Conversely, when a farmer adopts cover cropping or reduced tillage, an increase in phosphatase or urease activity is often the first measurable sign that the soil is healing.

4. The "Stoichiometric Balance" and Microbial Hunger

Microbes are strategic. They do not produce enzymes for free; it costs them energy and nitrogen. This leads to the concept of **Enzymatic Stoichiometry**. If a soil is low in phosphorus but high in carbon, microbes will pour their energy into producing *phosphatases* to "mine" the soil for phosphorus.

By measuring the ratios of different enzymes (e.g., the ratio of carbon-acquiring enzymes to phosphorus-acquiring enzymes), scientists can determine exactly what the "soil hunger" is. This allows for precision management, where amendments are added not based on guesswork, but on the metabolic demands of the soil life.

5. Climate Change and Enzyme Kinetics

Climate change is altering the "operating temperature" of soil enzymes. As global temperatures rise, the rate of enzyme-catalyzed reactions generally increases, which can lead to faster decomposition of soil organic carbon. This creates a potential feedback loop: warmer soils lead to more active enzymes, which release more CO₂, further warming the planet. Understanding the **temperature sensitivity** of these enzymes is now a frontier in climate-resilient agriculture, as we seek ways to stabilize enzymes and protect carbon stocks in a warming world.

6. Role of Soil Enzymes in Sustainable Agriculture

Soil enzymes are central to achieving sustainability in agriculture:

- **Reduced Dependence on Chemical Fertilizers:** Efficient enzyme activity ensures natural nutrient mineralization, reducing external inputs.
- **Improved Soil Fertility:** Continuous enzymatic processes enhance nutrient cycling and soil structure.
- **Support for Organic Farming:** Organic amendments such as compost and farmyard manure stimulate enzyme production.
- **Enhanced Crop Productivity:** Healthy enzyme activity ensures a steady nutrient supply, directly influencing yield and crop quality.

7. Indigenous Knowledge and Soil Biology

Traditional farming systems in India have long recognized the importance of soil biological activity, even without scientific terminology:

- Use of Jeevamrit, Beejamrit, and Panchagavya enhances microbial and enzymatic activity.
- Mixed cropping and crop rotation naturally stimulate diverse enzyme production.
- Application of organic residues and mulching maintains enzyme-friendly environments.

Integrating modern enzymology with indigenous knowledge systems can lead to more resilient and sustainable farming practices.

8. Factors Influencing Soil Enzyme Activity

Soil enzyme activity is not constant; it is highly dynamic and influenced by multiple environmental and management factors:

- **Soil Moisture:** Adequate moisture enhances enzyme mobility and substrate availability. However, waterlogging can create anaerobic conditions, reducing enzyme efficiency.
- **Temperature:** Each enzyme has an optimum temperature. Moderate warming increases activity, but extreme heat can denature enzymes.
- **Soil pH:** Most enzymes function best in near-neutral pH. Highly acidic or alkaline soils can inhibit enzymatic reactions.
- **Organic Matter Content:** Soils rich in organic matter provide both substrates and habitats for enzyme-producing microbes.
- **Soil Texture:** Clay soils often stabilize enzymes better than sandy soils due to adsorption onto mineral surfaces.

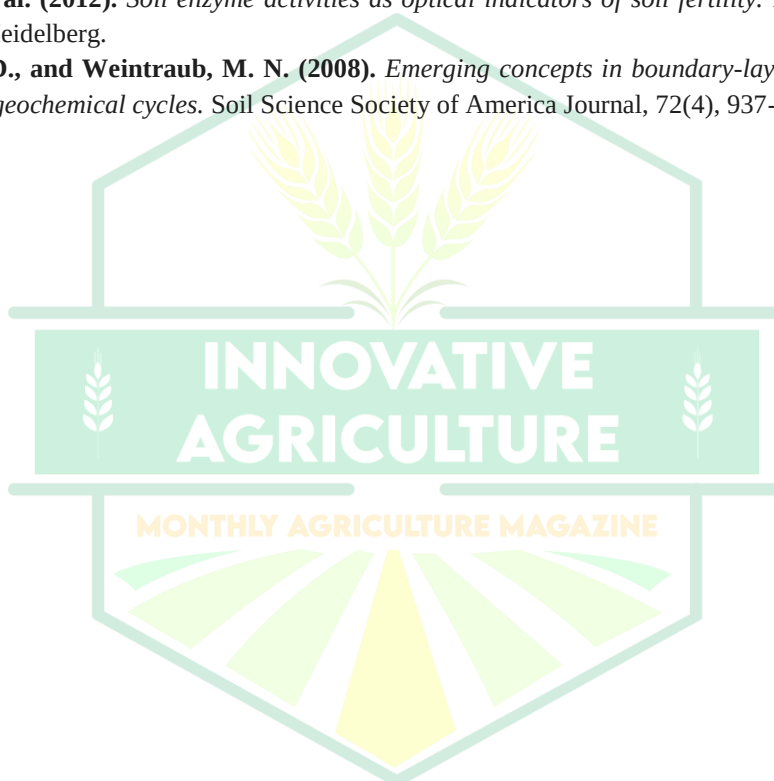
8. Conclusion: Managing the Invisible

Soil health is more than just a list of nutrients on a lab report; it represents the soil's capacity to sustain life. Soil enzymes are the key drivers of this capacity, regulating nutrient availability, organic matter decomposition, and overall ecosystem functioning. Their activity reflects the true biological vitality of soil and serves as an important indicator of long-term fertility. For farmers, researchers, and policymakers, protecting these biological engines is essential. Practices such as maintaining diverse plant cover, minimizing soil disturbance, and applying balanced

organic inputs help sustain enzyme activity and improve soil productivity. These approaches not only support crop yields but also reduce reliance on chemical inputs and enhance sustainability. In the context of climate change and land degradation, soil enzymes also play a critical role in carbon cycling and ecosystem resilience. Promoting their activity through sustainable and regenerative practices can support soil restoration and environmental stability. Ultimately, managing soil enzymes means nurturing the living system beneath our feet. Strengthening this biological foundation is vital for ensuring food security, sustainable agriculture, and long-term ecological balance.

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Soil Health as a “Sponge”: Preventing the Next Great Flood



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Abstract

The intensification of the global hydrological cycle, fueled by climate change, has led to an increase in the frequency and severity of extreme precipitation events. While much of the engineering focus for flood mitigation remains on "grey infrastructure" like dams, levees, and drainage canals, there is a growing scientific consensus that the most effective tool for managing excess water lies beneath our feet. The concept of the "Soil Carbon Sponge" describes the capacity of healthy, carbon-rich soil to absorb, store, and slowly release water, acting as a natural buffer against both floods and droughts. Understanding the mechanisms behind this sponge effect is critical for developing land-management strategies that ensure regional safety in an era of climatic instability.

1. Introduction

Flooding has become one of the most serious environmental challenges in recent decades, largely due to climate change and unsustainable land-use practices. The intensification of the global hydrological cycle has led to irregular rainfall patterns, characterized by prolonged dry periods followed by intense and sudden precipitation events. These extreme conditions often exceed the capacity of conventional flood-control systems such as dams, levees, and drainage networks. While such grey infrastructure is expensive, resource-intensive, and often inadequate under extreme climatic stress. As a result, there is increasing recognition of the need for sustainable, nature-based solutions that can complement traditional engineering approaches in managing water effectively.

One of the most promising natural solutions lies in improving soil health. Soil is a complex, living system that plays a crucial role in regulating water movement within ecosystems. Healthy, carbon-rich soils function like a sponge, absorbing, storing, and gradually releasing water, thereby reducing surface runoff and minimizing flood risks. In contrast, degraded soils affected by excessive tillage, deforestation, and poor management lose their structure and become compacted, leading to reduced infiltration and increased runoff. By enhancing soil organic carbon and promoting better soil structure, it is possible to significantly improve water retention, support groundwater recharge, and maintain moisture availability during dry periods. Thus, soil health offers a sustainable and cost-effective approach to addressing both flooding and water scarcity, making it a key component of climate-resilient land management.

2. The Architecture of the Sponge: Beyond Dirt

To understand how soil prevents flooding, one must differentiate between "dirt" (mineral sand, silt, and clay) and "soil" (a living matrix of minerals and organic matter). In degraded landscapes, soil particles are often dispersed and compacted. When heavy rain hits such surfaces, the water cannot penetrate; instead, it becomes surface runoff, carrying topsoil into rivers and contributing to rapid downstream flooding.

In contrast, healthy soil is structured into stable aggregates. Soil organic matter (SOM) acts as a biological "glue," primarily through the secretion of glomalin by arbuscular mycorrhizal fungi and various bacterial polysaccharides. These glues bind mineral particles into crumbs or aggregates, creating a network of pores.

- **Macropores:** These large channels, often created by earthworms and decaying root systems, allow for rapid infiltration during the initial stages of a heavy downpour, moving water away from the surface and into the subsurface.
- **Micropores:** These tiny spaces within aggregates hold water against the pull of gravity through capillary action. This is where the "storage" happens, keeping moisture available for plants long after the rain has stopped.

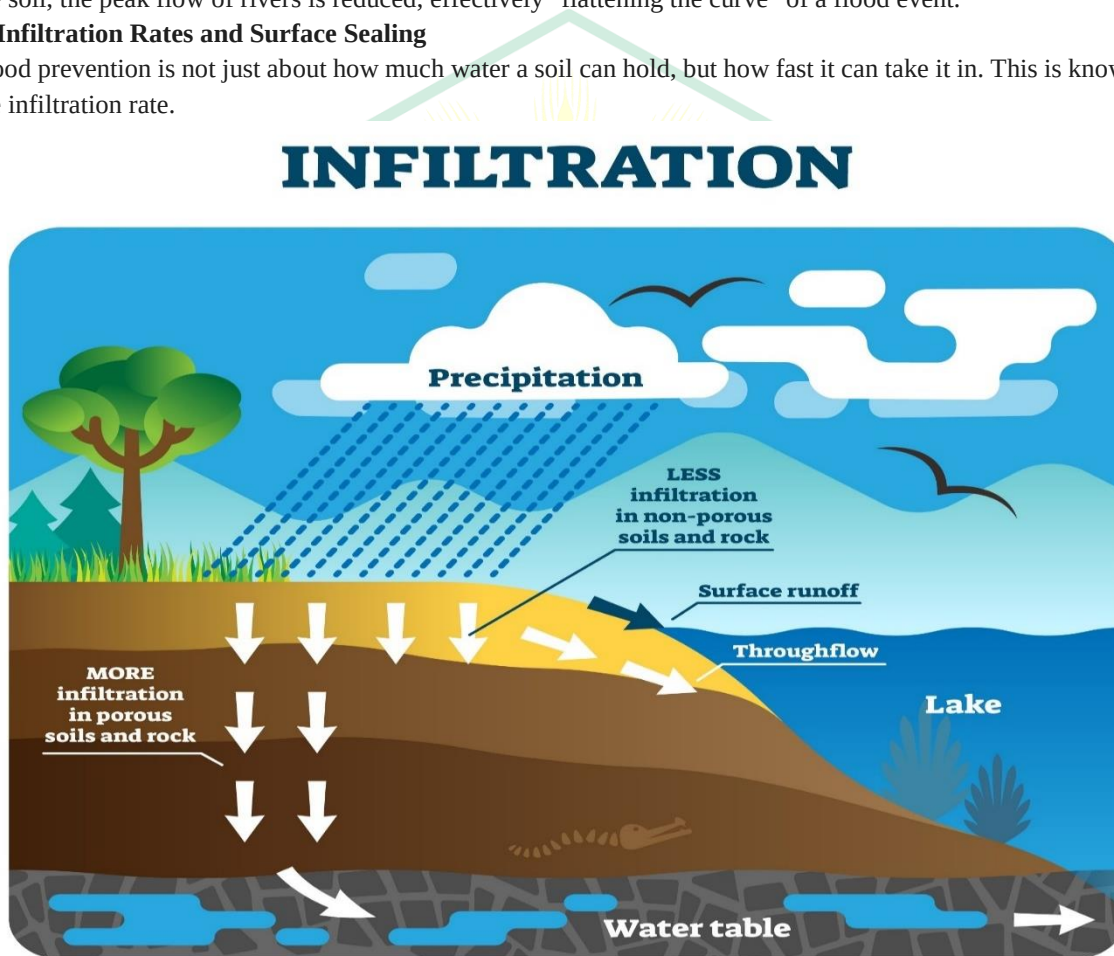
3. The Quantitative Power of Carbon

The relationship between soil organic carbon (SOC) and water-holding capacity (WHC) is one of the most powerful levers in environmental management. A widely cited benchmark in soil science suggests that for every 1% increase in SOC, the soil can hold an additional 20,000 to 25,000 gallons of water per acre.

This capacity transforms the landscape's hydrology. In a watershed where the soil is "carbon-hungry," a four-inch rain event might lead to immediate saturation and catastrophic runoff. However, in a watershed managed for high SOC, that same volume of water is absorbed into the soil profile. By increasing the "residence time" of water in the soil, the peak flow of rivers is reduced, effectively "flattening the curve" of a flood event.

4. Infiltration Rates and Surface Sealing

Flood prevention is not just about how much water a soil can hold, but how fast it can take it in. This is known as the infiltration rate.



- **The Crust Effect:** On degraded or tilled soils, the impact of raindrops physically breaks apart surface aggregates, creating a "seal" or crust. This seal acts like a layer of concrete, forcing even moderate rain to stay on the surface as runoff.
- **The Sponge Protection:** Healthy soil is usually protected by a layer of organic mulch or cover crops. This layer dissipates the kinetic energy of raindrops, preventing surface sealing and maintaining high infiltration rates throughout a storm.

Research indicates that a healthy "sponge" can maintain infiltration rates that are ten to one hundred times higher than those of compacted or conventionally tilled soils. This massive difference is often the deciding factor between a manageable rain event and a localized disaster.

5. Soil Health as a Buffer for Baseflow and Drought

The "sponge" metaphor extends beyond the flood itself. A sponge that is full of water eventually drips. In geological terms, this is the slow recharge of groundwater and the maintenance of baseflow in streams.

When a landscape loses its sponge capacity, it experiences a "yo-yo" effect: immediate flooding during rain followed by the rapid drying of streams during dry spells. By storing water in the soil matrix, healthy land management ensures that water is released slowly into the subsoil and aquifers. This keeps rivers flowing during droughts and prevents the total collapse of local water tables. Thus, soil health is the rare climate solution that mitigates two opposite disasters flooding and water scarcity simultaneously.

6. Management Strategies for Building the Sponge

Building a soil sponge requires a departure from "extractive" agriculture and a shift toward "restorative" practices. To maximize water retention, management must focus on four pillars:

- **Minimizing Disturbance:** Reducing or eliminating tillage preserves the delicate network of pores and fungal hyphae that facilitate water movement.
- **Continuous Living Roots:** Living roots provide a constant supply of carbon (exudates) to feed the microbes that build soil structure.
- **Biodiversity:** A diverse range of plants leads to a diverse range of root depths and microbial communities, creating a more complex and resilient sponge architecture.
- **Cover Cropping and Mulching:** Keeping the soil covered prevents the "surface sealing" mentioned earlier and reduces evaporation, keeping the sponge "primed" for the next rain event.

7. Scaling Up: The Watershed Perspective

While individual farmers can improve the sponge on their own land, the true power of this concept is realized at the watershed scale. If an entire valley or mountain range is managed for soil health, the cumulative impact on downstream flood risk is immense.

Pedometric mapping and machine learning are now being used to identify "critical source areas" specific parts of a landscape that contribute the most to runoff. By targeting these areas for soil restoration (e.g., converting steep slopes to silvopasture or restoring riparian buffers), policymakers can achieve flood-mitigation results that would otherwise cost billions in concrete infrastructure.

8. Conclusion: The Living Infrastructure

The "Soil Carbon Sponge" is not a passive feature of the landscape; it is a living infrastructure that requires constant maintenance through biological activity. As we face a future of increasingly unpredictable "great floods," the most resilient strategy is to restore the natural absorptive capacity of our land. By investing in soil health, we are not just improving crop yields; we are building a continental-scale buffer that protects our cities, our rivers, and our future.

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Integrated Plant Disease Management: A Sustainable Approach for Crop Protection



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Introduction

Plant diseases are caused by both biotic and abiotic agents that adversely affect plant health. Biotic agents include organisms such as fungi, bacteria, viruses, viroids, virus-like organisms, phytoplasmas, protozoa, nematodes, and parasitic plants. Abiotic factors, on the other hand, involve unfavorable environmental conditions such as deficiency or excess of nutrients, moisture, and light, as well as the presence of toxic chemicals in air or soil.

A plant disease may be defined as a series of harmful physiological processes caused by continuous irritation of the plant by a primary agent, or as a physiological or structural imbalance induced by external factors. In essence, plant disease results in structural abnormalities, physiological disorders, or both, which may affect the entire plant, its parts, or its products, ultimately reducing their economic value.

Traditionally, plant disease control has relied heavily on chemical pesticides. However, excessive and indiscriminate use of these chemicals has led to several problems, including the development of pathogen resistance, environmental pollution, and potential risks to human health.

To address these challenges, the concept of Integrated Plant Disease Management (IDM) has emerged as a sustainable and eco-friendly approach. Derived from the principles of Integrated Pest Management (IPM), IDM involves regular monitoring (scouting) and the timely application of a combination of strategies. It emphasizes the coordinated use of cultural, biological, physical, and chemical methods in a holistic and scientifically informed manner to effectively manage plant diseases while minimizing negative impacts.

Concept and Definition of IDM

Integrated Plant Disease Management is a decision-based approach that involves the strategic integration of various compatible techniques to manage plant diseases effectively, economically, and with minimal environmental impact.

Rather than eliminating pathogens completely, IDM aims to maintain disease levels below economic threshold levels, ensuring sustainable crop production. It involves continuous monitoring, proper diagnosis, and timely intervention.

The approach is characterized by:

- Simultaneous management of multiple diseases
- Regular monitoring of pathogens and their natural enemies
- Judicious use of chemicals based on economic thresholds
- Integration of multiple complementary control measures

Biological Basis of IDM

The effectiveness of IDM is rooted in fundamental plant pathology concepts, particularly the plant disease triangle, which includes:

- Host (susceptible plant)
- Pathogen (disease-causing organism)
- Environment (favorable conditions)

Disease develops only when all three components interact favorably. IDM works by disrupting one or more of these components, thereby preventing disease development.

Additionally, IDM targets different stages of the disease cycle, such as survival, inoculum production, dispersal, infection, and colonization, to minimize disease spread.

Principles of Plant Disease Management

IDM is based on six fundamental principles of disease control:

1. Avoidance

Avoidance prevents disease by selecting a time of the year or a site where there is no inoculum or where the environment is not favorable for infection.

2. Exclusion

Exclusion prevents the introduction of inoculum. It is legal restriction of the movement of agricultural commodities for the purpose of exclusion of plant disease in uninfected areas. It can be achieved by Seed treatment, Inspection and certification and Quarantine.

3. Eradication

Eradication eliminates, destroy, or inactivate the inoculum.

4. Protection

Protection prevents infection by means of a toxicant or some other barrier to infection. It involves physical and chemical control methods.

5. Resistance

Resistance utilizes cultivars that are resistant to infection.

6. Therapy

Therapy cures plants that are already infected. It involves chemotherapy and thermotherapy.

These principles form the backbone of all IDM strategies.

Factors Affecting Disease Development

Plant disease occurrence depends on both **biotic and abiotic factors**.

Biotic factors include pathogens such as fungi, bacteria, viruses, and nematodes. These organisms infect plants by producing enzymes or toxins that disrupt normal physiological processes.

Abiotic factors include environmental conditions like temperature, moisture, soil pH, nutrient imbalance, and pollutants. These factors can directly or indirectly influence disease development.

For disease establishment, several conditions must be met:

- Presence of viable inoculum
- Effective dispersal mechanisms (wind, water, insects)
- Entry through wounds or natural openings
- Availability of nutrients within the host plant

Components of Integrated Disease Management

1. Cultural Methods

Cultural practices are the foundation of IDM and aim to create unfavorable conditions for pathogens while promoting plant health. These include crop rotation, sanitation, proper spacing, irrigation management, and balanced fertilization.

Practices such as deep ploughing, flooding, and fallowing help reduce soil-borne pathogens by disrupting their survival cycle.

2. Biological Control

Biological control involves the use of beneficial microorganisms such as *Trichoderma*, *Pseudomonas*, and *Bacillus* species to suppress pathogens. These organisms act through mechanisms like competition, antibiosis, and induced resistance, enhancing soil health and sustainability.

3. Physical Methods

Physical methods include techniques like hot-water seed treatment, soil solarization, and removal of infected plant parts. These methods are particularly useful in controlling seed-borne and soil-borne diseases without chemical inputs.

4. Host Plant Resistance

The use of disease-resistant varieties is one of the most economical and effective IDM strategies. Resistant cultivars reduce pathogen establishment and disease spread, minimizing reliance on external inputs.

5. Chemical Control

Chemical control remains an important component but is used judiciously in IDM. Fungicides and bactericides are applied only when necessary, based on disease monitoring and threshold levels.

Chemical methods include:

- **Seed treatment** – Controls seed-borne pathogens
- **Soil treatment** – Eliminates soil pathogens
- **Protective sprays** – Prevent infection on plant surfaces

Excessive use is avoided to prevent resistance development and environmental hazards.

Climate Change and Integrated Disease Management

Climate change is increasing plant disease pressure by altering environmental factors such as temperature, rainfall patterns, humidity, and pathogen distribution, which can accelerate pathogen life cycles, favor their spread, and introduce diseases into new regions while reviving previously controlled ones. In this situation, Integrated Disease Management (IDM) serves as a climate-smart and sustainable approach by combining multiple strategies such as resistant crop varieties, biological control, cultural practices, and careful chemical use. By promoting diversity, ecological balance, and continuous monitoring, IDM enhances the resilience of farming systems and supports adaptive management, ultimately reducing crop vulnerability to emerging and re-emerging diseases under changing climatic conditions.

Advantages of IDM

IDM offers numerous ecological, economic, and social benefits. It promotes sustainable agriculture by reducing dependence on chemicals and minimizing environmental risks.

Key advantages include:

- Reduced pesticide use and residue problems
- Protection of beneficial organisms
- Lower risk of environmental contamination
- Improved crop health and productivity
- Enhanced cost-effectiveness in the long term

Moreover, IDM contributes to climate-resilient agriculture by improving system stability and adaptability.

Challenges in IDM Implementation

Despite its benefits, the adoption of IDM faces several constraints, including:

- Limited awareness among farmers
- Lack of access to resistant varieties and biocontrol agents
- Need for technical knowledge and training
- Dependence on extension services and decision-support systems

Addressing these challenges requires coordinated efforts in research, policy support, and farmer education.

Conclusion

Integrated Plant Disease Management represents a paradigm shift from conventional chemical-based control to a holistic, sustainable, and knowledge-driven approach. By integrating cultural, biological, physical, and chemical methods, IDM ensures effective disease suppression while safeguarding environmental and human health.

In the context of increasing food demand, climate change, and ecological concerns, IDM is not just an option but a necessity for achieving sustainable and resilient agricultural systems.

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Vertical Farming and Urban Agriculture: Feeding Cities Sustainably



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Abstract

Rapid urbanization, shrinking arable land, and increasing food demand have created serious challenges for urban food security. Vertical farming and urban agriculture offer innovative solutions by producing food locally, reducing transportation costs, and minimizing resource use. These approaches use technologies such as hydroponics, aeroponics, controlled-environment agriculture, and LED lighting systems to maximize yield per unit area (Kalantari et al., 2017). Beyond food production, urban agriculture improves environmental sustainability, creates employment, and enhances urban resilience. This article explores techniques, benefits, challenges, and future prospects of vertical farming in India and highlights successful case studies from urban centres.

Introduction

Urban areas are home to over 35% of India's population, a figure expected to rise to 50% by 2035 (World Bank, 2020). Rapid urbanization has put immense pressure on food supply chains, making cities dependent on long-distance transport, which increases costs and carbon emissions. Traditional agriculture often cannot meet urban demand for fresh, safe, and nutritious produce, especially in cities where land availability is limited (Banerjee & Adenauer, 2014).

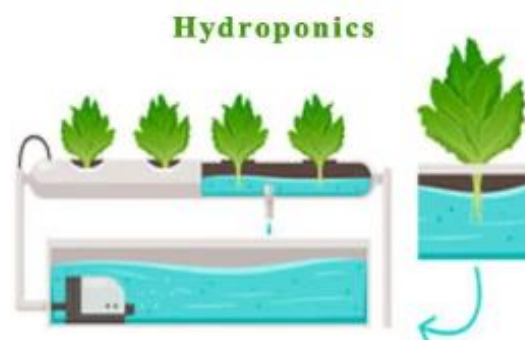
Vertical farming and urban agriculture provide a sustainable alternative by integrating food production into urban spaces. These systems not only optimize space but also reduce water use, carbon emissions, and dependence on chemical inputs (Kozai, Niu, & Takagaki, 2016). In India, urban centers such as Delhi, Bengaluru, and Mumbai are adopting hydroponic rooftop farms, vertical plant walls, and indoor urban farms to enhance local food security, generate employment, and support sustainable urban living (Kalantari et al., 2017; FAO, 2020).

For example, Bengaluru's "Ecozen Farms" uses hydroponics and vertical racks to produce over 2,000 kg of vegetables monthly from just 500 m² of space. Similarly, Delhi's "Farmizen" integrates rooftop gardens with community participation to supply fresh greens directly to households. These examples demonstrate the potential for scalable and profitable urban agriculture in India.

Key Techniques in Vertical Farming and Urban Agriculture

1. Hydroponics

Hydroponics is a soilless cultivation method where plants grow in nutrient-rich water solutions, allowing precise control over nutrients, water, and pH (Kozai, Niu, & Takagaki, 2016). Crops such as lettuce, spinach, herbs, and strawberries thrive in hydroponic systems. Hydroponics is widely adopted in India in both commercial and home-scale urban farms. For example, Pune-based "Sky Greens" uses modular hydroponic towers to grow leafy greens with minimal water, achieving yields 10–12 times higher than traditional farming.



2. Aeroponics



Aeroponics involves suspending plant roots in air and periodically misting them with nutrient solutions (Kalantari *et al.*, 2017). This method reduces water usage by up to 90%, accelerates growth, and minimizes disease risks. Indian startups such as “Crofarm” and “UrbanKisaan” are experimenting with aeroponics for high-value crops, providing fresh produce to urban consumers while saving water in drought-prone regions like Maharashtra.

3. Controlled-Environment Agriculture (CEA)

CEA uses LED lighting, climate control, and automated irrigation to create ideal conditions for indoor crop production (Kozai, Niu, & Takagaki, 2016). By adjusting light intensity, temperature, and humidity, crops can be grown year-round regardless of seasonal constraints. In India, CEA is being integrated in smart cities and tech parks, such as Bengaluru’s WTC farm, where fully indoor vertical farms produce fresh vegetables and herbs for nearby office cafeterias.



4. Rooftop and Community Farming

Rooftop farms and urban community gardens utilize unused urban spaces for growing vegetables and fruits (FAO, 2020). Mumbai’s “Grow-Trees” initiative and Delhi’s “Farmizen” project combine rooftop farming with community participation to supply local households, improve green cover, and mitigate urban heat islands (Specht *et al.*, 2014). These models also raise awareness about sustainable farming practices among city residents.



Benefits of Vertical Farming and Urban Agriculture

1. **Space Efficiency** – Vertical farms can produce 10–15 times more yield per m² than conventional soil farming (Kalantari *et al.*, 2017).
2. **Resource Efficiency** – Water usage is reduced by 70–90%, and nutrient recycling minimizes fertilizer dependence (Kozai, Niu, & Takagaki, 2016).
3. **Local Food Security** – Producing food near consumption points reduces transportation costs, spoilage, and carbon emissions (Specht *et al.*, 2014).
4. **Economic Opportunities** – Urban farming creates jobs in farming, technology, and logistics (Banerjee & Adenaeuer, 2014).
5. **Environmental Sustainability** – Rooftop and vertical farms reduce urban heat islands, improve air quality, and enhance biodiversity (FAO, 2020).

Challenges and Future Prospects

High initial capital investment, energy costs for lighting and climate control, and technical expertise remain major challenges (Kalantari *et al.*, 2017). However, India is witnessing rapid growth in agri-tech startups and government support for urban farming. Programs under the National Urban Livelihoods Mission (NULM) and Smart Cities Mission are promoting rooftop gardens and vertical farms, providing training and microfinance to urban farmers (FAO, 2020). Innovations in solar-powered LED lighting, low-cost hydroponic systems, and AI-driven climate control are making vertical farming more feasible and sustainable for Indian cities.

Conclusion

Vertical farming and urban agriculture offer innovative solutions to India's growing urban food security challenges. By integrating modern technologies with space-efficient farming techniques, cities can produce fresh, safe, and nutritious food while conserving water, reducing carbon emissions, and creating economic opportunities. Successful examples in Bengaluru, Delhi, and Mumbai demonstrate the feasibility and potential profitability of these systems. With policy support, technological innovation, and community participation, vertical farming can transform Indian cities into resilient, self-sufficient, and sustainable food hubs.

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Smart Irrigation and Water-Saving Technologies in Indian Agriculture



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Abstract:

Water scarcity is one of the most critical challenges in Indian agriculture. With nearly 70% of freshwater being used for irrigation, traditional methods often lead to inefficiency, soil degradation, and environmental stress. Smart irrigation and water-saving technologies provide a solution by optimizing water use, improving crop productivity, and promoting sustainable resource management. This article explores modern irrigation techniques, sensor-based systems, IoT integration, government initiatives, and the prospects of adopting these technologies across India.

Introduction

India, an agrarian economy, relies heavily on agriculture for food security, employment, and rural livelihoods. Agriculture contributes around 18% to India's GDP and employs nearly half of the country's workforce. Water is indispensable for crop production, yet India faces severe water challenges due to population growth, changing rainfall patterns, and over-extraction of groundwater. Traditional irrigation methods such as flood and furrow irrigation are not only water-intensive but also inefficient, often resulting in wastage and soil nutrient leaching (Kumar *et al.*, 2021).

To address these challenges, smart irrigation and water-saving technologies have emerged as game-changers. These practices use precision tools, modern irrigation systems, and data-driven approaches to deliver water efficiently, conserve resources, and enhance crop yield.

Modern Irrigation Methods

1. Drip Irrigation

Drip irrigation delivers water directly to the plant root zone through a network of pipes, valves, and emitters. This method drastically reduces water loss due to evaporation or surface runoff. Studies have shown water savings of 30–50% compared to conventional irrigation, along with 20–30% higher crop yields in crops like sugarcane, tomatoes, and grapes (Singh & Sharma, 2020).

In India, states like Maharashtra, Karnataka, and Tamil Nadu have successfully implemented drip irrigation for high-value crops. Farmers benefit from reduced labor costs, efficient fertilizer use, and improved crop quality. Integration with fertigation systems allows simultaneous application of nutrients with water, further boosting productivity.



2. Sprinkler Irrigation

Sprinkler systems distribute water uniformly over the crop canopy and are particularly suitable for uneven terrains, orchards, and vegetables. Sprinkler irrigation saves 25–40% of water while improving nutrient use efficiency. In regions like Punjab and Haryana, sprinkler systems have been widely adopted for wheat and maize cultivation, resulting in higher yield stability (Sharma *et al.*, 2019).



3. Subsurface Drip Irrigation

Subsurface drip irrigation (SDI) delivers water directly below the soil surface to the root zone, significantly reducing evaporation losses. SDI is especially effective in water-scarce regions like Rajasthan and Gujarat. By maintaining soil moisture at optimal levels, it also enhances microbial activity, improves soil fertility, and prevents salinity issues.

4. Alternate Wetting and Drying (AWD)

Used mainly in paddy cultivation, AWD involves controlled irrigation where fields are allowed to dry intermittently. This reduces water usage by up to 30%, lowers methane emissions, and improves nitrogen-use efficiency. Research in states like West Bengal and Odisha shows AWD as an environmentally sustainable approach for rice cultivation.

Smart Water-Saving Technologies

• Sensor-Based Irrigation Systems

Soil moisture sensors, tensiometers, and weather stations enable precise irrigation scheduling. Sensors measure soil water content in real time, allowing automated irrigation systems to apply water only when needed. This prevents over-irrigation, conserves water, and reduces energy costs.

• Internet of Things (IoT) and Remote Sensing

IoT-based smart irrigation systems combine sensor data with cloud-based analytics for remote monitoring. Drones and satellites provide detailed information on crop health, soil moisture, and evapotranspiration. Farmers receive actionable insights on irrigation timing, ensuring water efficiency. States like Andhra Pradesh and Telangana are implementing IoT-based irrigation projects for large-scale farms.

• Rainwater Harvesting and Micro-Catchments

Rainwater harvesting structures such as ponds, tanks, and check dams can store monsoon water for irrigation during dry periods. Micro-catchments and farm ponds not only improve water availability but also recharge groundwater, mitigate drought impact, and support fish culture and livestock watering.

• Crop Selection and Water-Smart Farming Practices

Choosing drought-resistant and short-duration crop varieties reduces irrigation needs. Practices like crop rotation, intercropping, mulching, and conservation tillage improve soil moisture retention and water-use efficiency. For example, the introduction of drought-tolerant wheat and maize varieties in Rajasthan has helped farmers adapt to low-water conditions.

Government Initiatives and Support

Several government schemes in India promote the adoption of smart irrigation and water-saving technologies:

- **Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):** Focuses on efficient water use, micro-irrigation adoption, and watershed development.
- **National Mission on Micro Irrigation (NMMI):** Provides subsidies to farmers for installing drip and sprinkler systems.
- **Soil Health Card Scheme:** Encourages balanced nutrient management, which complements efficient irrigation.

Case Studies in India

1. **Maharashtra:** Sugarcane farmers adopting drip irrigation have increased yield by 25% while saving 40% water. Fertigation through drip lines further enhanced crop quality.
2. **Punjab and Haryana:** Sprinkler systems for wheat and maize reduced water consumption by 30–35% and improved yield stability under erratic rainfall conditions.
3. **Andhra Pradesh:** IoT-based irrigation monitoring in large-scale farms showed a reduction of up to 20% in water use, optimizing labor and energy costs.

Environmental and Economic Benefits

Smart irrigation not only conserves water but also contributes to sustainable agriculture:

- Reduces waterlogging, salinity, and nutrient leaching.
- Decreases energy consumption for pumping water.
- Lowers greenhouse gas emissions through efficient water and nutrient use.

- Enhances farmer income by improving crop yield and quality.

Challenges and Future Prospects

Despite significant benefits, adoption of smart irrigation faces challenges:

- High initial investment costs.
- Limited awareness and technical knowledge among small farmers.
- Maintenance requirements for sensor and IoT systems.

Addressing these challenges requires targeted training, government support, affordable technology solutions, and integration with precision agriculture. Emerging technologies such as AI-driven irrigation scheduling, solar-powered pumps, and machine learning for water demand forecasting hold immense potential for transforming Indian agriculture.

Conclusion

Smart irrigation and water-saving technologies are crucial for addressing water scarcity and improving agricultural sustainability in India. By optimizing water use, enhancing productivity, and conserving natural resources, these approaches can ensure food security and economic stability for farmers. Government support, combined with technological innovations and farmer awareness, can accelerate the adoption of efficient irrigation practices, making Indian agriculture more resilient and environmentally sustainable.

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Farmer Producer Organizations (FPOs): A Sustainable Model for Agricultural Development



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Introduction

Agriculture is the backbone of the Indian economy and provides livelihood opportunities to a large section of the population. Despite its significance, Indian agriculture faces several structural and economic challenges such as fragmented landholdings, low productivity, declining natural resources, rising input costs, inadequate market access, and fluctuating prices of agricultural commodities. The majority of farmers in India belong to the small and marginal category, owning less than two hectares of land. Due to limited production capacity and poor bargaining power, these farmers often struggle to obtain fair prices for their produce and face difficulties in accessing quality inputs, institutional credit, modern technologies, and storage facilities.

To overcome these constraints, collective approaches to farming and marketing have gained importance in recent decades. One such institutional innovation is the Farmer Producer Organization (FPO), which has emerged as an effective mechanism for empowering farmers economically and socially. FPOs enable farmers to work collectively in production, procurement, processing, marketing, and value addition activities. Through collective action, farmers can achieve economies of scale, reduce transaction costs, strengthen bargaining power, and improve access to markets and financial institutions.

The Government of India has recognized FPOs as an important strategy for doubling farmers' income and strengthening rural livelihoods. In recent years, several schemes and policy initiatives have been introduced to support the formation and promotion of FPOs across the country. These organizations are increasingly playing a crucial role in improving agricultural productivity, promoting entrepreneurship, encouraging sustainable agriculture, and ensuring inclusive rural development.

Concept of an FPO

A Producer Organization (PO) is a legally recognized institution formed by primary producers such as farmers, fishermen, weavers, milk producers, rural artisans, and craftsmen. A Farmer Producer Organization (FPO) is a specialized form of producer organization in which the members are exclusively farmers engaged in agricultural and allied activities. FPOs are generally registered under the Companies Act as Farmer Producer Companies (FPCs) and function as business-oriented entities for the welfare of farmers.

The concept of FPOs was introduced to address the economic disadvantages faced by small and marginal farmers. Individually, farmers often lack sufficient resources, market information, and bargaining capacity to compete effectively in modern agricultural markets. By organizing themselves into groups, farmers can collectively purchase agricultural inputs, access technologies, avail institutional credit, and market their produce more efficiently. This collective approach reduces costs and increases profitability for members.

The primary objective of an FPO is to enhance the income and socio-economic condition of farmers through collective action. FPOs undertake activities such as procurement of seeds and fertilizers, aggregation of produce, grading, processing, packaging, branding, transportation, storage, and marketing. Many FPOs also provide extension services, training programmes, insurance support, and financial assistance to their members.

FPOs may be commodity-based or resource-oriented organizations. Commodity-based FPOs focus on crops or products such as fruits, vegetables, dairy, spices, fisheries, or grains, whereas resource-oriented organizations are associated with irrigation management, natural resource conservation, or community development activities.

Thus, the concept of FPOs combines the welfare-oriented approach of cooperatives with the efficiency and professionalism of corporate enterprises, creating a farmer-centric model for agricultural development.

Registration Process of Farmer Producer Organizations (FPOs)

The registration of Farmer Producer Organizations is primarily governed by the Companies Act, 2013. Earlier, Producer Companies were registered under the Companies Act, 1956 after the amendment introduced in 2002 on the recommendations of the Y. K. Alagh Committee. The legal framework was designed to combine the beneficial features of cooperative societies and private companies for the advantage of farmers.

The registration process of an FPO involves several important steps:

1. Mobilization of Farmers

The first step involves identifying and mobilizing farmers who share common agricultural interests and objectives. Farmers are encouraged to come together to form a producer group based on crops, geographical location, or allied agricultural activities.

2. Formation of a Promoting Group

A core group of promoters is formed to initiate the process of establishing the FPO. This group coordinates meetings, awareness programmes, and preparation of necessary documents.

3. Selection of Name

A suitable name is selected for the organization. The name must end with the words “Producer Company Limited” as per legal requirements.

4. Preparation of Memorandum and Articles of Association

The promoters prepare the Memorandum of Association (MoA) and Articles of Association (AoA), which define the objectives, functions, governance structure, and operational rules of the FPO.

5. Minimum Membership Requirements

An FPO requires a minimum of ten producer members or two producer institutions for registration. Additionally, a minimum of five directors and a maximum of fifteen directors are required to manage the organization.

6. Capital Requirements

The organization must have a minimum paid-up capital of ₹10,000. Share capital is generally contributed by member farmers.

7. Registration with Registrar of Companies

The necessary documents, including identity proofs, address proofs, MoA, AoA, and digital signatures of directors, are submitted to the Registrar of Companies (ROC). After verification, the ROC issues a Certificate of Incorporation, officially recognizing the FPO as a legal entity.

8. Post-registration Activities

After registration, the FPO opens a bank account, obtains PAN and GST registration if required, and begins business operations. Elections for the Board of Directors are conducted within 90 days of registration.

The registration process ensures transparency, accountability, and legal recognition, enabling FPOs to function as organized business enterprises for the benefit of farmers.

Organizational Framework of Farmer Producer Organizations

The organizational framework of an FPO is designed to ensure democratic participation, professional management, and efficient functioning. The structure generally consists of the General Body, Board of Directors, Executive Body, General Manager, and operational staff.

• General Body

The General Body is the supreme authority of the FPO and consists of all shareholder members. It is responsible for framing policies, approving annual plans, reviewing performance, and ensuring accountability within the organization.

• Board of Directors

The Board of Directors is elected by the General Body and is responsible for strategic planning, policy implementation, financial management, and supervision of business activities. Directors represent the interests of member farmers and ensure smooth governance.

- **Executive Body**

The Executive Body manages day-to-day operational activities such as procurement, marketing, accounting, logistics, and coordination with stakeholders.

- **General Manager and Staff**

Professional managers and staff are appointed to handle technical, administrative, and financial activities of the organization. They assist in implementing business plans and improving organizational efficiency.

- **Local Resource Persons**

Many FPOs also involve local resource persons and extension workers who provide technical guidance, training, and awareness programmes to farmers.

This organizational framework promotes collective decision-making while ensuring professional business management and accountability.

Key Characteristics and Core Features of FPOs

Farmer Producer Organizations possess several unique characteristics that distinguish them from traditional cooperative societies and private enterprises.

1. Legal Entity

An FPO is a registered legal organization recognized under the Companies Act. This legal status allows it to undertake business activities, enter contracts, and access institutional finance.

2. Farmer Ownership

The members of the organization are farmers who act as shareholders and owners of the enterprise. Each member has a role in decision-making and governance.

3. Collective Action

FPOs operate on the principle of collective action, where farmers work together for procurement, production, processing, and marketing activities.

4. Business-oriented Approach

Unlike traditional welfare-based organizations, FPOs function as business enterprises aimed at generating profits and improving farmers' income.

5. Democratic Governance

The management of FPOs is based on democratic principles where members elect representatives to manage the organization.

6. Profit Sharing

A part of the profit earned by the organization is distributed among members, while the remaining surplus is reinvested for expansion and development.

7. Value Addition and Market Integration

FPOs engage in activities such as grading, processing, branding, packaging, and direct marketing to increase the value of agricultural produce.

8. Support Services

Many FPOs provide services such as crop insurance, credit facilities, training programmes, technological guidance, and market information to members.

These features make FPOs an effective institutional mechanism for promoting sustainable agricultural development and rural entrepreneurship.

Major Institutions Supporting the Promotion of FPOs

Several government and non-government institutions play an important role in promoting and supporting FPOs in India.

- **Small Farmers' Agribusiness Consortium (SFAC)**

SFAC is one of the leading organizations promoting FPOs in India. It provides financial assistance, equity grants, credit guarantee support, market linkages, and capacity-building programmes for FPO development.

- **National Bank for Agriculture and Rural Development (NABARD)**

NABARD supports FPOs through the Producer Organization Development Fund (PODF). It provides financial assistance, training programmes, business planning support, and credit facilities to producer organizations.

- **Government Departments**

The Department of Agriculture and Farmers' Welfare, Ministry of Food Processing Industries, and various state agricultural departments support FPOs through schemes, subsidies, and infrastructure development programmes.

- **Non-Governmental Organizations (NGOs)**

Several NGOs and voluntary organizations assist in farmer mobilization, awareness generation, training, and capacity building for FPOs.

- **International Aid Agencies**

International development organizations support FPOs through technical cooperation, financial assistance, and knowledge-sharing initiatives.

- **Corporate and Private Institutions**

Private companies and agribusiness firms collaborate with FPOs for contract farming, input supply, value chain development, and market access.

The coordinated efforts of these institutions are crucial for strengthening FPOs and ensuring their long-term sustainability.

Constraints and Challenges Faced by Farmer Producer Organizations

Despite their growing importance, FPOs face several challenges that limit their effectiveness and sustainability.

- **Financial Constraints**

Many FPOs suffer from inadequate capital, limited access to institutional credit, and shortage of working capital. Banks are often hesitant to provide loans due to weak business records and lack of collateral.

- **Poor Infrastructure**

Inadequate storage facilities, transportation systems, processing units, and market infrastructure result in post-harvest losses and reduced profitability.

- **Weak Management Capacity**

Many FPOs lack professional expertise in business planning, financial management, accounting, and marketing.

- **Limited Farmer Participation**

Lack of awareness, trust, and understanding among farmers often affects active participation and collective decision-making.

- **Market Linkage Problems**

FPOs frequently face difficulties in establishing strong market connections and competing with private traders and large agribusiness firms.

- **Technological Limitations**

Limited access to digital technologies, market intelligence systems, and modern agricultural innovations restricts the growth of FPOs.

- **Sustainability Issues**

Maintaining long-term sustainability remains a major challenge due to operational inefficiencies, governance issues, and inadequate support services.

Addressing these constraints requires continuous capacity building, infrastructure investment, financial support, and policy interventions.

Conclusion

Farmer Producer Organizations have emerged as an effective institutional mechanism for improving the socio-economic condition of small and marginal farmers in India. By promoting collective action, strengthening market access, reducing input costs, and encouraging value addition, FPOs contribute significantly to increasing farmers' income and enhancing rural livelihoods. The organizational structure and legal framework of FPOs provide farmers with opportunities to function as business entrepreneurs while safeguarding their collective interests.

Government initiatives, financial support from institutions like NABARD and SFAC, and increasing policy attention have accelerated the growth of FPOs across the country. However, challenges related to finance, infrastructure, professional management, and market integration continue to affect their performance and sustainability.

For FPOs to realize their full potential, greater emphasis must be placed on capacity building, digital integration, infrastructure development, market linkages, and institutional handholding. Strengthening FPOs can play a transformative role in achieving inclusive agricultural growth, sustainable rural development, and economic empowerment of farmers in India.

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Nano DAP: Revolutionizing Sustainable Nutrient Management in Modern Agriculture



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Introduction

Agriculture is the backbone of food security and economic development in many countries across the world. With the global population increasing rapidly, the demand for food production is continuously rising. To meet this growing demand, modern agriculture has become heavily dependent on chemical fertilizers for enhancing crop productivity. Among these fertilizers, nitrogen (N) and phosphorus (P) are considered the most essential nutrients required for proper plant growth and development.

Phosphorus plays a crucial role in various physiological and biochemical processes in plants, including energy transfer, root development, photosynthesis, flowering, seed formation, and crop maturity. Diammonium phosphate (DAP) has been one of the most widely used phosphorus fertilizers globally due to its high nutrient content. However, conventional DAP fertilizers suffer from several limitations such as low nutrient use efficiency, nutrient fixation in soil, leaching losses, environmental pollution, and rising production costs.

In recent years, nanotechnology has emerged as a transformative tool in agriculture. The integration of nanoscience into fertilizer technology has led to the development of nano-fertilizers, which are designed to improve nutrient delivery, reduce nutrient losses, and increase fertilizer efficiency. Among these innovations, Nano DAP has gained significant attention as a sustainable and efficient alternative to conventional DAP fertilizers.

Nano DAP represents a major breakthrough in precision agriculture and smart nutrient management. Due to its nano-sized particles and controlled-release properties, it ensures better nutrient absorption and utilization by plants while minimizing environmental damage. Nano DAP not only enhances crop growth and productivity but also contributes toward reducing fertilizer consumption, lowering production costs, and promoting environmental sustainability.

Concept of Nanotechnology in Agriculture

Nanotechnology refers to the manipulation and application of materials at the nanoscale level, generally between 1 and 100 nanometers. Materials at this scale exhibit unique physical, chemical, and biological properties compared to their bulk forms. These properties include:

- Higher surface area
- Enhanced reactivity
- Improved solubility
- Better absorption capability
- Controlled release behavior

In agriculture, nanotechnology has opened new possibilities for:

- Precision farming
- Smart nutrient delivery
- Pest and disease management
- Soil improvement
- Water conservation
- Crop monitoring

Nano-fertilizers are one of the most promising applications of nanotechnology in agriculture. They are designed to release nutrients gradually and in synchronization with plant demand, thereby improving nutrient use efficiency and reducing environmental losses.

What is Nano DAP?

Nano DAP is a nano-formulated liquid fertilizer containing nano-sized particles of diammonium phosphate suspended in an aqueous medium. These nanoparticles are extremely small, usually less than 100 nanometers in size, which enables efficient penetration into plant tissues through stomata, leaf pores, and cellular membranes. Nano DAP serves as a source of two essential macronutrients:

- Nitrogen (N)
- Phosphorus (P)

Unlike conventional granular DAP fertilizers, Nano DAP is mainly used as a foliar spray, allowing rapid nutrient absorption and utilization. The nano-sized particles possess a very high surface area-to-volume ratio, which increases their interaction with plant cells and enhances nutrient uptake efficiency.

Composition of Nano DAP

Different formulations of Nano DAP are available depending on the manufacturing technology and company specifications.

General Composition

Nano DAP commonly contains:

- Nitrogen (N)
- Phosphorus pentoxide (P_2O_5)
- Stabilizers
- Biopolymers
- Nano-carrier materials

Example Formulations

IFFCO Nano DAP

- 8% Nitrogen (N)
- 16% Phosphorus (P_2O_5)

Coromandel Nano DAP

- 2% Nitrogen (N)
- 5% Phosphorus pentoxide (P_2O_5)

The nanoparticles are often functionalized using biopolymers and advanced stabilizing agents to improve:

- Stability
- Nutrient dispersion
- Plant assimilation
- Shelf life

Need for Nano DAP

Limitations of Conventional Fertilizers

Traditional fertilizers have been instrumental in increasing agricultural productivity, but they also present serious challenges.

1. Low Nutrient Use Efficiency

Only a small proportion of applied fertilizers is actually utilized by plants. Large amounts are lost through:

- Leaching
- Runoff
- Volatilization
- Fixation
- Denitrification

Phosphorus fertilizers are especially prone to fixation in soil, where they become unavailable to plants.

2. Environmental Pollution

Excessive fertilizer application contributes to:

- Water pollution
- Eutrophication

- Soil degradation
- Greenhouse gas emissions
- Groundwater contamination

Phosphorus runoff into lakes and rivers causes algal blooms and ecological imbalance.

3. High Production and Transportation Costs

Conventional fertilizers require:

- Large quantities for application
- Bulk transportation
- High storage capacity

This increases overall agricultural expenses.

4. Resource Depletion

Phosphorus is a finite and non-renewable resource. Continuous overuse of phosphate fertilizers threatens future phosphorus availability.

5. Imbalanced Fertilizer Application

Indiscriminate fertilizer use often leads to nutrient imbalance in soil, affecting long-term soil fertility and crop productivity.

Nano DAP has emerged as a promising solution to address these challenges.

Characteristics of Nano DAP

Nano DAP possesses several unique characteristics that distinguish it from conventional fertilizers.

Characteristics	Nano DAP	Conventional DAP
Particle Size	Less than 100 nm	Large granules
Nutrient Release	Slow and controlled	Rapid
Surface Area	Very high	Low
Nutrient Efficiency	High	Low
Nutrient Loss	Minimal	Significant
Solubility	Improved	Moderate
Environmental Impact	Low	Higher
Uptake Efficiency	Enhanced	Limited
Mode of Application	Foliar spray	Soil application

Mechanism of Action of Nano DAP

Nano DAP functions through a smart nutrient delivery system that improves nutrient absorption and utilization by plants.

1. Enhanced Surface Area

The extremely small particle size provides a large surface area, increasing interaction between nutrients and plant cells.

2. Efficient Penetration

Nano particles easily enter plant tissues through:

- Stomata
- Leaf cuticles
- Epidermal pores
- Root tissues

3. Controlled Nutrient Release

Nano DAP releases nutrients slowly and steadily according to plant demand. This controlled release prevents sudden nutrient loss and ensures long-term nutrient availability.

4. Improved Nutrient Mobility

Nano-sized particles move efficiently within plant systems, improving nutrient translocation to various plant parts.

5. Reduced Nutrient Fixation

Nano DAP minimizes phosphorus fixation in soil, increasing nutrient availability to plants.

Smart Nutrient Delivery System

Nano DAP acts as a Smart Nutrient Delivery System (SNDS), which is one of the most advanced concepts in modern fertilizer technology.

Features of Smart Delivery System

- Time-regulated nutrient release
- Targeted nutrient delivery
- Controlled nutrient availability
- Synchronization with plant demand
- Reduced nutrient wastage

This system ensures that plants receive nutrients precisely when required, thereby enhancing fertilizer use efficiency.

Advantages of Nano DAP

1. Higher Nutrient Use Efficiency

Nano DAP improves the efficiency of nitrogen and phosphorus utilization by plants due to better absorption and controlled nutrient release.

2. Reduced Fertilizer Requirement

Because of its high efficiency, smaller quantities of Nano DAP are required compared to conventional fertilizers.

3. Improved Crop Growth

Nano DAP promotes:

- Better root development
- Enhanced chlorophyll synthesis
- Increased photosynthetic activity
- Vigorous vegetative growth
- Improved flowering and fruiting

4. Controlled Release of Nutrients

The gradual nutrient release pattern ensures continuous nutrient supply during different crop growth stages.

5. Reduction in Nutrient Losses

Nano DAP significantly reduces:

- Leaching losses
- Runoff losses
- Nutrient fixation
- Volatilization losses

6. Environmental Sustainability

Nano DAP minimizes environmental pollution and promotes eco-friendly farming practices.

7. Enhanced Soil Health

Balanced nutrient availability improves soil fertility and microbial activity.

8. Better Economic Returns

Farmers benefit from:

- Reduced fertilizer consumption
- Lower transportation costs
- Improved crop productivity
- Increased profitability

9. Precision Agriculture Support

Nano DAP supports modern precision farming systems by delivering nutrients accurately and efficiently.

Application Methods of Nano DAP

Nano DAP can be applied through multiple methods depending on crop type and growth stage.

1. Seed Treatment

Nano DAP can be used for seed treatment to improve:

- Germination
- Seed vigor
- Early root growth

Recommended Dose

- 3–5 ml per kg of seed

2. Root or Tuber Treatment

Used for transplanted crops and tubers.

Recommended Dose

- 3–5 ml per liter of water

3. Foliar Spray

Foliar application is the most common and effective method.

Recommended Dose

- 2–4 ml per liter of water

Spray Timing

- Vegetative stage
- Tillering or branching stage
- Pre-flowering stage

Foliar application enables direct nutrient absorption through leaves.

4. Drone Application

Nano DAP can also be applied using drones in precision agriculture systems.

This method:

- Saves labor
- Ensures uniform spraying
- Reduces application time

Role of Nano DAP in Sustainable Agriculture

Nano DAP contributes significantly toward sustainable agricultural development.

1. Resource Conservation

It reduces excessive fertilizer use and conserves non-renewable phosphorus resources.

2. Reduced Environmental Damage

Controlled nutrient release minimizes soil and water pollution.

3. Climate-Smart Agriculture

Nano DAP supports climate-resilient farming practices by improving nutrient efficiency and reducing greenhouse gas emissions.

4. Support for Precision Farming

Nano DAP aligns well with advanced agricultural technologies and precision nutrient management systems.

Environmental Benefits of Nano DAP

Reduced Groundwater Pollution

Nano DAP minimizes nutrient leaching into groundwater.

Lower Eutrophication Risk

Reduced phosphorus runoff decreases algal bloom formation in water bodies.

Reduced Carbon Footprint

Lower fertilizer requirement reduces:

- Manufacturing emissions

- Transportation emissions
- Energy consumption

Improved Ecosystem Health

Balanced nutrient application helps maintain ecological balance.

Challenges Associated with Nano DAP

Despite its advantages, Nano DAP faces certain limitations.

1. High Production Cost

Nano-fertilizer manufacturing requires sophisticated technology and infrastructure.

2. Limited Farmer Awareness

Many farmers are still unfamiliar with nano-fertilizer technology and application methods.

3. Need for Scientific Validation

Long-term studies are needed to evaluate:

- Soil health impacts
- Residual effects
- Environmental safety
- Crop-specific responses

4. Regulatory Challenges

Clear policies and standards for nano-fertilizers are still under development in many countries.

5. Storage and Handling Issues

Proper storage conditions are necessary to maintain product stability.

Future Prospects of Nano DAP

Nano DAP has enormous potential to transform future agriculture.

Emerging Possibilities

- Smart fertilizers integrated with sensors
- AI-based nutrient management
- Precision nutrient application systems
- Nano-enabled climate-smart farming
- Sustainable nutrient management programs

As research advances, Nano DAP may become an integral component of next-generation agriculture.

Importance of Nano DAP in India

India is one of the largest consumers of DAP fertilizers. Due to limited domestic phosphate reserves, the country depends heavily on fertilizer imports.

Nano DAP offers several advantages for Indian agriculture:

- Reduced import dependency
- Lower subsidy burden
- Improved fertilizer efficiency
- Increased farmer income
- Promotion of sustainable agriculture

The adoption of Nano DAP can contribute significantly toward achieving self-reliance in fertilizer management.

Conclusion

Nano DAP is a revolutionary innovation in agricultural fertilizer technology that combines the principles of nanoscience with sustainable nutrient management. It offers a highly efficient, environmentally friendly, and economically viable alternative to conventional phosphorus fertilizers.

Through its nano-sized particles, controlled-release mechanism, and smart nutrient delivery system, Nano DAP enhances nutrient use efficiency, improves plant growth, reduces nutrient losses, and minimizes environmental pollution. Its role in precision agriculture and climate-smart farming makes it an important tool for the future of sustainable agriculture.

Although challenges such as high production cost, limited awareness, and regulatory concerns still exist, continued research and technological advancement are expected to promote wider adoption of Nano DAP worldwide.

In the coming years, Nano DAP has the potential to revolutionize fertilizer management practices and contribute significantly toward global food security, environmental conservation, and sustainable agricultural development.

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Conservation Agriculture: Transforming Indian Farming for a Sustainable Future



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Abstract

Conservation Agriculture (CA) is a sustainable farming approach that combines productivity with environmental protection. Based on minimal soil disturbance, permanent soil cover, and crop diversification, it improves soil health, water use efficiency, and climate resilience. Practices such as zero tillage, raised beds, green manuring, and mulching support resource conservation. However, adoption in India faces economic, technological, and socio-cultural challenges. Despite this, CA has shown positive impacts on crop yield, soil quality, and sustainability, making it a promising pathway for climate-resilient agriculture.

Keywords: Conservation Agriculture, sustainable farming, soil health, zero tillage, climate resilience

Introduction

Agriculture today faces the dual challenge of increasing food production while preserving natural resources. Conventional farming practices, characterized by intensive tillage and excessive input use, have contributed to soil degradation, declining fertility, and environmental imbalance. In this context, Conservation Agriculture (CA) has emerged as a sustainable alternative that ensures long-term productivity while maintaining ecological integrity. CA is founded on three interrelated principles: minimal soil disturbance, permanent soil cover, and crop diversification. These principles aim to improve soil structure, enhance biological activity, and optimize nutrient cycling. By reducing soil erosion and improving water retention, CA contributes significantly to sustainable agricultural development and climate change mitigation.

Concept and Evolution of Conservation Agriculture

Conservation Agriculture (CA) developed as a response to soil erosion, declining fertility, and the negative impacts of intensive tillage. Early pioneers like Sir Albert Howard emphasized soil health and organic matter recycling, while Edward Faulkner challenged conventional plowing practices, promoting minimal soil disturbance. The Dust Bowl crisis in the 1930s further highlighted the need for sustainable practices, leading to the development of soil conservation techniques and eventually zero-tillage systems. With advancements in machinery and herbicides during the mid-20th century, CA became more practical and widely adoptable. Over time, CA evolved from simple reduced tillage into a holistic system based on three key principles: minimal soil disturbance, permanent soil cover, and crop diversification. Its success in countries like Brazil and the USA demonstrated benefits such as improved soil health, reduced costs, and better climate resilience. In India, CA gained importance in the Indo-Gangetic Plains with the adoption of zero-tillage and technologies like the Happy Seeder. Today, CA integrates modern tools with ecological principles, making it a key approach for sustainable and climate-resilient agriculture.

Difference between Conservation agriculture and conventional agriculture

They differ mainly in their approach to soil and resource management. Conservation agriculture focuses on minimal soil disturbance, retention of crop residues, and crop diversification, which helps improve soil health, conserve moisture, and enhance long-term sustainability. In contrast, conventional agriculture relies on intensive tillage, removal or burning of residues, and monocropping, often leading to soil degradation, higher input use, and environmental stress. While conventional methods may provide short-term yield gains, conservation agriculture promotes resource efficiency, climate resilience, and sustained productivity over time.

Machinery Used in Conservation Agriculture

1. Zero Till Seed Drill

Used for direct seeding without plowing the field. It places seeds and fertilizers in a single operation, conserving soil moisture and reducing fuel and labor costs.

2. Happy Seeder

A highly important machine in India that allows sowing of crops (especially wheat) directly into standing crop residues like rice stubble, eliminating the need for burning.

3. Super Straw Management System (Super SMS)

Attached to combine harvesters, it spreads crop residues evenly across the field, making it easier to manage residues for the next crop.

4. Mulcher/Shredder

Used to cut and spread crop residues into small pieces, which act as mulch and improve soil organic matter.

5. Rotavator (Limited Use)

Used for shallow tillage where necessary, though excessive use is avoided in CA to prevent soil structure damage.

6. Laser Land Leveler

Ensures uniform leveling of fields, leading to efficient irrigation, better germination, and reduced water wastage.

7. Raised Bed Planter (FIRB Machine)

Forms raised beds and furrows for planting, improving water use efficiency and root growth.

8. Direct Seeded Rice (DSR) Drill

Used for sowing rice directly into the field without puddling, saving water and labor.

9. Strip Till Drill

Disturbs only a narrow strip of soil where seeds are placed, leaving the rest of the soil undisturbed.

10. Sprayers (for Weed Management)

Since tillage is minimized, herbicide application using knapsack or boom sprayers becomes important for weed control.

Constraints in implementing Conservation Agriculture (CA) in India

It includes high initial costs of specialized machinery like zero-till drills and Happy Seeders, which many small farmers cannot afford. There is also limited awareness and technical knowledge about CA practices, along with inadequate extension services. Crop residue management poses challenges, especially where residues are traditionally burned. Weed control becomes more difficult under reduced tillage, increasing reliance on herbicides. Additionally, fragmented landholdings, traditional farming habits, and insufficient policy support further hinder large-scale adoption of CA in India.

Case studies and success stories of Conservation Agriculture (CA) adoption in India

Conservation Agriculture (CA) has shown promising results across different regions of India, particularly in the Indo-Gangetic Plains (IGP). One of the most successful examples is zero-tillage wheat cultivation in Punjab, Haryana, and western Uttar Pradesh. Farmers adopted zero-till seed drills to sow wheat directly after rice harvest, which reduced turnaround time, saved fuel and labor costs, and increased yields by enabling timely sowing. It also improved soil moisture retention and reduced production costs. Another notable success is the use of the Happy Seeder technology in Punjab and Haryana. This machine allows wheat sowing in standing rice residues, effectively addressing the issue of stubble burning. Farmers using this technology reported improved soil health, reduced air pollution, and comparable or higher yields. In eastern India, particularly in Bihar and West Bengal, the adoption of Direct Seeded Rice (DSR) has helped farmers save water and labor compared to traditional puddled transplanting. This method also reduced methane emissions and improved crop establishment. The Furrow Irrigated Raised Bed (FIRB) system has been successfully implemented in parts of Haryana and Uttar Pradesh, leading to better water use efficiency, reduced waterlogging, and higher productivity in crops like wheat and maize. Additionally, farmer-led initiatives supported by institutions like ICAR and CIMMYT have demonstrated that CA practices improve soil organic carbon, reduce input costs, and enhance resilience to climate variability.

Implementing Conservation Agriculture (CA)

It involves a gradual approach starting with assessing farm conditions such as soil, climate, and cropping system. Farmers then reduce tillage and adopt zero or minimum tillage practices using suitable machinery. Crop residues are retained on the field instead of being burned to improve soil health and moisture retention. Crop rotation and cover cropping are introduced to enhance fertility and control pests. Efficient water management and integrated weed control practices are also essential. Regular monitoring and starting on a small scale before expanding help ensure successful and sustainable adoption of CA.

Economic and Environmental Sustainability

Conservation Agriculture (CA) ensures both economic and environmental sustainability by reducing production costs while improving natural resource health. Economically, CA lowers expenses on fuel, labor, and inputs through reduced tillage and efficient resource use, leading to better profitability over time. Environmentally, it enhances soil health by increasing organic matter, reducing erosion, and improving water retention. CA also conserves water, supports biodiversity, and helps mitigate climate change through carbon sequestration and reduced greenhouse gas emissions. Together, these benefits make CA a sustainable and resilient approach to modern agriculture.

Potential in climate change mitigation

Conservation Agriculture (CA) has strong potential in climate change mitigation by reducing greenhouse gas emissions and enhancing carbon sequestration. Practices like zero tillage and residue retention help store carbon in the soil, lowering atmospheric CO₂ levels. Reduced use of heavy machinery cuts fuel consumption and emissions, while improved nitrogen management decreases nitrous oxide release. CA also enhances soil moisture retention and resilience to droughts, making farming systems more adaptable to climate variability. Overall, it serves as a climate-smart approach that both mitigates emissions and supports sustainable agricultural production.

Summary

Conservation Agriculture (CA) is a sustainable farming approach that improves soil health, conserves water, and enhances productivity through practices like minimal tillage, residue retention, and crop diversification. It reduces input costs and environmental impact while increasing resilience to climate change. Despite challenges in adoption, successful examples in India highlight its potential to transform agriculture. Overall, CA offers a practical pathway for achieving long-term economic viability and environmental sustainability in farming systems.

Balancing Growth for Better Yield: Paclobutrazole in Groundnut



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India is one of the leading producers in world, cultivating groundnut on nearly 5–6 million hectares with a production of around 9–10 million tonnes, although productivity (1800 kg ha^{-1}) finds out to be lower than the global average due to various constraints (Directorate of Economics and Statistics, 2022). Biotic, abiotic constraints and limitations of genotypic performance stand as preliminary reasons for this sub optimised productivity of Groundnut.

In this context, application of plant growth regulators or growth stimulants comes into picture. Paclobutrazole (PBZ) is a triazole compound and one of most studied growth stimulant available in market for farmers and being widely adopted for various crops like groundnut, chillies and mango. PBZ is available in two forms 23% SC and 40 % SC.

Paclobutrazole is widely reported to enhance chlorophyll content, better assimilate partitioning capacity leading to crop with better flowering, peg fixation, pod setting and harvest index. Harnessing role of paclobutrazole could lead to improvements in yield attributes such as pod number, kernel weight and harvest index (Barman *et al.*, 2017; Lenka *et al.*, 2023). Absorption of paclobutrazole occurs primarily through roots and leaves and translocated via the xylem, which enables systemic action within the plant system (Fletcher *et al.*, 2000; Desta *et al.*, 2021).

Crops	Typical Dosage	Stage of Application	Primary Effects	Key References
Cereal Crops: Rice, Wheat, Maize	50–100 ppm (foliar) or 200–400 g a.i. ha^{-1}	Early vegetative stage (tillering)	Reduced plant height, improved lodging resistance	Kamran <i>et al.</i> , 2017; Rademacher, 2015
Oilseed Crops: Groundnut, Soybean, Mustard	50–150 ppm (foliar spray)	25–35 DAS or early flowering	Reduced vegetative growth, improved pod/seed development	Barman <i>et al.</i> , 2017; Lenka <i>et al.</i> , 2023
Vegetable crops: Tomato, Brinjal, Chilli, Pepper	25–75 ppm (foliar spray)	Pre-flowering or early flowering	Compact growth, increased flowering and fruit set	Davis <i>et al.</i> , 1988; Fletcher <i>et al.</i> , 2000; Desta <i>et al.</i> , 2021
Fruit & Plantation Crops: Mango, Citrus, Apple, Guava	1–5 g a.i. per tree (soil drench) or 500–1000 ppm (foliar)	Post-harvest or pre-flowering	Flower induction, control of vegetative flush	Kulkarni, 1988; Yeshitela <i>et al.</i> , 2004
Ornamental crops	50–200 ppm (foliar or drench)	Active vegetative growth	Growth retardation, improved plant form	Rademacher, 2015

The mode of action of paclobutrazole is through inhibition of gibberellins biosynthesis, by inhibiting ent kaurene oxidase activity. Thus, this significantly influences cell division, thereby resulting shorter internodes,

compact growth habit of plant. This translates into improved canopy structure, enabling better assimilate translocation and partitioning efficiency.

Paclobutrazole also affects the hormonal balance of plants by influencing cytokinin concentration, gibberellin synthesis. PBZ affects the chlorophyll synthesis and positively effects the assimilation efficiency of plant. Furthermore, PBZ promotes accumulation of Proline and soluble sugars concentration. This enables the plant to maintain cell turgor and enzyme stability under stress conditions.

Reduced plant height and internodal length are the primary effects of paclobutrazole on crop growth. And PBZ also reported to increase root to shoot ratio as a result of suppressing shoot length. The information on dosage, time of application of paclobutrazole in various crops is furnished hereunder.

Conclusion:

Paclobutrazole can be understood as an effective growth regulator for Groundnut through targeted hormonal regulation, cell biology, growth habit and partitioning efficiency. It Can be used in various crops commercially at field level. However, the optimised dosage, timing and compatibility are to be studied and standardised further.



Hydroponic Fodder Production



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Introduction

Livestock farming plays a vital role in the agricultural economy of India. The country possesses one of the largest livestock populations in the world, including cattle, buffaloes, sheep, goats and poultry. However, livestock productivity in terms of milk, meat and reproductive performance remains comparatively low due to inadequate availability of quality feed and fodder. Feed alone accounts for nearly 60–70% of the total cost of livestock production, and shortage of green fodder has become one of the major constraints affecting sustainable dairy and livestock farming.



Figure 1: Hydroponic Fodder

India has only about 4–5% of its cultivable land under fodder cultivation, while the demand for nutritious green fodder is continuously increasing because of rising livestock population and shrinking grazing lands. The projected deficit of green fodder in India has been estimated at more than 60%, creating a serious challenge for farmers and dairy industries. Traditional fodder cultivation also requires large quantities of land, water, labour and favourable climatic conditions, which are becoming increasingly scarce due to urbanization, industrialization and climate variability.

To overcome these challenges, hydroponic fodder production has emerged as an innovative and efficient technology. Hydroponics refers to the cultivation of plants without soil using water or nutrient-rich solutions under controlled environmental conditions. In hydroponic fodder production, cereal and legume seeds are germinated and grown for a short duration, usually 7–8 days, to produce lush green fodder mats rich in nutrients and highly palatable to livestock.

Hydroponic fodder technology has gained importance because it can produce green fodder throughout the year using minimal land and water. The method is especially suitable for areas facing water scarcity, land limitations and erratic climatic conditions.

Concept of Hydroponic Fodder Production

The word “hydroponics” is derived from the Greek words “Hydro” meaning water and “Ponic” meaning working. Hydroponics is therefore the science of growing plants without soil by providing water, nutrients and suitable environmental conditions directly to the plant roots.

Hydroponic fodder production involves the germination and growth of fodder crops such as maize, barley, jowar, cowpea, horse gram and millets in specially designed trays or chambers. Seeds are soaked in water, allowed to germinate and then spread in trays inside hydroponic chambers. Water is supplied through sprinklers or foggers at regular intervals. Within 7–8 days, dense green fodder mats are formed consisting of shoots, roots and partially germinated seeds. These mats are directly fed to livestock.

Unlike conventional fodder cultivation, hydroponic systems do not require soil, fertilizers or pesticides. The fodder is produced under controlled temperature and humidity conditions, ensuring rapid growth and uniform

quality. Hydroponic fodder is highly nutritious because the sprouting process activates enzymes, increases digestibility and enhances nutrient availability.

The technology has two major components:

1. **Plant physiology and nutrition** – providing optimum conditions for seed germination and plant growth.
2. **Engineering and environmental control** – maintenance of temperature, humidity, light and water supply within the hydroponic chamber.

Importance of Green Fodder

Green fodder is considered the natural and most nutritious feed for livestock. It improves digestion, enhances milk yield and increases reproductive efficiency. Green fodder is rich in vitamins, minerals, carotenoids and omega-3 fatty acids, which improve animal health and milk quality.

The importance of green fodder includes:

- Improves milk production and fat percentage.
- Supplies essential vitamins and minerals.
- Enhances reproductive performance.
- Improves animal immunity and health.
- Reduces dependence on concentrate feed.
- Maintains rumen health and digestion.

Due to increasing fodder deficits and shrinking grazing lands, hydroponic fodder has become an effective alternative for continuous supply of fresh green feed.

Advantages of Hydroponic Fodder Production

Hydroponic fodder production offers several advantages over conventional fodder cultivation systems.

1. Water Conservation

Hydroponic systems consume significantly less water. Only about 2–3 litres of water are required to produce 1 kg of green fodder compared to 80–90 litres in conventional methods. This results in nearly 95–98% water saving.

2. Minimal Land Requirement

Hydroponic fodder production requires very less area. Approximately 480 square feet area is sufficient to produce around 1000 kg of green fodder daily, whereas conventional methods may require 25 acres of land.

3. Faster Growth

Hydroponic fodder is ready within 7–8 days, whereas conventional fodder crops generally require 45–60 days.

4. Round-the-Year Production

The technology allows continuous fodder production throughout the year irrespective of rainfall, season or climatic conditions.

5. High Nutritional Value

Hydroponic fodder contains higher crude protein, enzymes, vitamins and minerals. The fodder is highly digestible and palatable to livestock.

6. Reduced Labour Requirement

Only 2–3 hours of labour per day is generally required for managing a hydroponic fodder unit.

7. Chemical-Free Production

Hydroponic fodder is produced without pesticides or herbicides, making it safe and environmentally friendly.

Crops Suitable for Hydroponic Fodder

Various cereal and legume crops can be successfully grown under hydroponic systems. Commonly used crops include:

- Maize
- Barley
- Jowar
- Bajra
- Ragi
- Cowpea
- Horse gram

- Sun hemp
- Foxtail millet
- Kodo millet
- Little millet
- Moth bean

Among these crops, maize is the most commonly preferred due to its high biomass production and excellent palatability.



Figure 2: Hydroponic Fodder Production Unit

Procedure for Hydroponic Fodder Production

1. Seed Selection and Cleaning

Healthy seeds with high germination percentage are selected. Broken and damaged seeds are removed and seeds are washed thoroughly to eliminate dirt and impurities.

2. Seed Soaking

Seeds are soaked in clean water or stimulant solution for specific durations depending on crop type. Maize seeds generally require about 20 hours of soaking.

3. Germination

After soaking, seeds are wrapped in moist gunny bags and allowed to germinate for 24 hours under shaded conditions. During germination, seed weight increases by 35–40% due to water absorption.

4. Tray Loading

Germinated seeds are evenly spread in clean trays and placed on racks inside the hydroponic chamber.

5. Watering and Environmental Control

Water is sprinkled regularly through automated sprinklers or foggers. Temperature and humidity are maintained under controlled conditions for optimum growth.

6. Shifting of Trays

Trays are shifted daily from one rack level to another to maintain uniform growth stages.

7. Harvesting

Hydroponic fodder becomes ready within 8–9 days and is harvested as a complete fodder mat containing shoots, roots and germinated grains.

Nutritional Composition of Hydroponic Fodder

Hydroponic fodder is rich in crude protein, digestible nutrients and minerals. Nutritional quality varies with crop species and growth stage.

For example, hydroponic maize fodder at 8 days contains approximately:

- Crude Protein (CP): 10.55%
- Crude Fibre (CF): 5.51%
- Ether Extract (EE): 4.62%

Leguminous fodders such as sun hemp and horse gram possess even higher crude protein content, reaching up to 38%. Hydroponic fodder is highly digestible because sprouting converts complex compounds into simpler forms, improving nutrient availability.

Effect on Livestock Productivity

Several studies have demonstrated positive effects of hydroponic fodder feeding on livestock productivity.

Research conducted in Maharashtra reported an increase of 0.5–2.5 litres of milk per animal per day after feeding hydroponic fodder. Another study observed a 13.7% increase in milk yield and improved feed conversion efficiency in dairy cows fed hydroponic maize fodder.

Benefits observed in livestock include:

- Increased milk production
- Higher milk fat percentage
- Better fertility and conception rate
- Faster body weight gain
- Reduced feed cost
- Improved immunity and health
- Better digestibility and palatability

Constraints and Challenges

Despite its advantages, hydroponic fodder production also faces certain limitations.

1. High Initial Investment

Commercial hydroponic machines and environmental control systems require substantial capital investment.

2. Dependence on Electricity

Continuous power supply is essential for lighting, water circulation and temperature control.

3. Risk of Fungal Growth

High humidity conditions may encourage fungal contamination if proper sanitation is not maintained.

4. Requirement of Good Quality Seeds

Poor quality seeds reduce germination percentage and fodder yield.

5. Technical Management

Farmers require proper training for maintaining hygiene, water quality and environmental conditions.

Future Prospects of Hydroponic Fodder in India

Hydroponic fodder production has tremendous potential in India, especially in drought-prone, peri-urban, hilly and water-scarce regions. With increasing pressure on land and water resources, hydroponics offers a sustainable alternative for livestock feeding. Government support through subsidy schemes, training programmes and research initiatives can promote adoption of hydroponic systems among farmers. Development of low-cost rural-friendly hydroponic devices by institutions such as TANUVAS can make the technology affordable for small and marginal farmers. Integration of hydroponic fodder units with dairy farming can significantly improve livestock productivity, reduce feed scarcity and enhance farmers' income.

Conclusion

Hydroponic fodder production is an innovative and sustainable technology capable of addressing the growing fodder deficit in India. The system requires less land, water and labour while producing highly nutritious green fodder throughout the year. Hydroponic fodder improves livestock productivity, milk yield, reproductive efficiency and overall animal health. Although challenges such as high initial investment and technical management exist, the long-term benefits of hydroponic fodder production make it a promising solution for future

livestock farming. With increasing awareness, technological improvements and institutional support, hydroponic fodder production can play a significant role in strengthening the dairy and livestock sector in India.

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Utilization of Fish By-products for Value Addition



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Abstract

The rapid growth of the global fisheries and aquaculture sectors has significantly increased the generation of fish-processing by-products. These by-products, including heads, skin, scales, bones, viscera, and fins, constitute nearly 50–70% of the total fish biomass and are often discarded as waste. Improper disposal of fish waste creates environmental pollution and economic losses. However, fish by-products are rich sources of proteins, collagen, gelatin, omega-3 fatty acids, enzymes, minerals, and bioactive compounds that can be transformed into high-value products for the food, pharmaceutical, cosmetic, agricultural, and biomedical industries. This paper reviews the various methods used for the valorization of fish by-products and highlights their industrial applications. Recent advances in extraction technologies, bioactive peptide production, and circular bioeconomy approaches have enhanced the sustainable utilization of fish waste. The study concludes that efficient utilization of fish by-products can reduce environmental burdens, improve profitability in the seafood industry, and support sustainable development.

Keywords: By-products, Waste, Utilization, Sustainable, Valorization

Introduction:

Fish and fishery products are among the most important sources of animal protein worldwide. The expansion of aquaculture and seafood processing industries has resulted in a large quantity of fish-processing residues. During fish processing, edible portions account for only 30–50% of the total body weight, while the remaining parts such as skin, bones, heads, scales, fins, and viscera are discarded as waste (Ghalamara et al., 2024).

Traditionally, fish-processing wastes were used for low-value applications such as fishmeal and fertilizers. However, recent studies have shown that fish by-products contain numerous bioactive compounds with high commercial potential (Roy et al., 2023). The concept of waste valorization and circular bioeconomy has encouraged researchers and industries to convert fish waste into valuable products.

Fish by-products are rich in collagen, gelatin, omega-3 fatty acids, peptides, enzymes, minerals, and chitin/chitosan compounds, which have broad applications in nutraceuticals, pharmaceuticals, cosmetics, and functional foods (Jimenez-Champi et al., 2024). Therefore, effective utilization of fish by-products is essential for environmental sustainability and economic growth.

Types of Fish By-products:

1. Fish heads – rich in proteins, oils, and enzymes.
2. Fish skin – major source of collagen and gelatin.
3. Fish bones – rich in calcium and minerals.
4. Fish scales – source of collagen and hydroxyapatite.
5. Viscera – contain digestive enzymes and oils.
6. Fins and tails – useful for gelatin extraction.

Nutritional and Bioactive Components of Fish By-products:

Proteins and Peptides

Fish waste contains high-quality proteins and essential amino acids. Enzymatic hydrolysis of fish proteins produces bioactive peptides with antioxidant, antimicrobial, antihypertensive, and anti-inflammatory activities (Li et al., 2024).

Collagen and Gelatin

Fish skin, bones, and scales are excellent sources of collagen and gelatin. Fish collagen is widely preferred because of its high biocompatibility and lower risk of disease transmission compared to mammalian collagen (Blanco et al., 2023).

Fish Oil and Omega-3 Fatty Acids

Fish viscera and heads are rich in fish oil containing omega-3 fatty acids such as EPA and DHA. These fatty acids help reduce cardiovascular diseases, inflammation, and neurological disorders (Roy et al., 2023).

Methods of Utilization and Value Addition:

Production of Fishmeal and Fish Silage

Fishmeal production is one of the oldest methods of utilizing fish waste. Fishmeal is a rich protein source used in poultry, livestock, and aquaculture feeds. Fish silage, produced by acidification and fermentation of fish waste, is another economical animal feed ingredient.

Extraction of Collagen and Gelatin

Collagen extraction involves acid, alkaline, or enzymatic treatment of fish skin and bones. Gelatin is produced by controlled hydrolysis of collagen. Fish-derived collagen is extensively used in cosmetics, pharmaceuticals, and biomedical engineering because of its excellent biocompatibility (Blanco et al., 2023).

Production of Bioactive Peptides

Bioactive peptides are produced through enzymatic hydrolysis of fish proteins. These peptides possess health-promoting properties such as antioxidant activity, antihypertensive effects, antimicrobial properties, and anti-obesity functions.

Industrial Applications of Fish By-products:

Food Industry

Fish by-products are utilized in protein supplements, functional foods, flavor enhancers, edible films, and food preservatives. Bioactive peptides and collagen are increasingly added to health foods due to their nutritional benefits.

Pharmaceutical Industry

Fish-derived bioactive compounds exhibit therapeutic properties including antioxidant, anti-inflammatory, antimicrobial, and anticancer activities. Fish collagen and gelatin are commonly used in capsules, wound dressings, and tissue engineering products.

Cosmetic Industry

Marine collagen and gelatin are extensively used in anti-aging creams, moisturizers, hair-care products, and facial masks. Fish collagen enhances skin elasticity and hydration.

Environmental and Economic Benefits:

Utilization of fish by-products offers several environmental and economic advantages:

- Reduction in environmental pollution
- Minimization of waste disposal problems
- Generation of additional income
- Improved sustainability in seafood industries
- Promotion of circular bioeconomy

Challenges in Utilization of Fish By-products:

Despite significant progress, several challenges remain:

1. Lack of advanced processing infrastructure.
2. High transportation and storage costs.
3. Limited awareness among small-scale processors.
4. Seasonal variability in raw materials.
5. Regulatory and quality-control issues.

Conclusion

Fish-processing by-products are no longer considered mere waste materials but valuable resources containing proteins, collagen, omega-3 fatty acids, enzymes, minerals, and bioactive compounds. Their effective utilization

contributes to environmental sustainability, waste reduction, and economic development. Sustainable valorization of fish waste can enhance resource efficiency, reduce pollution, and create additional revenue streams for the seafood industry.

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Integrated Farming System: A Sustainable Approach for Profitable Agriculture



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Introduction

Agriculture is the backbone of rural livelihoods and food security in many developing countries. However, increasing input costs, declining soil fertility, climate change, and fragmented landholdings have made conventional farming less profitable and sustainable. In this context, the Integrated Farming System (IFS) has emerged as an effective and eco-friendly farming approach that combines various agricultural enterprises in a complementary manner. It aims to maximize productivity, profitability, employment generation, and resource-use efficiency while minimizing environmental degradation.

An Integrated Farming System is a holistic agricultural approach in which different farm enterprises such as crops, livestock, poultry, fisheries, horticulture, agroforestry, beekeeping, mushroom cultivation, and biogas production are integrated on a single farm. The waste or by-products of one enterprise become the input for another, thereby reducing dependency on external inputs and improving farm sustainability.

IFS is particularly suitable for small and marginal farmers because it provides diversified income sources, reduces production risk, and ensures year-round employment and nutritional security.

Concept of Integrated Farming System

The concept of IFS is based on the principle of “nothing is waste and everything is reused.” It promotes the recycling of farm resources in a scientific and efficient manner. For example:

- Crop residues can be used as fodder for livestock.
- Animal dung can be converted into compost or biogas.
- Fish pond water enriched with nutrients can be used for irrigation.
- Poultry droppings can serve as manure for crops or fish feed.

Thus, all enterprises are interconnected and support each other, resulting in enhanced productivity and sustainability.

Objectives of Integrated Farming System

The major objectives of Integrated Farming System are:

1. To increase farm productivity and profitability.
2. To ensure sustainable use of natural resources.
3. To provide regular income and employment throughout the year.
4. To improve soil fertility and environmental health.
5. To reduce dependence on chemical fertilizers and pesticides.
6. To enhance nutritional security for farm families.
7. To minimize risks associated with monocropping.
8. To encourage efficient recycling of farm waste.

Components of Integrated Farming System

IFS include several interrelated enterprises depending on the climatic conditions, farm size, and farmer preferences.

1. Crop Production

Crop cultivation forms the base of IFS. Farmers grow cereals, pulses, oilseeds, vegetables, fruits, and fodder crops according to local suitability. Crop diversification helps improve soil health and reduce pest incidence.

Benefits

- Provides food and fodder

- Generates crop residues for livestock
- Enhances income through multiple cropping

2. Livestock Farming

Livestock such as cows, buffaloes, goats, and sheep play an important role in IFS. Animals provide milk, meat, manure, and draught power.

Benefits

- Continuous source of income
- Organic manure for crops
- Utilization of crop residues as feed

Animal dung can also be used in biogas plants to produce energy for household use.

3. Poultry Farming

Poultry farming includes the rearing of chickens, ducks, or quails for meat and eggs. It requires less space and investment.

Benefits

- Quick economic returns
- Poultry litter acts as organic manure
- Improves nutritional security through egg production

4. Fish Farming

Fish farming or aquaculture can be integrated with agriculture and livestock enterprises. Fish ponds can utilize farm waste and nutrient-rich water.

Benefits

- High protein food source
- Efficient utilization of water resources
- Additional farm income

Integrated fish farming with ducks or poultry is highly profitable because droppings serve as fish feed.

5. Horticulture

Horticultural crops such as fruits, vegetables, flowers, and medicinal plants improve farm profitability and nutritional security.

Benefits

- Higher income per unit area
- Efficient land utilization
- Improves dietary diversity

6. Agroforestry

Agroforestry involves growing trees along with crops and livestock on the same land.

Benefits

- Prevents soil erosion
- Improves soil fertility
- Provides fuelwood, fodder, and timber

7. Mushroom Cultivation

Mushroom production is an emerging enterprise in IFS that utilizes agricultural waste such as straw and husk.

Benefits

- Additional income source
- Requires little land
- Agricultural waste recycling

8. Beekeeping

Beekeeping supports pollination and increases crop productivity while producing honey and wax.

Benefits

- Enhances crop yield through pollination

- Provides additional income
- Requires low investment

Resource Recycling in Integrated Farming System

Resource recycling is the key feature of IFS. Recycling reduces production costs and environmental pollution.

Examples of Resource Recycling

Farm Enterprise	By-product/Waste	Utilization
Crop production	Crop residues	Livestock feed, compost
Livestock	Dung and urine	Biogas, organic manure
Poultry	Poultry litter	Fish feed, compost
Fish pond	Nutrient-rich water	Irrigation for crops
Biogas plant	Slurry	Organic fertilizer

This cyclic utilization improves resource efficiency and sustainability.

Advantages of Integrated Farming System

1. Increased Productivity

IFS combines crops, livestock, fisheries, and other enterprises on the same farm. The efficient utilization of land, water, and other resources increases overall farm production. It provides higher output per unit area compared to traditional single-enterprise farming.

2. Higher Profitability

IFS generates income from multiple farm enterprises throughout the year. Farmers are less dependent on a single crop or seasonal harvest for earnings. The recycling of farm resources also reduces production costs and increases net profit.

3. Employment Generation

Different farming activities create continuous work opportunities for family members. Enterprises like dairy, poultry, and mushroom cultivation provide year-round employment. IFS helps reduce rural unemployment and migration to urban areas.

4. Improved Soil Fertility

Organic manures prepared from farm wastes improve soil health naturally. Crop rotation and recycling enhance microbial activity and nutrient availability in the soil. This system maintains long-term soil productivity and reduces soil degradation.

5. Reduced Environmental Pollution

Farm wastes are effectively recycled and reused within the farming system. The use of organic inputs reduces dependence on chemical fertilizers and pesticides. IFS helps maintain ecological balance and minimizes environmental contamination.

6. Risk Reduction

Diversification of enterprises reduces the risk of complete income loss from crop failure. Farmers can earn from livestock, fishery, or poultry even during adverse climatic conditions. IFS provides economic stability against market price fluctuations and natural disasters.

7. Nutritional Security

IFS provides a variety of food products such as cereals, milk, eggs, vegetables, fruits, and fish. Farm families receive balanced nutrition from different farm enterprises. It improves food availability and health conditions in rural households.

8. Sustainable Agriculture

IFS promotes efficient utilization and conservation of natural resources. It improves biodiversity, soil health, and water-use efficiency on the farm. IFS supports environmentally friendly and climate-resilient agricultural practices.

Integrated Farming Models

Different IFS models are practiced based on regional conditions and available resources.

1. Crop-Livestock System

Combination of crop production with dairy or goat farming.

2. Crop-Fish System

Fish farming integrated with paddy cultivation or irrigation systems.

3. Crop-Livestock-Poultry System

A highly efficient model where wastes are recycled among enterprises.

4. Horticulture-Based System

Fruit orchards combined with vegetable cultivation and livestock.

Role of Integrated Farming System in Sustainable Agriculture

IFS contributes significantly to sustainable agriculture by maintaining ecological balance and reducing dependence on synthetic inputs. It conserves biodiversity, improves nutrient cycling, and enhances resilience against climate change.

The system also supports:

- Organic farming practices
- Water conservation
- Carbon sequestration
- Climate-resilient agriculture

Therefore, IFS is considered a promising strategy for achieving long-term agricultural sustainability.

Challenges in Integrated Farming System

1. Lack of Technical Knowledge among Farmers

Many farmers are unaware of scientific methods and proper management of integrated farming practices. Insufficient training and awareness limit the successful adoption of IFS models.

2. Initial Investment Requirements

Setting up multiple enterprises such as dairy, poultry, or fishery requires substantial initial investment. Small and marginal farmers often face financial difficulties in adopting IFS.

3. Limited Access to Credit and Markets

Farmers may not receive adequate loans and financial support from banks or institutions. Poor market access and price fluctuations also affect the profitability of integrated farming.

4. Inadequate Extension Services

Lack of proper guidance and technical support from agricultural extension agencies creates challenges for farmers.

Limited field demonstrations and training programs reduce awareness about IFS benefits.

5. Labour-Intensive Management

Integrated farming involves the management of several enterprises simultaneously. This requires more labour, time, and careful supervision throughout the year.

Future Prospects of Integrated Farming System

The future of IFS is highly promising due to increasing awareness regarding sustainable agriculture and climate change adaptation. Modern technologies such as precision farming, solar energy, protected cultivation, and digital advisory services can further improve the efficiency of integrated farming systems.

IFS can play a major role in:

- Doubling farmers' income
- Enhancing rural livelihoods
- Ensuring food and nutritional security
- Promoting climate-smart agriculture

Research institutions and agricultural universities are continuously developing region-specific IFS models suitable for different agro-climatic conditions.

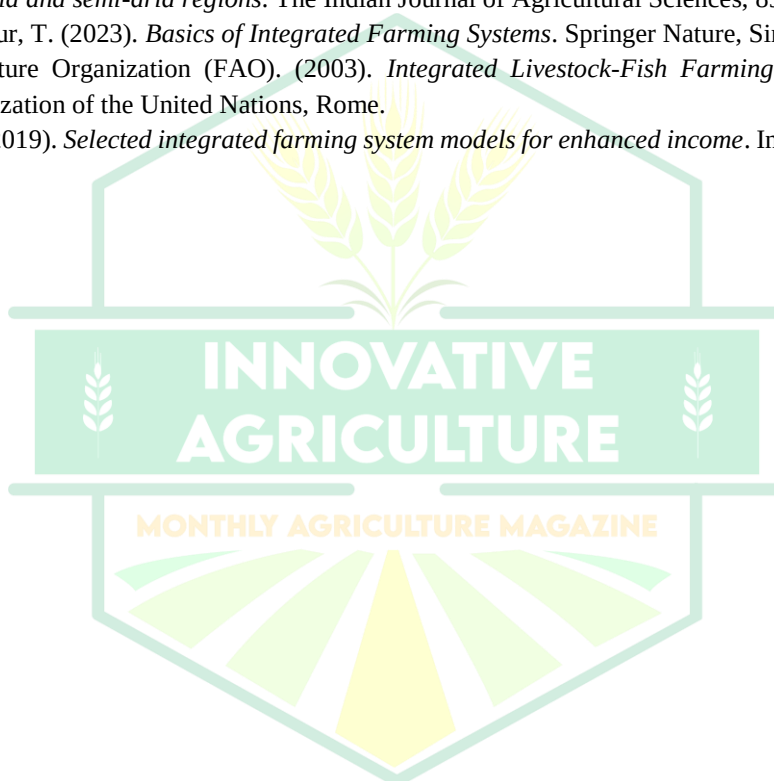
Conclusion

Integrated Farming System is an efficient, profitable, and environmentally sustainable approach to agriculture. By integrating crops, livestock, fisheries, horticulture, and other enterprises, farmers can achieve better resource utilization, higher productivity, and stable income. The recycling of wastes within the farm reduces production costs and minimizes environmental pollution.

IFS is especially beneficial for small and marginal farmers because it ensures year-round employment, nutritional security, and resilience against climatic and market risks. With proper policy support, technical guidance, and farmer awareness, IFS can become a key strategy for sustainable agricultural development and rural prosperity in the future.

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Functional Ingredients from Fruits: Role of Phenolics, Carotenoids, and Antioxidants



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Abstract

Fruits are rich sources of bioactive compounds that provide significant health benefits beyond basic nutrition. Among these, phenolics, carotenoids, and antioxidants are functional ingredients known for their protective roles against oxidative stress and chronic diseases. These compounds exhibit strong antioxidant, anti-inflammatory, and antimicrobial properties. In addition, they contribute to improving immune function, reducing cellular damage, and enhancing overall metabolic health. They also play an important role in maintaining the sensory quality and shelf life of fruits by preventing oxidative deterioration and microbial spoilage. This article presents a comprehensive analysis of phenolic compounds, carotenoids, and antioxidants derived from fruits, their mechanisms of action, and their significance in health promotion and food preservation.

1. Introduction

Fruits play a crucial role in human nutrition as they are abundant in vitamins, minerals, dietary fiber, and bioactive compounds. These components not only support basic physiological functions but also contribute to disease prevention. Fruits are considered functional foods due to the presence of compounds such as phenolics and carotenoids that provide additional health benefits. However, fruits are highly perishable due to their high moisture content and metabolic activity, which leads to rapid deterioration and nutrient loss (Kumar *et al.*, 2023). Oxidative stress, caused by an imbalance between reactive oxygen species (ROS) and antioxidant defenses, is a major factor in the development of chronic diseases. Functional compounds in fruits play a key role in neutralizing these free radicals and protecting cellular integrity. Additionally, natural antioxidants from fruits are increasingly being used as alternatives to synthetic preservatives due to concerns regarding food safety and environmental sustainability (Shahbaz *et al.*, 2022; Muthusamy *et al.*, 2024).

Furthermore, the presence of these bioactive compounds enhances the nutritional and therapeutic value of fruits, making them essential components of a balanced diet. They also contribute to improving the shelf life and quality of fruits by reducing oxidative damage and microbial spoilage. The increasing awareness among consumers regarding healthy dietary habits has led to a growing demand for fruit-based functional foods. Consequently, research on fruit-derived bioactive compounds continues to expand, highlighting their importance in both nutrition and food technology.

2. Phenolic Compounds in Fruits

Phenolic compounds are a diverse group of secondary metabolites widely present in fruits. These include flavonoids, phenolic acids, tannins, and anthocyanins. Phenolics are known for their strong antioxidant properties, which arise from their ability to donate electrons and neutralize free radicals. This helps in reducing oxidative stress and preventing cellular damage.

In addition to their antioxidant activity, phenolic compounds exhibit antimicrobial effects. Studies have shown that plant-derived phenolics can inhibit the growth of spoilage microorganisms such as bacteria and fungi, thereby extending the shelf life of fruits and vegetables (Shahbaz *et al.*, 2022; Patrignani *et al.*, 2015).

Furthermore, phenolic compounds play a significant role in maintaining the quality of fruits by reducing enzymatic browning and preserving nutritional content during storage (Li *et al.*, 2021).

3. Carotenoids in Fruits

Carotenoids are naturally occurring pigments responsible for the yellow, orange, and red coloration of fruits. Important carotenoids include β -carotene, lycopene, lutein, and zeaxanthin. These compounds are essential for human health, particularly as precursors of vitamin A, which is necessary for vision, immune function, and cellular development. Carotenoids also function as potent antioxidants by scavenging free radicals and reducing oxidative stress. Their antioxidant activity contributes to the prevention of chronic diseases such as cancer and cardiovascular disorders.

Moreover, carotenoids play a role in maintaining fruit quality by preventing oxidative deterioration during storage, thereby preserving color and nutritional value (Muthusamy *et al.*, 2024; Kumar *et al.*, 2023).

4. Role of Antioxidants in Fruits

Antioxidants are compounds that inhibit oxidation and protect cells from damage caused by free radicals, which are highly reactive molecules capable of inducing cellular injury and accelerating aging processes. Fruits are rich sources of natural antioxidants such as vitamin C, vitamin E, phenolic compounds, and carotenoids, all of which play a vital role in maintaining physiological balance and protecting against oxidative stress. These compounds act either by directly scavenging free radicals or by enhancing the body's endogenous antioxidant defense systems.

These antioxidants contribute significantly to human health by:

- Reducing oxidative stress, thereby minimizing cellular damage and maintaining metabolic stability
- Preventing inflammation, which is a key factor in many chronic and degenerative diseases
- Enhancing immune response, helping the body defend against infections and environmental stressors
- Lowering the risk of chronic diseases, including cardiovascular diseases, cancer, diabetes, and neurodegenerative disorders

In addition to their health-promoting effects, antioxidants derived from fruits play a crucial role in food systems. They act as natural preservatives by delaying oxidative reactions that lead to spoilage, inhibiting enzymatic browning caused by enzymes such as polyphenol oxidase, and maintaining the overall physicochemical and sensory quality of fruits and vegetables during storage (Muthusamy *et al.*, 2024; Shahbaz *et al.*, 2022).

Furthermore, botanical antioxidants are increasingly being utilized as safe and eco-friendly alternatives to synthetic preservatives, as they leave minimal toxic residues and are biodegradable in nature (Kumar *et al.*, 2023). Their incorporation into modern food preservation systems not only improves shelf life but also aligns with the growing consumer demand for natural, clean-label, and sustainable food products.

5. Mechanisms of Action

5.1 Free Radical Scavenging

Phenolics and carotenoids neutralize reactive oxygen species by donating electrons, thereby preventing oxidative damage to cells.

5.2 Metal Chelation

Phenolic compounds bind metal ions, reducing their role in generating free radicals.

5.3 Enzyme Inhibition

These compounds inhibit oxidative enzymes such as polyphenol oxidase, which are responsible for browning and deterioration of fruits.

5.4 Antimicrobial Activity

Bioactive compounds disrupt microbial cell membranes and interfere with metabolic processes, leading to reduced microbial growth and delayed spoilage (Patrignani *et al.*, 2015; Shahbaz *et al.*, 2022).

6. Health Implications

Regular consumption of fruits rich in phenolics, carotenoids, and antioxidants is associated with numerous health benefits. These include reduced risk of cardiovascular diseases, protection against cancer, anti-inflammatory effects, improved immune function, and enhanced eye health. The presence of these compounds in fruits contributes significantly to disease prevention and overall health improvement.

7. Industrial and Nutritional Applications

Functional ingredients derived from fruits have wide applications in food and pharmaceutical industries. They are used in the development of functional foods, nutraceuticals, dietary supplements, and natural preservatives. Botanical compounds such as plant extracts and essential oils are increasingly used in post-harvest preservation to maintain fruit quality and extend shelf life (Anjum *et al.*, 2024; Ghosh *et al.*, 2024). Additionally, advances in technologies such as nano-emulsions and edible coatings have enhanced the effectiveness of these natural compounds in food preservation (Wang *et al.*, 2025; Shan *et al.*, 2023). Furthermore, these innovations improve the stability, bioavailability, and controlled release of bioactive compounds, thereby increasing their efficiency in maintaining product quality. The growing consumer preference for natural and chemical-free food products has further accelerated the adoption of fruit-derived functional ingredients in modern food systems.

8. Conclusion

Functional ingredients derived from fruits, particularly phenolics, carotenoids, and antioxidants, play a pivotal role in promoting human health and enhancing food quality. These compounds exhibit strong antioxidant, antimicrobial, and anti-inflammatory properties, which contribute to the prevention of chronic diseases and the preservation of food products. Their natural origin and effectiveness make them promising alternatives to synthetic additives. Continued research and technological advancements will further expand their applications in sustainable food systems and health promotion. Moreover, these bioactive compounds contribute to improving nutritional security by enhancing the quality of diets and supporting overall well-being. Their incorporation into functional foods and value-added products is gaining increasing attention in both developed and developing countries. In addition, they play a significant role in reducing post-harvest losses by maintaining the physicochemical and sensory attributes of fruits. The integration of these natural compounds into modern food processing systems highlights their potential in developing safer, healthier, and more sustainable food products.

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From Compost to Cardboard: The Rise of Organic Peel Paper



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Abstract

The global push toward sustainable materials has accelerated innovation in biodegradable and eco-friendly alternatives to conventional paper and packaging. Among these innovations, organic peel paper derived from fruit and vegetable waste such as banana peels, orange rinds, and agricultural residues has emerged as a promising solution. This article explores the development, production processes, environmental benefits, economic feasibility, and future prospects of organic peel paper. By transforming organic waste into usable materials, this innovation not only reduces landfill burden but also contributes to circular economy models. The study highlights how organic peel paper can reshape the packaging industry and reduce dependence on wood-based paper production.

1. Introduction

The rapid expansion of industrialization and consumer-driven economies has significantly increased global demand for paper and packaging materials. Traditionally, this demand has been met through the large-scale harvesting of timber, making the paper industry one of the leading contributors to deforestation and environmental degradation. Forest ecosystems, which play a crucial role in maintaining biodiversity, regulating climate, and supporting livelihoods, are increasingly under threat due to unsustainable extraction practices. According to the Food and Agriculture Organization, deforestation continues at an alarming rate, with millions of hectares of forest lost annually, much of it linked to agricultural expansion and industrial uses such as pulp and paper production.

At the same time, the world faces another pressing environmental challenge: the management of organic waste. A significant proportion of municipal solid waste consists of biodegradable materials, particularly fruit and vegetable peels generated from households, markets, and food processing industries. Improper disposal of this waste leads to landfill accumulation, where it decomposes anaerobically and releases methane—a greenhouse gas far more potent than carbon dioxide. This dual challenge—resource depletion on one hand and waste accumulation on the other—has prompted researchers, policymakers, and innovators to explore sustainable, circular solutions. Organic peel paper emerges as a compelling response to these interconnected issues. By utilizing agricultural by-products such as banana peels, orange rinds, onion skins, and other cellulose-rich residues, this innovative material transforms waste into a valuable resource. The concept aligns with the principles of a circular economy, where materials are continuously reused and repurposed rather than discarded. Unlike conventional paper production, which relies heavily on virgin wood pulp and energy-intensive processes, peel-based paper leverages existing biomass, thereby reducing both environmental impact and production costs.

Moreover, the development of organic peel paper reflects broader shifts in material science and sustainable design. Advances in green chemistry and eco-friendly processing techniques have made it possible to extract cellulose fibers from unconventional sources without relying on harmful chemicals. This not only minimizes pollution but also enhances the safety and biodegradability of the final product. As global awareness of environmental sustainability grows, industries are increasingly seeking alternatives that balance functionality with ecological responsibility.

In addition, the rise of organic peel paper is closely tied to changing consumer preferences. Modern consumers are more informed and environmentally conscious, often favoring products that are biodegradable,

recyclable, and ethically produced. This shift in demand has encouraged businesses to adopt sustainable materials and invest in innovative packaging solutions. Organic peel paper, with its low environmental footprint and unique aesthetic qualities, is well-positioned to meet these evolving expectations.

This article aims to explore the rise of organic peel paper as a sustainable alternative to traditional paper products. It examines the materials and processes involved in its production, evaluates its environmental and economic implications, and discusses its potential applications and future prospects. By analyzing this emerging innovation, the paper highlights how simple organic waste can be transformed into a powerful tool for environmental conservation and sustainable development.

2. Raw Materials and Production Process

Organic peel paper is typically produced from agricultural waste such as banana peels, citrus rinds, onion skins, and corn husks. These materials are rich in cellulose, a key component required for paper production.

2.1 Collection and Preparation

Peels are collected from households, food processing industries, or agricultural markets. They are then cleaned and dried to remove impurities and excess moisture.

2.2 Pulping Process

The dried peels undergo mechanical or chemical pulping. In some methods, natural binders or mild alkaline treatments are used to break down lignin and hemicellulose, releasing cellulose fibers.

2.3 Sheet Formation

The pulp is spread into thin layers and pressed into sheets. These sheets are then dried under controlled conditions to form durable paper.

2.4 Finishing

Depending on the intended use, the paper may be treated for smoothness, strength, or water resistance using eco-friendly coatings.

This process requires significantly less energy and water compared to traditional wood pulp processing, making it a more sustainable alternative.

3. Environmental Impact

The environmental benefits of organic peel paper are substantial and multifaceted.

3.1 Waste Reduction

Organic waste often ends up in landfills, where it decomposes and produces methane a potent greenhouse gas. Converting this waste into paper reduces landfill burden and emissions.

3.2 Deforestation Mitigation

Traditional paper production depends heavily on logging. By substituting wood pulp with agricultural waste, organic peel paper reduces pressure on forests.

3.3 Lower Carbon Footprint

The lifecycle emissions of peel-based paper are significantly lower due to reduced energy use and the recycling of existing biomass.

3.4 Biodegradability

Unlike synthetic packaging materials, organic peel paper decomposes naturally without leaving toxic residues, aligning with global sustainability goals such as those outlined in the United Nations Sustainable Development Goals (SDGs).

4. Economic Viability

The economic potential of organic peel paper lies in its dual role as a waste management solution and a value-added product.

4.1 Cost Efficiency

Raw materials are essentially free or low-cost, as they are derived from waste streams. This reduces production costs compared to wood-based paper.

4.2 Employment Opportunities

The collection, processing, and manufacturing of peel paper can create jobs, particularly in rural and agricultural communities.

4.3 Market Demand

With increasing consumer awareness of sustainability, there is growing demand for eco-friendly packaging. Companies are actively seeking alternatives to plastic and conventional paper.

4.4 Circular Economy Integration

Organic peel paper supports circular economy principles by turning waste into resources, thereby minimizing environmental impact while generating economic value.

5. Applications and Case Studies

Organic peel paper has a wide range of applications:

5.1 Packaging Industry

It is increasingly used for biodegradable packaging, including bags, wraps, and containers.

5.2 Stationery Products

Notebooks, envelopes, and greeting cards made from peel paper are gaining popularity among environmentally conscious consumers.

5.3 Art and Craft

Artists and designers value the unique textures and natural aesthetics of peel-based paper.

5.4 Real-World Innovations

Startups and research institutions worldwide are experimenting with peel-based materials. For example, initiatives in India and Southeast Asia are using banana fiber and agricultural residues to create sustainable paper alternatives.

6. Challenges and Limitations

Despite its promise, organic peel paper faces several challenges:

6.1 Scalability

Large-scale production requires consistent supply chains for raw materials, which can be difficult to maintain.

6.2 Quality Consistency

Variability in raw materials can lead to inconsistencies in texture, strength, and durability.

6.3 Processing Limitations

Some organic materials require additional processing to achieve the same quality as traditional paper.

6.4 Market Competition

Established paper industries benefit from economies of scale, making it challenging for new alternatives to compete on price and distribution.

7. Future Prospects

The future of organic peel paper is closely tied to advancements in material science and sustainable technology.

7.1 Technological Innovation

Improved pulping techniques and natural additives can enhance the strength and versatility of peel paper.

7.2 Policy Support

Government incentives and environmental regulations can encourage the adoption of sustainable materials.

7.3 Consumer Awareness

As awareness grows, demand for eco-friendly products is expected to increase, driving market expansion.

7.4 Integration with Other Technologies

Combining peel paper with innovations such as biodegradable coatings and smart packaging could further expand its applications.

8. Conclusion

Organic peel paper represents a transformative approach to both waste management and sustainable manufacturing. By converting organic waste into valuable products, it addresses critical environmental challenges such as deforestation, landfill overflow, and carbon emissions. While challenges remain in terms of scalability and consistency, ongoing research and innovation are likely to overcome these barriers. As industries and consumers increasingly prioritize sustainability, organic peel paper has the potential to become a mainstream alternative, paving the way for a greener and more circular economy.

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Assessing Heat-Induced Yield Loss in Mango: Vulnerabilities and Mitigation Strategies



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The mango (*Mangifera indica*) is a primary global fruit crop recognised as King of tropical fruits, serving as a national symbol for India, Pakistan, the Philippines, and Bangladesh. It accounts for 50% of all tropical fruit production worldwide, with 70% of this output concentrated in Asia. India is the leading global producer, contributing approximately 43% of total yield roughly 20.92 million metric tons across 2.33 million hectares in 2022-23. Cultivation is centred in Uttar Pradesh, Andhra Pradesh, Karnataka, Bihar, and Gujarat. India's export market is equally significant; in 2023-24, the nation exported 30.03 thousand metric tons (valued at 46,061.39 lakhs), primarily from Maharashtra and Gujarat to the UAE, UK, and USA. This data highlights the mango's dominance in both international trade and regional agricultural economies.

Global & National Challenge:

This King of Fruits in tropical climates is currently facing an unprecedented physiological crisis due to the intensification of global warming. Historically, these trees thrived within a stable temperature bracket of 24°C to 30°C, but the modern climate reality frequently pushes orchard temperatures beyond the critical 40°C threshold (Muthuramalingam *et al.*, 2023). This shift has transformed heat from a manageable environmental factor into a primary driver of agricultural instability. Recent data indicates that the frequency of extreme heat waves during sensitive phenological stages such as flowering and fruit set has surged by approximately 25% over the last decade, leading to catastrophic yield gaps in major producing regions like India and Mexico (Ashraf *et al.*, 2026).

Across India's major mango belts from the fertile Gangetic plains of Uttar Pradesh to the coastal stretches of Maharashtra and the arid plateaus of Andhra Pradesh this balance is being shattered. Recent data from the 2024–2026 seasons shows ambient temperatures frequently surging to 41°C–47°C, turning heat from a manageable seasonal variable into a primary abiotic stressor that destabilizes the entire production cycle. Compounding this vulnerability, in 2024, India experienced its warmest year since 1901, with temperatures +0.65°C above average (IMD, 2024). In 2025, India's annual mean temperature was +0.28°C above the long-term average, marking it the eighth warmest year on record. January and February recorded extreme anomalies of +0.98°C and 1.36°C, respectively among the highest monthly temperatures since 1901. Farmers have reported early flowering, reduced fruit sweetness, lower yields due to poor fruit set, and shortened pickle shelf-life, indicating climate-induced stress on agriculture.

Heat Crisis in Karnataka:

This challenge is particularly acute in Karnataka, India's fourth-largest mango producer. The state's mango heartlands comprising the high-density belts of Kolar (Srinivasapur), Chikkaballapur, Ramanagara, and the coastal districts of Dharwad and Belagavi—are facing a new climatic normal. While Karnataka's output is projected to

rise by 20% in 2026 due to favourable early flowering, this potential is constantly threatened by late-season heatwaves (Fresh Plaza, 2026).

In the 2024 season, Karnataka emerged as a primary mango sourcing region with superior availability relative to neighbouring states, attributable to favourable rainfall and extensive cultivation. Despite this, total production declined from the previous year due to poor fruit set. Alphonso mangoes exhibited high quality, characterized by excellent colour, flavour, and elevated Brix levels from reduced fruit water content. The peak season spanned April–June, with harvesting and processing commencing in the second week of May. However, the high-value Alphonso (Badami) orchards in the Belagavi and coastal belts are increasingly plagued by spongy tissue, a heat-induced ripening disorder that renders the fruit commercially unviable. Simultaneously, in the dry-land belts of Southern Karnataka, the ubiquitous Totapuri and Mallika varieties face severe mummification and sunscald as the trees reach their thermal breaking point.

In contrast, for 2026, the state which produced 13–14 lakh metric tonnes of mangoes last season—faces a projected yield of 9–10 lakh metric tonnes. Officials from the Karnataka State Mango Development and Marketing Corporation Limited attribute this decline to unseasonal rainfall, persistent humidity, cloudy weather, and sudden pest infestations, which caused substantial fruit drop and disrupted exports and local supply chains. Major Alphonso production hubs, including Ramanagara, Kolar, and Srinivasapur (Kolar district), have been severely affected.

In Karnataka's mango heartlands, escalating this tropical heat poses not only a scientific challenge but also a fundamental threat to the state's economic heritage, necessitating an urgent transition to climate-resilient orchard management practices.

Impact of heat waves (high temperature) on yield and quality of mango:

1. Physiological and Biochemical Disruptions

The physiological impact of heat stress on mangoes begins with the disruption of the photosynthetic apparatus and water management systems. When ambient temperatures rise, the mango tree experiences an increase in vapor pressure deficit (VPD), which pulls moisture from the leaves and fruit at an unsustainable rate. To prevent total dehydration, the tree closes its stomata, but this defence mechanism creates a bottleneck that prevents carbon dioxide from entering the leaves. Consequently, the enzyme Rubisco begins to fix oxygen instead of CO_2 through photorespiration, a process that wastes energy and reduces dry matter accumulation. At the cellular level, extreme heat directly damages photosystem II (PSII), the most thermally sensitive component of the photosynthetic chain, often leading to chlorosis or sunburn on the fruit surface as chlorophyll degrades under thermal stress.

Biochemically, high temperatures trigger an oxidative burst characterized by the overproduction of reactive oxygen species (ROS). These unstable molecules, such as hydrogen peroxide and superoxide radicals, attack the lipid bilayer of cell membranes through lipid peroxidation. This causes the membranes to become leaky, leading to the loss of electrolytes and cellular compartmentation. In mangoes, this internal breakdown often precedes physiological disorders like spongy tissue and jelly seed. Although the plant attempts to mitigate this damage by producing heat shock proteins (HSPs) which act as molecular chaperones to stabilize denaturing proteins prolonged exposure to temperatures above 40°C typically overwhelms these natural defence mechanisms.

The ripening chemistry of mango fruit is also fundamentally altered by heat, leading to significant quality degradation. High temperatures accelerate the activity of enzymes like polygalacturonase and pectin methyl esterase, which break down cell walls and cause the fruit to soften prematurely or become mummified. Furthermore, the balance between sugars and acids is disrupted; organic acids (malic and citric) are rapidly consumed as respiratory substrates, while the conversion of starch to sugar occurs so quickly that it can lead to a fermented flavour profile. This is compounded by a shift in volatile organic compounds (VOCs), where the typical fruity terpenes are replaced by off-flavours like ethanol and acetaldehyde, leaving the fruit with a flat, alcoholic, or overly pungent taste that reduces its market value.

2. Phenological Disruptions:

The phenological cycle of the mango is highly dependent on specific temperature windows, and heat stress acts as a primary disruptor of these natural rhythms. One of the most critical impacts occurs during the transition from vegetative to reproductive growth; extreme heat can cause vegetative reversion, where buds that were intended

to become flowers revert into leafy shoots, or shy flowering, where floral induction is delayed or erratic. When flowering does occur under high-temperature regimes, the entire phenophase is drastically compressed. Research indicates that a rise in average temperature can shorten the flowering duration by nearly half, reducing the window for successful pollination. Furthermore, individual flower longevity is truncated, meaning the blossoms wither before they can be effectively fertilized, leading to poor fruit set.

During the anthesis and pollination phase, heat stress creates a physiological asynchrony between male and female reproductive organs. High temperatures often lead to the desiccation of the stigma and the abortion of pollen grains, rendering the flowers sterile.

Interestingly, warm temperatures may increase the rate of anther dehiscence (release of pollen), but this is often negated by reduced pollen viability. Even if pollination occurs, the heat can inhibit pollen tube growth, preventing fertilization from reaching the ovary (Shu, 1999; Liu *et al.*, 2023). This disruption is often compounded by the behaviour of pollinators; extreme heat reduces the activity of the insects required for cross-pollination, leading to a further decline in the number of fruits that successfully develop. In some cases, the burning of delicate panicles under intense solar radiation causes the entire floral structure to drop prematurely, a phenomenon known as panicle necrosis (Liu *et al.*, 2023; Lisann Dias, 2025).

As the fruit enters the development and maturity stages, heat stress continues to accelerate the phenological timeline to the detriment of fruit quality. Elevated temperatures trigger a spike in Absciscic Acid (ABA) and ethylene, which signals the tree to shed its fruit early, resulting in massive fruit drop during heatwaves. For the fruits that remain on the tree, the rapid metabolic rate forced by the heat leads to premature ripening. While this might suggest an earlier harvest, the fruit often fails to accumulate sufficient biomass or develop complex flavour profiles, resulting in smaller, mummified, or undersized mangoes. This compression of the fruit-filling stage ensures that the mangoes reach physiological maturity before they have reached their full physical and chemical potential.

3. Quality Deterioration:

Excessive heat often manifests as visible physical damage, which immediately reduces the commercial value of the crop. High temperatures (up to 47°C) cause burning symptoms characterized by blackened tips and yellow halos on the fruit skin (Damodaran *et al.*, 2025). Heat accelerates transpiration and respiration, leading to significant physiological loss in weight (PLW); for instance, Dashehari mangoes ripened at room temperature or higher show much higher PLW (14.7%) compared to those kept at 20°C, leading to shrivelling and loss of turgidity (Gill *et al.*, 2017). High heat also accelerates the activity of cell-wall degrading enzymes (like polygalacturonase and cellulase), causing the fruit to soften prematurely or unevenly, and in severe cases, this leads to tissue mummification (Damodaran *et al.*, 2025; Gill *et al.*, 2017).

The internal chemistry of the mango is highly sensitive to thermal stress, leading to imbalances in sweetness and flavour. Heat stress causes an abnormal spike in total soluble solids (TSS), with affected areas in sensitive genotypes found to have TSS levels exceeding 25°Brix, indicating a forced and often unbalanced ripening process (Damodaran *et al.*, 2025). While starch-to-sugar conversion is accelerated, the natural degradation of organic acids (titratable acidity) happens too quickly at high temperatures (40°C), which can leave the fruit with a flat or overly sweet taste without the characteristic mango acidity (*Indian Journal of Horticulture*, 2023). Heat waves modulate metabolic pathways, specifically altering aroma compounds like caryophyllene and humulene, which can create off-flavors or a reduction in the complex fruity bouquet expected of elite cultivars (Khanum *et al.*, 2020; Damodaran *et al.*, 2025).

Certain silent disruptions occur within the pulp that may not be visible until the fruit is cut open. In heat-sensitive cultivars like Alphonso, high temperatures are a primary trigger for spongy tissue formation, while in Dashehari, it manifests as internal tissue breakdown, both of which make the fruit inedible (Damodaran *et al.*, 2025). Molecular analysis shows that intense heat waves (44°C) activate the GABA-shunt pathway and increase the expression of stress-related genes like glutathione S-transferase 1, indicating the fruit is actively fighting oxidative damage at the cost of its nutritional quality (Khanum *et al.*, 2020).

The cumulative effect of these disruptions is a drastically reduced post-harvest life. Higher temperatures increase ethylene production and respiration rates, pushing the fruit toward senescence (aging) much faster than

normal. The loss of membrane integrity and the breakdown of protective waxes at high temperatures make the fruit more susceptible to post-harvest pathogens, further shortening its shelf life.

4. Internal and external Disorders:

Heat stress is a primary environmental factor that triggers several physiological and chemical disorders in mango. When temperatures exceed critical thresholds, the plants internal metabolic regulation fails, leading to symptoms that range from localized tissue death to systemic failure of the fruit to ripen properly.

Spongy tissue is perhaps the most notorious heat-induced disorder, particularly affecting the Alphonso cultivar. It is caused by high temperatures and convective heat from the soil, where excessive heat within the fruit inactivates ripening enzymes, preventing a specific patch of the pulp from ripening normally. The affected area remains as a yellowish-white, corky, and acidic patch within the otherwise ripe pulp. Studies using oxygen isotope analysis show that spongy tissue is characterized by low transpiration and high respiration rates, which leads to a buildup of heat and eventual tissue breakdown (Shivashankar, 2008).

Internal tissue breakdown is similar to spongy tissue but observed in different cultivars like Dashehari and Chiin Hwang. Elevated temperatures disrupt the regular process of converting starch into soluble sugars, often initiating a detrimental anaerobic respiration pathway within the fruit (Lin *et al.*, 2013). It manifests as a disintegration of the internal pulp, often accompanied by a fermented odor or jelly-like consistency (Kushwaha *et al.*, 2025).

Recent research on extreme heat waves (temperatures 41--47°C) has identified acute physical disorders like burning and tissue mummification. Chronic exposure to extreme heat combined with high solar radiation leads to lethal cellular injury and total loss of membrane semipermeability. Affected fruits show blackened tips surrounded by a yellow halo, and in severe cases, the entire fruit undergoes mummification, where it dries up and shrivels while still on the tree (Kushwaha *et al.*, 2025).

Lumpy and ricey tissue disorders are linked to the uneven ripening caused by heat-induced metabolic shifts. Lumpy tissue is characterized by high starch concentrations (up to 18.46%) that fail to break down into sugars during the ripening phase due to enzymatic inactivation (Lin *et al.*, 2013). Ricey tissue is a condition where the pulp texture becomes granular or rice-like due to heat-accelerated maturation that prevents uniform starch degradation.

Pitting necrosis, while often linked to calcium (Ca) deficiency, is exacerbated by heat stress that disrupts the transpiration stream carrying Ca to the fruit; low Ca levels (down to 0.008%) lead to cell wall collapse and necrotic pits (Lin *et al.*, 2013). Fruit cracking occurs when high temperatures are compounded by water scarcity and low relative humidity, causing the fruits skin to lose elasticity and crack under internal pressure (Kushwaha *et al.*, 2025).

5. Ripening and Shelf Life:

Heat stress acts as a major catalyst for accelerated senescence in mangoes, primarily by disrupting the hormonal and enzymatic regulation of ripening. High temperatures trigger a premature spike in ethylene production, which signals the fruit to begin ripening before it has achieved full physiological development. This results in a drastically shortened shelf life, as the fruit moves from harvest-mature to overripe in a fraction of the usual time (Hossain *et al.*, 2014). Furthermore, heat-stressed mangoes exhibit a higher respiration rate and increased physiological loss in weight (PLW) due to excessive transpiration, which leads to rapid shriveling and loss of fruit turgidity (Gill *et al.*, 2017).

The biochemical quality of the fruit during this shortened ripening window is often poor. High temperatures (above 35°C) accelerate the activity of pectin-degrading enzymes like polygalacturonase and pectin methyl esterase, causing the pulp to lose its structural integrity and become excessively soft or mushy (Hossain *et al.*, 2014). Additionally, while starch-to-sugar conversion is fast-tracked, the natural degradation of organic acids is also accelerated, resulting in a fruit that may be high in total soluble solids (TSS) but lacks the characteristic flavor balance of a slow-ripened mango (Gill *et al.*, 2017). The breakdown of cellular membranes under thermal stress also makes the fruit highly susceptible to post-harvest pathogens, such as anthracnose and stem-end rot, further compromising its marketability (Muthuramalingam *et al.*, 2023).

6. Pest and Disease resurgence:

High temperatures, heat waves, and humidity fluctuations, coupled with erratic weather (e.g., premature warm spells, sudden spikes, cool nights/warm days, morning dew), promote pest and disease resurgence in mango. These factors enhance pest reproductive rates, metabolic activity, oviposition, hatching, population peaks, and pathogen development, resulting in secondary effects such as sooty mould from honeydew. Consequences include sap sucking, fruit blackening, flower drop, blossom blight, reduced photosynthesis, tree growth, fruit set, and yield losses up to 90%.

Key Pests and Heat-Driven Resurgence:

i. Thrips and hoppers:

Thrips have escalated from minor to major pest status in recent years, driven by their high reproductive rates in warm conditions and the indiscriminate use of pesticides. Significant positive correlations exist between thrips populations and the Humid Thermal Ratio (HTR), indicating that warm, humid weather directly promotes outbreaks.

Mango Hoppers are the most prevalent and damaging pest. Although populations persist year-round, recent observations reveal sharp spikes during February–April and June–August, periods that often coincide with temperature fluctuations (ICAR, 2024).

In 2025, mango hoppers and thrips severely reduced yield quality in Kolar and Ramanagara districts. By sucking sap from fruits, hoppers induce blackened mangoes, causing reduced market prices to ₹25–₹40 per kg far below the typical retail average of over ₹100 per kg.

In Jagtial and Warangal, mango growers reported a second consecutive year of crop loss. Sudden heat spikes in February, following a cold January, promoted Thrips and Sooty Mold (often associated with honeydew from pests), causing up to 90% of flowers to wither in some areas (Deccan Chronicle, 2026).

ii. Mealy Bug:

Recent reports from March and April 2026 confirm a significant resurgence of the mango mealybug (*Drosicha mangiferae* and *Rastrococcus invadens*) across several key belts in India. The recent population resurgence is driven by erratic weather patterns: premature warm spells in February 2026 facilitated hatching and rapid expansion during moderate phases, allowing populations to peak before the onset of lethal mid-summer extremes.

In March 2026, scientists from Tamil Nadu Agricultural University (TNAU) issued urgent guidance after detecting high infestations in orchards around Pollachi and Coimbatore district. The infestation poses a serious threat, particularly affecting tree growth, flowering, and fruit set (The Hindu, 2026).

Although the primary focus in Kolar and Ramanagara (Major mango belts of Karnataka) has been on thrips and hoppers, mealybug populations have shown a localized resurgence. High humidity in early 2026, followed by sudden dry heat, produced a honeydew effect, where pest secretions promoted sooty mold fungus and further reduced tree photosynthetic capacity in the region (The Hindu, 2026).

Reports from Karimnagar and Warangal (Major mango belts of Telangana) (March 2026) indicate that Teane Manchu (honeydew), a byproduct of mealybug and hopper activity, has devastated large-scale flowering. This marks a second consecutive year of crop loss for many farmers (Deccan Chronicle, 2026).

iii. Fruit Flies (*Bactrocera* spp.):

These continue to be a primary concern for export markets. High metabolic rates in ripening fruit during heat waves attract higher densities of female flies for oviposition (ICAR, 2024)

Key Diseases and Heat-Driven Resurgence

i. Anthracnose (*Colletotrichum gloeosporioides*):

High temperatures combined with high relative humidity are critical drivers for anthracnose outbreaks. Research indicates that specific humid thermal ratios (HTR)—the ratio of temperature to relative humidity—can be used to predict disease variability, with higher temperatures often favouring rapid pathogen development (Shukla & Adak, 2017).

ii. Powdery Mildew (*Oidium mangiferae*):

This pathogen thrives in warm, dry weather with high diurnal temperature variations (cool nights and warm days). Recent reports indicate that prolonged heat followed by morning dew in early 2026 led to massive flower drop and blossom blight symptoms in Southern India

Gujarat (January 2026): South Gujarat growers faced heightened risks of powdery mildew and anthracnose after light unseasonal showers and cloudy weather during the flowering stage increased localized humidity (Times of India, 2026).

iii. Blossom Blight:

Karnataka (March 2026): In the Haveri district, a catastrophic outbreak described as Blossom Blight (a complex of fungal and viral pathogens) wiped out nearly 90% of the yield. Despite heavy initial flowering, blossoms turned black and withered due to high humidity paired with erratic heat (News18 Kannada, 2026).



Blossom blight



Mealy Bug

Adaptation and Mitigation Strategies:

1. Strategic selection of varieties and rootstocks:

Strategic selection of resilient germplasm is a primary defense against the increasing frequency of extreme heat waves (41–47°C). Recent scientific findings from 2024–2026 emphasize that heat tolerance is not just a trait of the scion but a synergistic outcome of rootstock-scion interactions, which can buffer physiological stress through improved water relations and biochemical signalling.

- i. **Variety Selection:** Cultivars with late maturity traits, such as Amrapali and hybrids involving late-maturing parents, demonstrated better tolerance by avoiding peak heat periods, suggesting the utility of late maturity as a potential selection trait in breeding climate-resilient mango varieties (Kushwaha *et al.*, 2025).

Differential Responses of Mango Cultivars to High-Temperature Stress Events (Kushwaha *et al.*, 2025)

Resilience Category	Cultivars	Observed Impact
Highly Sensitive	Dashehari, Himsagar, Bombay Green	Up to 50–80% fruit damage; severe tissue mummification.
Moderately Sensitive	Mallika, Langra, Amrapali	25–30% of fruits affected by heat-induced lesions.
Tolerant/Late Maturing	Kesar, Rataul, Elite Hybrids	Minimal symptoms as they were immature during peak stress.

ii. Rootstock Selection:

Rootstocks serve as the initial line of resistance by sustaining transpirational cooling and nutrient uptake under high soil temperatures. Rootstocks that maintain high transpiration rates under heat stress promote leaf cooling. Recent research (2026) indicates that resistant rootstocks can induce Systemic Acquired Resistance (SAR) in the scion, thereby protecting it from both heat stress and subsequent pest/disease resurgences (Ali *et al.*, 2026).

- **Polyembryonic Rootstocks:** Uniformity in polyembryonic rootstocks (e.g., Olour, Kurukkan) is prioritized for climate-adaptive orchards.
- **Olour:** Recent trials (2021–2024) at ICAR-IARI highlight Olour as a superior rootstock for enhancing net photosynthetic rates and intercellular CO₂ concentration in scions under stress (Jain *et al.*, 2025). It maintains higher stomatal conductance and favorable gas exchange traits under thermal stress, particularly when combined with vigorous rootstocks like Olour (Jain *et al.*, 2025).

- **Vellai Kolumban:** This continues to be evaluated for its dwarfing potential, which facilitates better canopy microclimate management and reduced transpirational demand.

2. Strategic Grafting & Interstock Combinations

The use of interstocks (double-grafting) is an emerging strategy to modulate vigor and resilience.

Combination	Impact on Resilience
Olour / Mallika / Olour	Highest photosynthetic rate ($8.51 \mu\text{mol m}^{-2} \text{s}^{-1}$) and leaf total sugar content; highly resilient to thermal stress (Jain <i>et al.</i> , 2025)
Chulucanas / Julie / Kent	Reduced tree height by 11.70%, facilitating easier canopy management and protective shading (Casas-Nino <i>et al.</i> , 2025).
Olour / Amrapali / Olour	Increased Proline content ($1.06 \mu\text{g g}^{-1} \text{FW}$), acting as an osmoprotectant against dehydration during heat waves (Jain <i>et al.</i> , 2025).

3. Cultural and Orchard Management (Mitigation)

Field-level interventions can modify the microclimate of the orchard to reduce the direct impact of high solar radiation.

i. Canopy Management:

Strategic pruning enhances light penetration and air circulation, improving the internal microclimate and reducing water loss through evapotranspiration (Martins *et al.*, 2024). Maintaining an optimal canopy cover of 76–80% provides sufficient shade to protect main scaffold branches from sun-scald while ensuring adequate light reaches the lower canopy for photosynthesis (ICAR, 2024). Post-harvest pruning, through annual thinning of dead and cluttered branches, prevents an empty, leafless inner canopy and ensures internal fruit is protected by a healthy outer foliage layer (Normand and Bally, 2026). However, severe pruning should be avoided during peak heat waves, as it can cause excessive canopy temperature spikes by eliminating the transpirational cooling effect of leaves (Normand and Bally, 2026).

Modern orchard management emphasizes architectures that balance light interception with photoprotection to mitigate heat-induced oxidative stress; for instance, recent digital modeling of the Calypso cultivar demonstrates that espalier-trellis systems improve light distribution efficiency, providing a 3.6% productivity advantage per unit leaf area compared to conventional open-vase canopies by minimizing self-shading that promotes parasitic branches despite their smaller total leaf area (Cheesman *et al.*, 2025), while narrower hedge systems reduce pest prevalence like mango scale by 64–84% through enhanced air circulation and lower relative humidity that indirectly aids thermal stress tolerance (Jodie *et al.*, 2025), and judicious center-opening pruning facilitates air circulation to prevent humid-thermal pockets triggering anthracnose resurgences during heat waves (ICAR, 2024).

ii. Organic mulching:

Organic mulching serves as a biological thermal buffer protecting the rhizosphere from high temperatures, outperforming plastic mulches in tropical mango orchards by avoiding greenhouse trapping. Organic materials like paddy straw and mango leaf mulch maintain stable soil temperatures (avg. 27.23°C), reduce evaporative loss (27.8–28.5% higher moisture at 5–10 cm), and improve soil tilth/nutrients (N, P, K) for thermal stress resilience (Yasmin *et al.*, 2020; Das *et al.*, 2016). Paddy straw yields highest fruit retention (18.42 nos/panicle, 94.42 kg/plant), mango leaf mulch boosts TSS (20.20° Brix) with low acidity (0.60%), while rice straw/compost enhance minerals and microbiology; apply 6–10 Mg/ha before February/March heat in Karnataka to promote deep-root hydration via earthworms and porosity (Das *et al.*, 2017).

iii. Shade Netting:

Shade nets function as effective thermal buffers compared to open-field conditions, with all tested net colors (white, yellow, red, and pearl) significantly lowering maximum temperatures and increasing relative humidity, thereby creating a protective cooling dome that reduces transpirational shock during peak summer (Mohamed *et al.*, 2025). By elevating relative humidity, shade nets reduce the vapor pressure deficit, enabling longer stomatal opening and sustaining photosynthesis even when ambient temperatures would typically induce stomatal closure. Furthermore, research on Kensington Pride and Keitt mango cultivars indicates that shade netting virtually

eliminates sunburn damage, a major cause of fruit rejection in unshaded orchards during heat waves (Scuderi *et al.*, 2022).

Net Color	Impact on Mango (2025-2026 Findings)	Yield / Quality Outcome
White & Yellow	Optimal for Mango: Provides the best microclimate for growth; enhances water use efficiency (Mohamed <i>et al.</i> , 2025).	Highest yield and fruit count per plant.
Pearl/ Red	Increases Total Soluble Solids (TSS) and pericarp (peel) thickness; improves post-harvest shelf-life (Mohameda <i>et al.</i> , 2023).	Higher fruit mass and reduced physiological disorders.
Black	Not Recommended: Reduces light too much, leading to the lowest yields and poorer fruit quality (Mohamed <i>et al.</i> , 2025).	Lowest productivity in both Keitt and Kensington Pride trials.
Beige & Green	Improves photosynthetic rates and stem characteristics (Mohameda <i>et al.</i> , 2023).	Good yields, outperforming black nets by over 20%.



UV resistant brown paper bag

iv. Fruit covering:

Pre-harvest fruit bagging acts as a mechanical and thermal barrier protecting mangoes from extreme solar radiation and temperatures, while stabilizing microenvironment temperature, enhancing relative humidity, and reducing ripening and water loss versus unbagged fruits (Kushwaha *et al.*, 2025). In Himsagar and Mallika, it induces a diurnal temperature cut-off, preventing lethal surface peaks, dampening nocturnal fluctuations, and minimizing transpiration disorders like shrivelling and blackened tips via elevated humidity in brown paper or polybags (Dutta and Majumder, 2012; Kushwaha *et al.*, 2025).

Bagging material balances UV filtration, thermal buffering, and gas exchange. Brown or white paper bags optimize UV protection and light transmission, increasing fruit weight, soluble solids, ascorbic acid, and phenolics; black polythene raises internal heat, suiting growth but not heat mitigation (Kumari *et al.*, 2025). Muslin or sacks aid ventilation and pest exclusion but offer less sunburn protection than paper.

Bagging at 35–45 days post-fruit set delays maturity 5–10 days, avoiding peak heat, boosting carotenoids, flavonoids, and phytochemicals, and extending shelf-life (Dutta and Majumder, 2012). It excludes *Bactrocera* spp. oviposition and reduces anthracnose/stem-end rot by up to 60%, integrating heat, pest, and disease management.

Bagging Material	Impact on Heat & Quality	Notable Results
Brown Paper (UV/Water Resistant)	Top Performer: Optimal UV filtration; reduces sunburn while allowing light for ripening.	Highest fruit weight (630g) and TSS (22.6 Brix) in Mallika mangoes (Kumari <i>et al.</i> , 2025).
White Paper	Reflective; excellent for temperature reduction in high-heat zones.	Significant increase in Ascorbic Acid (Vit C) and total phenolic content (Kumari <i>et al.</i> , 2025).
Black Polythene	Increases internal bag temperature; used mainly for accelerating growth.	Not recommended for heat-wave mitigation as it can cause internal tissue damage (Dutta and Majumder, 2012).
Muslin Cloth / Sacks	High ventilation but lower UV protection.	Effective for pest exclusion but less efficient at preventing sunburn compared to paper.

V. Fruit fly trap: In Kerala, early summer heat has triggered a resurgence, prompting advisories for pheromone traps and physical fruit wrapping.

3. Water and Nutrient Management

Precision in resource application helps the tree maintain physiological efficiency during heatwaves.

- **Drip Irrigation:** Optimized irrigation systems ensure a consistent water supply, which is critical for transpirational cooling of the leaves and fruit.
- **Regulated deficit irrigation (RDI):** By employing RDI, growers can strategically induce water stress during less sensitive growth stages, effectively hardening trees against extreme heat without compromising the physiological processes essential for fruit development.
- **Micronutrient Foliar Sprays:** The application of micronutrients like **Zinc (Zn)** and **Boron (B)** has been found to enhance the trees resilience to climate-induced stressors.

4. Protective foliar treatments:

- **Osmo-protectants:** The accumulation of osmoprotectants within the plant helps maintain cellular integrity during periods of high evaporative demand.
- Application of **6% Kaolin** (a white reflective clay) has emerged as a high-efficiency strategy. It increases leaf surface area and canopy volume while significantly reducing the number of sunburned fruits. Kaolin works by reflecting UV and infrared radiation, effectively lowering the leaf temperature and protecting photosynthetic pigments like chlorophyll and carotenoid (Hamdy *et al.*, 2022)
- Concurrently, the use of chemical supplements such as potassium silicate (K_2SiO_3) and biostimulants like yeast extract enhances plant resilience by increasing antioxidant activity and stabilizing growth hormones such as IAA and GA under severe drought and heat stress.

4. Post-Harvest and Quality Control

Heat stress often shortens the shelf life and alters the flavor profile of the fruit.

- **Monitoring Maturity:** High temperatures accelerate ethylene production, leading to uneven ripening. Monitoring Total Soluble Solids (TSS) is vital, as heat-stressed fruits often show abnormally high TSS levels ($> 25^\circ B$) in affected tissues. Harvesting at 75 to 80% maturity will help to reduce these crises.
- **Hydro-cooling:** Rapidly removing field heat using cool water immersion (hydro-cooling) immediately after harvest is essential to slow down the metabolic processes accelerated by high ambient temperatures (TNAU, 2026).

Conclusion:

The physiological susceptibility of *Mangifera indica* L. to thermal stress underscores a critical threat to global food security and pomological stability. This assessment highlights that yield attrition is primarily driven by thermotolerance thresholds being exceeded during the phenological windows of anthesis and fruit-set, resulting in gametic sterility and premature abscission. Mitigation necessitates a transition from traditional practices to precision climate-smart interventions. Integrating canopy cooling technologies—such as reflective kaolin films and micro-irrigation—provides immediate thermoregulation, while the selection of heat-stable genotypes offers

a long-term genetic buffer against rising ambient temperatures. Ultimately, securing mango productivity in an era of climatic volatility requires a synergistic application of plant physiology research and adaptive orchard architecture. By implementing these evidence-based mitigation strategies, the industry can enhance orchard resilience, ensuring the continued viability of mango production despite intensifying global heat cycles.



SOIL CARBON SEQUESTRATION TECHNOLOGIES IN CLIMATE SMART AGRICULTURE



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Abstract

Agriculture contributes nearly 22% of global greenhouse gas emissions, with soil-derived CO₂ being a major component. Soil carbon sequestration offers a sustainable solution by capturing atmospheric CO₂ and storing it as soil organic carbon (SOC), thereby transforming agricultural soils into carbon sinks. Globally, soils store about three times more carbon than the atmosphere, yet intensive land use has reduced SOC stocks by 50–75%. Improved land management practices can sequester 0.9–1.85 Pg C annually, significantly mitigating climate change while enhancing soil fertility and productivity. Carbon stabilization occurs through pathways such as particulate organic matter formation, microbial necro-mass accumulation, depolymerization, and mineral-associated organic matter (MAOM) formation. Climate-smart agriculture practices play a key role, with biochar showing the highest SOC increase (~39%) due to its recalcitrant nature and ability to enhance microbial activity, aggregation, and organo-mineral interactions. Integrated approaches can increase SOC by more than 50% through synergistic effects. Advanced monitoring technologies such as remote sensing, AI sensors, and machine learning enable accurate assessment of soil carbon dynamics. Mechanistically, carbon sequestration is governed by biological inputs, physical protection within aggregates, chemical stabilization with minerals, and biochemical resistance. Soil carbon sequestration is a viable strategy for climate mitigation and agricultural productivity, provided it is supported by long-term validation and policy frameworks. Widespread adoption depends on financial incentives like carbon credit systems to bridge the gap between ecological potential and economic feasibility.

Keywords: Soil carbon sequestration; Soil organic carbon (SOC); Greenhouse gas emissions; Climate-smart agriculture (CSA); Biochar; Agroforestry; Conservation tillage; Carbon stabilization pathways; Microbial necro-mass; Mineral-associated organic matter (MAOM); Carbon sinks; Soil health; Carbon cycling; Sustainable agriculture; Remote sensing; Artificial intelligence; Carbon credit systems; Climate change mitigation

Introduction

Agriculture contributes nearly 22% of global greenhouse gas emissions, with soil-derived CO₂ emissions, particularly in arid regions, representing a significant source. Soil carbon sequestration refers to the process of capturing atmospheric CO₂ and storing it in soils, primarily as soil organic carbon (SOC). Through this mechanism, agricultural lands can transition from being carbon sources to carbon sinks, offering a viable nature-based solution to climate change. Globally, agricultural soils act as a major carbon reservoir, storing approximately three times more carbon than the atmosphere. However, intensive agricultural practices, deforestation, and land degradation over the past century have led to a substantial decline in SOC stocks, ranging from 50 to 75%. Improved land management practices have the potential to sequester approximately 0.9–1.85 petagrams of carbon annually, thereby mitigating anthropogenic emissions while enhancing soil health and productivity. Climate-smart agriculture (CSA) practices play a crucial role in increasing SOC levels, with biochar showing the highest impact (~39% increase), followed by cover crops (~6%) and conservation tillage (~5%). Agroforestry systems further contribute by storing carbon at rates of 0.5–3.0 Mg C ha⁻¹ yr⁻¹, while also improving soil structure and stability. Integrating multiple practices, such as biochar and agroforestry, can produce synergistic effects by enhancing moisture retention, nutrient availability, and long-term carbon sequestration.

Visualizing the mechanisms of Sequestration

To understand how carbon is stored, the sources describe specific visual frameworks regarding the biological and chemical pathways.

Plant and Microbial Residue Formation

Plant-derived inputs such as leaf litter, root biomass, and crop residues, along with microbial residues, form the primary source of soil organic matter. These materials, often traced using stable isotopes like carbon (^{13}C) and nitrogen (^{15}N), undergo physical fragmentation and biochemical decomposition by soil fauna and microorganisms. This process leads to the formation of particulate organic matter (POM), which is relatively labile and serves as an intermediate pool in the soil carbon cycle. POM plays an important role in nutrient cycling, improves soil structure, and acts as an initial substrate for further microbial transformation and stabilization processes.

In Vivo Stabilization (Microbial Necromass Formation)

Microorganisms assimilate decomposed organic substrates and convert them into microbial biomass through metabolic processes. Upon microbial death, the residual compounds contribute to microbial necromass, which is a major component of stable soil organic carbon. This necromass contains complex biomolecules such as amino sugars and cell wall components that are more resistant to decomposition. Additionally, microbial necromass has a high affinity for soil minerals, enhancing its stabilization and persistence in soil. This pathway is considered highly efficient for long-term carbon sequestration and contributes significantly to soil fertility and resilience.

Ex Vivo Transformation (Depolymerization and Mineral Interaction)

Outside microbial cells, complex organic compounds undergo enzymatic depolymerization into smaller, soluble molecules such as sugars, amino acids, and organic acids. These compounds interact with soil mineral surfaces, particularly clay minerals and metal oxides, forming mineral-associated organic matter (MAOM). This interaction involves adsorption, ligand exchange, and cation bridging, which protect organic molecules from microbial decomposition. Environmental factors such as soil pH, texture, and mineralogy strongly influence this process, making it a critical mechanism for stabilizing carbon in diverse soil systems.

Mineral-Associated Organic Matter Formation

Mineral-associated organic matter (MAOM) represents a highly stable and long-lasting pool of soil carbon formed through strong physico-chemical interactions between organic compounds and mineral fractions. This pool is characterized by slow turnover rates and resistance to microbial degradation. The formation of MAOM is driven by both microbial processing and mineral protection mechanisms, ensuring effective carbon stabilization over extended periods. It plays a vital role in enhancing soil health, improving nutrient retention, and mitigating atmospheric CO_2 levels. Management practices such as reduced tillage, organic amendments, and cover cropping can promote MAOM formation and enhance long-term carbon sequestration in agricultural soils.

Mechanisms by which Biochar Enhance

Recalcitrant Carbon Input

Biochar contributes to soil carbon sequestration primarily through the addition of recalcitrant carbon. Due to its aromatic and highly stable structure formed during pyrolysis, biochar resists microbial decomposition and persists in soil for long periods. This stable carbon pool significantly enhances soil organic carbon (SOC) levels and plays a crucial role in long-term carbon storage within agroforestry systems (AFS).

Enhanced Microbial Activity and Contributions

Biochar improves soil biological activity by providing a favorable habitat for microorganisms. Its porous structure offers shelter and surfaces for microbial colonization, leading to increased microbial biomass and activity. This, in turn, enhances microbial processing of organic matter and promotes the formation of microbial-derived carbon, which contributes to stable SOC pools.

Interactions with Beneficial Microbes (e.g., PGPR)

Biochar supports the proliferation of beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR). These microbes improve nutrient availability, stimulate root growth, and enhance plant health. The synergistic interaction between biochar and beneficial microbes strengthens soil biological functioning and indirectly contributes to increased carbon sequestration through enhanced plant biomass production.

Formation of Organo-Mineral Complexes

Biochar facilitates the formation of organo-mineral complexes by interacting with soil minerals such as iron (Fe) and calcium (Ca). These interactions stabilize organic matter through adsorption and chemical bonding, protecting

it from microbial decomposition. As a result, carbon becomes more resistant to mineralization, leading to improved long-term carbon storage in soils.

Promotion of Recalcitrant Compounds

The presence of biochar promotes the formation and accumulation of recalcitrant organic compounds in the soil. It can adsorb labile organic molecules and convert them into more stable forms, thereby reducing carbon losses through decomposition. This mechanism enhances the persistence of carbon in soils and contributes to sustained SOC buildup.

Improved Soil Aggregation

Biochar enhances soil aggregation by acting as a binding agent between soil particles and organic matter. Improved aggregation leads to the physical protection of organic carbon within soil aggregates, reducing its exposure to microbial degradation. This mechanism plays a vital role in stabilizing SOC and improving soil structure.

Increased Soil Cation Exchange Capacity (CEC)

Biochar increases the cation exchange capacity of soils due to its high surface area and functional groups. Enhanced CEC improves nutrient retention and availability, which supports plant growth and microbial activity. This indirectly contributes to higher carbon inputs into the soil through increased biomass production and residue return.

Enhanced Soil Fertility and Water Retention

Biochar improves soil fertility by enhancing nutrient retention, water-holding capacity, and overall soil physical properties. Improved moisture availability and nutrient supply promote better plant growth, leading to increased organic matter inputs into the soil. This process ultimately supports higher carbon sequestration in agroforestry systems.

Increased Soil Carbon in Agroforestry Systems (AFS)

Through the combined effects of physical, chemical, and biological mechanisms, biochar significantly enhances soil carbon storage in agroforestry systems. The integration of biochar with trees and crops creates a synergistic system that improves soil health, increases biomass production, and promotes long-term carbon sequestration, making it an effective climate-smart agricultural practice.

Integrated Soil Carbon Strategies for Climate Resilience and Food Security

Soil Carbon Sequestration: An Overview

Soil carbon sequestration refers to the process of capturing atmospheric carbon dioxide (CO₂) and storing it in the soil as organic carbon. This process plays a crucial role in mitigating climate change while simultaneously improving soil fertility and ensuring food security. By enhancing soil organic carbon (SOC), agricultural systems can become more resilient, productive, and sustainable.

Integrated Practices for Carbon Sequestration

The figure highlights key integrated practices such as biochar application, agroforestry, and conservation tillage. Biochar adds stable carbon to the soil, agroforestry integrates trees with crops to enhance biomass input and carbon storage, and conservation tillage reduces soil disturbance, thereby minimizing carbon loss. Together, these practices contribute to improved soil structure, enhanced microbial activity, and increased carbon stabilization in soils.

Role of Agroforestry Systems

Agroforestry systems play a significant role in carbon sequestration by storing carbon both aboveground (in tree biomass) and belowground (in roots and soil). The presence of trees increases litter fall and root biomass, which enriches soil organic matter. These systems also improve biodiversity, reduce erosion, and enhance nutrient cycling, thereby supporting long-term soil health and sustainability.

Advanced Monitoring Technologies

The figure also emphasizes the importance of advanced monitoring tools such as satellite sensing, AI sensors, and machine learning. These technologies enable precise measurement and monitoring of soil carbon levels, helping in better decision-making and management practices. They provide real-time data on soil conditions, crop performance, and environmental changes, ensuring efficient implementation of carbon sequestration strategies.

Impact on Soil Organic Carbon (SOC)

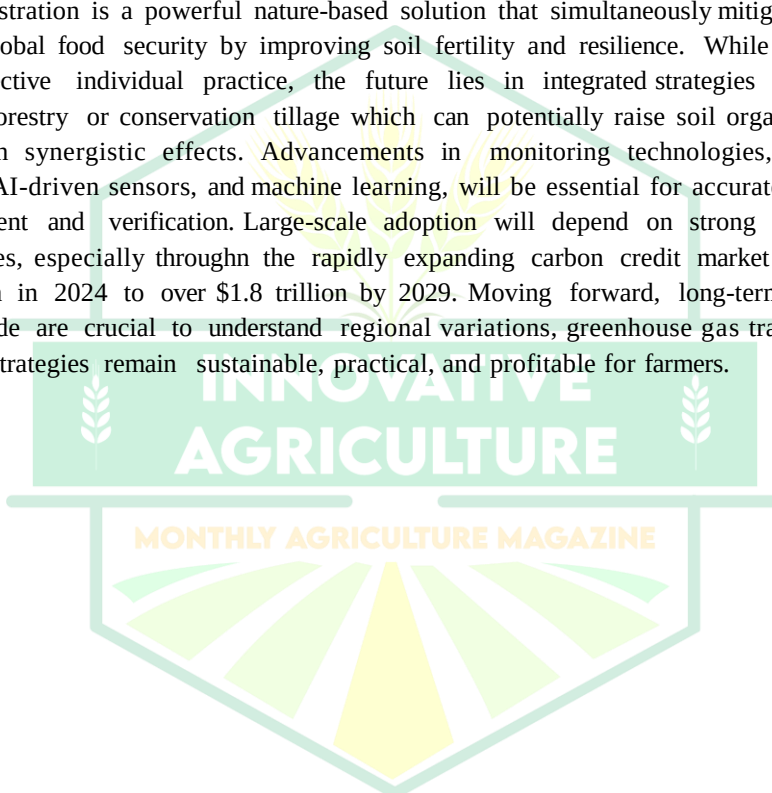
The integration of sustainable practices and modern technologies can significantly increase soil organic carbon levels, as indicated by the potential 50% increase shown in the figure. Higher SOC improves soil fertility, water retention, and nutrient availability, leading to enhanced crop productivity and resilience against climate stress.

Climate Change Mitigation and Food Security

Boosting soil carbon is a natural win-win: it pulls CO₂ out of the air while creating the rich, healthy ground we need to grow our food. It starts with plants "breathing" carbon into the earth through their roots. Once underground, this carbon stays put by hiding inside tiny soil clusters or clinging to minerals like a natural glue. Using biochar makes this even more effective—it's incredibly hardy and triggers "negative priming", which actually helps the soil hang onto the carbon it already has. By simply disturbing the ground less and using deep-rooted plants, we can tuck carbon away where it stays safe for years, turning our farms into a powerful tool for a healthier planet.

Conclusion and Future Perspectives on Soil Carbon Sequestration

Soil carbon sequestration is a powerful nature-based solution that simultaneously mitigates climate change and strengthens global food security by improving soil fertility and resilience. While biochar stands out as a highly effective individual practice, the future lies in integrated strategies such as combining biochar with agroforestry or conservation tillage which can potentially raise soil organic carbon by more than 50% through synergistic effects. Advancements in monitoring technologies, including satellite remote sensing, AI-driven sensors, and machine learning, will be essential for accurate and cost-effective carbon measurement and verification. Large-scale adoption will depend on strong policy support and financial incentives, especially through the rapidly expanding carbon credit market projected to grow from \$526 billion in 2024 to over \$1.8 trillion by 2029. Moving forward, long-term field experiments exceeding a decade are crucial to understand regional variations, greenhouse gas trade-offs, and ensure that soil carbon strategies remain sustainable, practical, and profitable for farmers.



Microplastics in Soil: The Invisible Threat to Agriculture



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Abstract

Microplastics are increasingly recognized as a novel and emerging contaminant in agricultural soils, yet their role extends beyond mere pollution to influencing soil functionality at multiple scales. This review highlights microplastics as “active modifiers” of soil systems rather than passive contaminants. Originating from agricultural plastics, wastewater inputs, and atmospheric deposition, microplastics interact with soil particles, organic matter, and microorganisms, thereby altering soil structure, porosity, and hydrological behaviour. More importantly, they act as carriers of toxic chemicals and heavy metals, facilitating their mobility and bioavailability in the soil environment. Recent evidence suggests that microplastics can reshape soil microbial communities, disrupt enzymatic activities, and influence rhizosphere interactions, ultimately affecting plant growth and nutrient uptake. Their potential to enter plant tissues and transfer through the food chain introduces a new dimension of risk to food safety and human health. Despite their microscopic size, microplastics represent a macro-level challenge to sustainable agriculture. Understanding their dynamic behavior and ecological implications is essential for developing innovative mitigation strategies, including biodegradable alternatives and integrated soil management practices. This emerging issue calls for interdisciplinary research to safeguard soil health in the era of plastic-intensive agriculture.

Keywords: Biodegradable alternatives; Food safety; Microplastics; Soil contamination; Soil health; Sustainable agriculture

Introduction:

Soil is a vital natural resource that underpins agricultural productivity, environmental sustainability, and food security. It serves as a medium for plant growth, a reservoir of nutrients, and a habitat for diverse biological communities. However, in recent years, soil systems have been increasingly exposed to a range of emerging contaminants, among which microplastics have gained significant attention. Unlike conventional pollutants, microplastics are not easily visible and often remain undetected, yet their presence in soil is steadily increasing due to intensive agricultural practices, improper waste management, and widespread use of plastic materials. These tiny particles accumulate over time, interacting with soil components and potentially altering its physical, chemical, and biological properties. The subtle and persistent nature of microplastic pollution makes it an “invisible threat,” capable of undermining soil health and long-term agricultural sustainability. Therefore, understanding this emerging issue is essential for safeguarding soil resources and ensuring sustainable food production in the future.

Microplastics: Small Particles with Significant Implications

Microplastics, defined as plastic particles smaller than 5 mm in size, represent a growing concern in soil environments due to their persistence, ubiquity, and complex interactions within the soil system. These particles originate either as primary microplastics, intentionally manufactured at microscopic sizes, or as secondary microplastics formed through the fragmentation of larger plastic materials such as agricultural mulches, packaging, and synthetic products. Despite their minute size, microplastics possess a high surface area and chemical stability, enabling them to interact actively with soil components including minerals, organic matter, and microbial communities. They can adsorb and transport toxic substances such as heavy metals and organic pollutants, thereby influencing their mobility and bioavailability in soils. Furthermore, microplastics have the potential to interfere with soil physical structure, alter water dynamics, and disrupt biological processes. Thus, these seemingly insignificant particles exert disproportionately large impacts on soil health and agricultural sustainability, underscoring the need for greater scientific attention and effective management strategies.

Sources and Pathways: How Microplastics Enter Agricultural Soils

Microplastics enter agricultural soils through a variety of direct and indirect pathways, largely driven by human activities. One of the primary sources is the widespread use of plastic materials in farming, particularly plastic mulches, greenhouse coverings, irrigation pipes, and packaging materials, which gradually degrade into smaller fragments under environmental conditions such as sunlight, temperature fluctuations, and mechanical stress. In addition, the application of sewage sludge and compost to agricultural fields introduces microplastics, as these organic amendments often contain residues from urban waste. Irrigation with contaminated water, especially when sourced from wastewater or polluted surface water bodies, further contributes to microplastic accumulation in soils. Atmospheric deposition also plays a role, with fine plastic particles transported through air and deposited onto land surfaces. Moreover, improper disposal and fragmentation of plastic waste in rural and peri-urban areas can lead to localized soil contamination. These multiple sources and pathways highlight the pervasive nature of microplastics and their increasing presence in agricultural soils.

Alteration of Soil Properties:

The presence of microplastics in soil leads to significant alterations in both its physical structure and biological functioning. Physically, microplastics interfere with soil aggregation and porosity, resulting in changes to bulk density, aeration, and water movement. Depending on their size and composition, they may either increase soil looseness or contribute to compaction, thereby affecting root penetration and water infiltration. These changes can disrupt the soil's ability to retain moisture and nutrients, ultimately influencing plant growth conditions. Biologically, microplastics impact the diversity and activity of soil microorganisms, which play a crucial role in nutrient cycling and organic matter decomposition. They may inhibit microbial enzyme activities or alter microbial community composition, leading to reduced soil fertility. Additionally, soil fauna such as earthworms and other invertebrates can ingest microplastics, causing physical stress and affecting their ecological functions. Thus, microplastics act as agents of change within the soil system, influencing its structure, function, and overall health.

From Soil to Food Systems:

The presence of microplastics in soil extends beyond soil health, influencing crop productivity and raising concerns about food safety. Microplastics can affect plant growth by altering root architecture, restricting nutrient uptake, and creating stress conditions within the rhizosphere. These changes may lead to reduced crop yield and quality over time. Moreover, recent studies suggest that microplastics and associated contaminants, such as heavy metals and organic pollutants, can be absorbed or adhered to plant tissues, thereby entering the food chain. This introduces potential risks to animal and human health through bioaccumulation and long-term exposure. The indirect effects, including reduced soil fertility and disrupted microbial activity, further compound the challenge by affecting overall agricultural productivity. Thus, the movement of microplastics from soil into food systems represents a critical emerging issue that connects environmental contamination with food security and public health.

Management Strategies and Future Outlook

Addressing the issue of microplastics in soil requires a combination of sustainable management practices, technological innovation, and policy support. Reducing the use of conventional plastics in agriculture, particularly through the adoption of biodegradable alternatives, is a crucial step in minimizing future contamination. Improved waste management practices, including proper collection, recycling, and disposal of agricultural plastics, can significantly limit their entry into soil systems. Additionally, promoting sustainable farming practices such as organic amendments with minimal contamination, precision agriculture, and reduced reliance on plastic inputs can help mitigate the problem. From a research perspective, there is a need to develop efficient methods for detecting, monitoring, and potentially removing microplastics from soil. Future strategies should also focus on raising awareness among farmers and stakeholders about the long-term impacts of plastic use. With coordinated efforts across scientific, agricultural, and policy domains, it is possible to move towards more resilient and sustainable soil management systems in the face of this emerging environmental challenge.

Conclusion

Microplastics in soil represent an emerging and largely invisible threat to agricultural sustainability, with implications that extend from soil health to food security and human well-being. Their persistent nature, widespread sources, and ability to interact with soil physical, chemical, and biological components make them particularly challenging to manage. As highlighted, microplastics not only alter soil structure and microbial activity but also influence crop productivity and may enter the food chain, raising serious environmental and health concerns. Despite growing awareness, significant knowledge gaps remain regarding their long-term behavior and impacts in soil ecosystems. Therefore, addressing this issue requires a proactive and integrated approach involving reduced plastic usage, adoption of sustainable alternatives, improved waste management, and continued scientific research. Protecting soil from microplastic contamination is essential for maintaining its productivity and ensuring a sustainable agricultural future.

“Protecting soil from plastic pollution is essential for ensuring sustainable agriculture and safe food for all.”



Interventions by Dr. K.L. Rao Krishi Vigyan Kendra under SCSP: Empowering Rural Communities through Nutrition Gardens and Value Addition



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ABSTRACT

This report highlights the impactful case studies documented by Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu, under the Scheduled Caste Sub Plan (SCSP). Spearheaded by the Subject Matter Specialist (SMS) in Home Science, the technical programme focused on enhancing household nutritional security and fostering rural entrepreneurship among marginalized communities. The core intervention involved the strategic distribution of vegetable seed kits to establish natural backyard nutrition gardens, alongside promoting value-addition in millets. Through comprehensive capacity-building programs, hands-on training, and rigorous follow-up by the Home Scientist and allied KVK personnel, the initiative successfully empowered beneficiaries to adopt natural farming practices and establish sustainable, low-investment micro-enterprises. The outcomes demonstrate significant improvements in family health, reduced daily market expenditures, and the generation of supplementary income, underlining the efficacy of targeted extension services.

Keywords: - Krishi Vigyan Kendra (KVK), Scheduled Caste Sub Plan (SCSP), Nutritional Security, Rural Entrepreneurship, Nutrition Gardens, Millet Value Addition, Natural Farming, Capacity Building, Micro-enterprises, Agricultural Extension Services, Marginalized Communities

INTRODUCTION

Under the aegis of the Scheduled Caste Sub Plan (SCSP), Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu, has implemented targeted technical programmes designed to uplift and empower rural farming families. Recognizing the dual challenges of nutritional insecurity and economic vulnerability among marginalized groups, the KVK initiated a comprehensive grassroots intervention. Driven by the technical programme of the Subject Matter Specialist (SMS) in Home Science, a pivotal first step was the distribution of high-quality, diverse seed kits to selected farmers. These kits were specifically curated to help families establish year-round kitchen and backyard nutrition gardens using natural farming principles. The initiative also expanded into the profitable sector of millet value-addition, creating pathways for landless farmers to achieve financial independence.

- **Capacity Building and Trainings:** Recognizing that input distribution must be paired with knowledge, the SMS Home Science organized extensive training sessions for the beneficiaries. These workshops provided critical education on establishing multi-seasonal crop cycles (Kharif, Rabi, Summer), implementing chemical-free natural farming techniques, and maximizing yield in small spaces. For entrepreneurial beneficiaries, specialized training was provided on processing raw millets into high-quality, FSSAI-compliant flours and ready-to-cook mixes, focusing on hygiene, shelf-life extension, and minimal-investment production.
- **Continuous Follow-Up and Technical Support:** The sustained success of the SCSP programme was anchored in the rigorous follow-up conducted by the Home Scientist and the broader KVK extension team. Regular field visits were scheduled to monitor the progress of the nutrition gardens, troubleshoot pest or soil issues using natural remedies, and ensure farmers were successfully transitioning to chemical-free cultivation. Furthermore, ongoing technical guidance was provided to rural entrepreneurs to help them maintain product quality, navigate market competition, and manage their businesses effectively.

Case study: 1 Nurturing Health and Savings through Natural Farming

S. Uma Rani, a 45-year-old educated farmer from Anumanchipalli village (Jaggayyapeta Mandal), is redefining her family's health through a thriving 2-cent backyard nutrition garden. Managing a one-acre landholding for her family of four, she realized the secret to true nutritional security starts at home.

By embracing 100% natural farming methods, Uma cultivates a vibrant, chemical-free food source year-round. Her garden's crop cycle is meticulously planned:

- **Kharif:** A variety of seasonal vegetables.
- **Rabi:** Eight diverse varieties of nutrient-rich green leafy vegetables.
- **Summer:** Five types of cucurbits and assorted beans.

The yields speak for themselves. From beans alone, her natural garden produced 100 kg. While 70 kg nourished her family, the surplus 30 kg was sold, generating additional household income.

For Uma, the greatest success is the peace of mind. *"I find immense joy in plucking fresh, pesticide-free vegetables right from my garden,"* she shares. Her initiative not only guarantees chemical-free nutrition but also drastically cuts down daily market expenses. S. Uma Rani's success is a brilliant reminder: growing your own food is a direct investment in both health and wealth.

Good quality photographs



The woman farmer initiated a nutrition garden in her backyard alongside a Home Science scientist

Case Study: 2 Empowering Rural Entrepreneurship through Millet Value Addition

At 38 years old, Smt. V. Rajyalakshmi from Seetharamapuram (NTR District, AP) has proven that owning land is not a strict prerequisite for agricultural success. With a 10th-standard education and a family of four to support, this landless entrepreneur turned to millet value addition. Her transformative journey was catalyzed by the technical programme of Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu, operating under the SCSP framework. Through rigorous training and continuous follow-up by the SMS Home Science, Rajyalakshmi developed a thriving, FSSAI-certified micro-enterprise.

She specializes in processing nutritious millets into high-demand products, including ragi and jowar flour, ravva, multi-grain mixes, and ready-to-cook pongali mixes. Operating efficiently with minimal financial investment and only the most essential tools, she caters to both wholesale markets and custom orders. Her products boast a solid six-month shelf life, making them highly attractive to bulk buyers.

Despite immense competition in the modern food market, Rajyalakshmi's unwavering commitment to quality has been her competitive edge. This dedication allowed her to scale her business remarkably, producing a staggering 30,000 kg of value-added products and yielding a net income of ₹55 per kilogram.

Rajyalakshmi's success story perfectly exemplifies how targeted institutional support empowers marginalized communities. By combining hard work with the technical guidance of KVK scientists, she bypassed the limitations of being a landless laborer. Today, she sustains a highly profitable business, ensures her family's financial security, and stands as an inspiring beacon of female rural entrepreneurship.

Good quality photographs



Distribution of Nutrition Garden Kits and creation of Awareness about Nutrition Gardens

Conclusion

The technical programme executed by Dr. K.L. Rao Krishi Vigyan Kendra, Garikapadu, under the SCSP framework stands as a highly successful model of agricultural extension. By combining the tangible distribution of seed kits with robust educational training and persistent follow-up by the SMS Home Science, the initiative transformed basic agricultural aid into holistic community empowerment. Beneficiaries have successfully converted small backyard spaces into abundant sources of pesticide-free nutrition and developed profitable agribusinesses. Ultimately, these case studies prove that when rural communities are equipped with the right inputs, continuous institutional support, and modern knowledge, they can achieve profound nutritional security and long-term economic resilience.

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Planktonic Biodiversity: A Key Indicator of Aquatic Ecosystem Health



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Abstract

Microscopic drifting organisms known as plankton are essential to preserving ecological equilibrium and serve as the biological base of aquatic environments. These include zooplankton, which transfers energy to higher trophic levels and phytoplankton, which uses photosynthesis to produce organic matter and oxygen in freshwater and marine environments. This article highlights the significance of planktonic biodiversity as a key indicator of aquatic ecosystem health. Environmental quality and ecosystem stability are reflected by components like species richness, functional diversity and evenness. While pollution, eutrophication, habitat degradation and climate change frequently result in toxic algal blooms, decreased biodiversity and the dominance of pollution-tolerant species and healthy water bodies are typically characterized by diverse and balanced plankton ecosystems.

1. Introduction: The Hidden World of Plankton

Plankton are among the most significant living organisms in aquatic ecosystems, and they are frequently hidden to the naked eye. The term "plankton" was first coined by Victor Hensen in 1887. Plankton - derived from the Greek word *planktos* meaning "to wander" or "to drifter" - are aquatic organisms that inhabit the water column, living in the pelagic zone away from the seabed. They are found in lakes, rivers, ponds, reservoirs, oceans, and seas. They serve as the biological basis for almost all aquatic food webs (Chowdhury et al., 2026). Planktons are a diverse assemblage of organisms that drift with water current and typically categorized trophic function into phytoplankton (photosynthetic microorganism such as dinoflagellates, cyanobacteria) and zooplankton (heterotrophic micro and meso-organisms such as rotifers, copepods, cladocerans etc.) In the majority of aquatic food webs, phytoplankton serve as the main producers, transforming light and inorganic nutrients into organic matter and oxygen. Zooplankton feed on bacteria and phytoplankton, transferring energy up the food chain to fish and other consumers. Together, they influence primary production, nutrient cycling, carbon sequestration, and food-web dynamics, resulting in response ecosystem functioning and services (such as carbon uptake and fisheries support (Lindemann et al., 2025). Rivers, lakes, wetlands, estuaries, and coastal waters are examples of highly productive and biologically diversified aquatic ecosystems that provide vital ecosystem services like food production, habitat distribution, nutrient cycling, water purification, and climate regulation. Anthropogenic stressors, including as industrial discharge, agricultural runoff, habitat loss, and climate change, represent a growing threat to these ecosystems by reducing water quality and disturbing natural processes. Monitoring aquatic health is consequently essential for ensuring the resilience and sustainability of ecosystems (Wang, 2024).

2. What Is Planktonic Biodiversity?

The variety, quantity, and biological variations among plankton species found in aquatic environments like lakes, rivers, ponds, estuaries, and seas are referred to as planktonic biodiversity. It comprises the variety of functional roles that species play in the environment (functional diversity), the number of species that exist (species richness), and the evenness of the distribution of individuals among those species. In simple terms, planktonic biodiversity refers to the variety of microscopic floating organisms found in water and their interactions with the environment and each other (Borics et al., 2021).

- **Species Richness:** Planktonic biodiversity and general ecological health are mostly determined by species richness, which is the total number of plankton species in an aquatic habitat. While losses in species richness are frequently linked to pollution, eutrophication, habitat disturbance, and other environmental stressors, high species

richness usually represents stable environmental conditions, balanced trophic interactions, and adequate water quality. The quick response of plankton communities to environmental gradients like temperature and nutrient availability means that shifts in species richness can serve as early indicators of ecosystem change (Lim et al., 2025).

- **Functional Diversity:** In plankton communities, functional diversity is the range, distribution, and relative abundance of functional traits that influence how species use resources and participate in ecosystem processes. Examples of these traits include cell size, nutrient uptake strategies, thermal tolerance, feeding modes, and growth rates. The way biological traits control ecosystem functioning, productivity, trophic transfer, nutrient cycling, and carbon dynamics is captured by functional diversity, as opposed to simply counting species (Krztoń et al., 2022). Communities with more functional variety have been found to have higher primary productivity, better resource complementarity, increased stability, and greater tolerance to environmental changes including temperature shifts, eutrophication, and climate change (Zhang et al., 2022). Diverse trait assemblages sustain ecosystem processes even when species composition shifts through mechanisms like functional stability. As a result, functional diversity is a sensitive and effective predictor of the health of aquatic ecosystems, directly connecting patterns of biodiversity to ecological performance and long-term environmental stability.
- **Evenness:** The distribution of individual organisms among the species that form a plankton community is measured by its evenness. In addition to species richness, which simply examines the number of species but evenness evaluates whether populations are dominated by a small number of taxa or distribution. High evenness denotes a stable ecosystem with balanced resource utilization and less competitive eliminations as species are present in comparatively similar amounts. On the other hand, poor evenness indicates that the community is dominated by one or a few numbers of opportunistic or tolerant species, which frequently happens under environmental stressors like pollution, eutrophication, or habitat disturbance. Evenness is therefore a sensitive measure of environmental health and ecological change in aquatic habitats (Theodorou et al., 2023).

3. Plankton as Natural Indicators of Water Health

Plankton are highly effective natural bioindicators of aquatic ecosystem health because they respond rapidly to environmental changes such as nutrient enrichment, pollution, temperature fluctuation, dissolved oxygen decline, and salinity variation. Changes in plankton abundance, diversity, and species composition rapidly reflect fluctuating ecosystem conditions because of their brief life periods and direct contact to surrounding water. A diverse and balanced community of phytoplankton and zooplankton is often supported by a healthy body of water, strengthening food webs and ecological stability (Sahoo et al., 2024). On the other hand, hazardous algal blooms, oxygen depletion, and the extinction of vulnerable species are frequently caused by pollution and eutrophication, showing ecological stress. Additionally, recent research indicates that while climate change is changing plankton distribution and seasonal patterns globally, zooplankton community shifts may reveal habitat deterioration and land-use pressure. Thus, monitoring plankton communities offers an early, economical, and scientifically reliable technique to evaluate water quality and manage aquatic ecosystems (Li et al., 2025).

4. What Healthy Water Looks Like Through Plankton Diversity

A diversified, balanced, and seasonally stable plankton community with several phytoplankton and zooplankton species living without excessive dominance by any one group defines healthy aquatic ecosystems. Nutrient cycling, oxygen production, water transparency and effective energy transmission to fish and other aquatic organisms are all supported by such biodiversity. Diatoms, green algae, rotifers, cladocerans, and copepods are examples of beneficial organisms that support ecological balance and protect against harmful algal blooms. On the other hand, rising temperatures, pollution and nutrient enrichment frequently damage food webs and ecological stability by decreasing plankton diversity and increasing the dominance of tolerant or bloom-forming species. Thus, one of the best biological markers of healthy and sustainable aquatic ecosystems is abundant plankton diversity (Zhao et al., 2024).

5. Signs of Pollution Seen in Plankton Communities

- **Harmful algal blooms (HABs):** Algal and cyanobacterial growth is frequently accelerated by excess nutrients like nitrogen and phosphorus from runoff, fertilizers, and sewage. These blooms reduce oxygen levels during decomposition, decrease water transparency and may release poisons.

- **Reduced plankton diversity:** When sensitive phytoplankton and zooplankton disappear from contaminated waters, the number of plankton species frequently decreases. Food webs are reduced and ecosystem stability is decreased by lower biodiversity.
- **Dominance of tolerant species:** Sensitive groups like diatoms and copepods may be replaced by pollution-tolerant organisms like rotifers, opportunistic microbes, and certain cyanobacteria. This shows an imbalance in the environment.
- **Low dissolved oxygen:** When dense plankton blooms decompose, oxygen is consumed, resulting in hypoxic conditions that can harm or kill fish and other aquatic life.
- **Changes in community structure:** The usual equilibrium between phytoplankton and zooplankton is frequently interrupted by pollution, which disrupts nutrient cycle and feeding relationships.
- **Frequent bloom recurrence:** Seasonal blooms that reoccur frequently are an indication of persistent fertilizer contamination and inadequate water quality control.

6. Factors That Affect Plankton Diversity

- **Temperature:** The metabolism, growth rate, reproduction, and seasonal distribution of plankton are all significantly impacted by water temperature. Rising temperatures could change the composition of communities by favoring bloom-forming algae and decreasing cold-adapted organisms.
- **pH:** A moderate pH range is ideal for the growth of most plankton species. While adaptable species may predominate, highly acidic or alkaline environments can stress sensitive species and lower overall biodiversity.
- **Nutrients:** Silica, phosphorus, and nitrogen are necessary for plankton growth. While high fertilizer availability frequently results in eutrophication and hazardous algal blooms, which reduce variety, moderate nutrient availability promotes production.
- **Light Availability:** Photosynthetic phytoplankton depends on sunlight. Light penetration and plankton productivity are impacted by water turbidity, depth, suspended particles, and seasonal variations in sunlight.
- **Dissolved Oxygen (DO):** For zooplankton and other aquatic life, there must be enough oxygen. Food webs can be disrupted and vulnerable species eliminated by low oxygen levels brought on by pollution or decomposition.
- **Contaminants and Pollution:** Plankton can be contaminated by heavy metals, pesticides, plastics, sewage and industrial effluents. They may also prevent growth, disrupt reproduction, and lower species richness.
- **Salinity:** Salinity variations affect the survival and distribution of plankton in coastal and estuary waters. Freshwater or marine-adapted species may be under stress from sudden alterations.
- **Water Movement:** Plankton suspension, oxygen distribution and nutrient transport are all impacted by currents, mixing and stratification, resulting shaping diversity patterns.
- **Predation Pressure:** Fish grazing on zooplankton and zooplankton grazing on phytoplankton controls population size and preserves ecological equilibrium.
- **Climate Change:** Plankton variability, migration, and biodiversity in aquatic environments can be affected by long-term warming, changes in rainfall, droughts, and extreme weather.

7. Importance of Monitoring Lakes, Rivers, and Ponds

For the purpose of evaluating and maintaining the health of aquatic ecosystems, regular monitoring of lakes, rivers and ponds through plankton research is important. Plankton are early indicators of pollution, eutrophication, biodiversity loss, invasive species and climate-related stress because of their quick reaction to changes in water quality. Plankton diversity and abundance changes frequently indicate ecological disruptions before they have an impact on larger animals. Since plankton form the base of aquatic food webs, their monitoring also supports fisheries management, aquaculture productivity, and biodiversity conservation. As a result, routine plankton study is regarded as an economical and evidence-based method for managing water resources sustainably and protecting freshwater ecosystems.

8. Plankton and Climate Change

Plankton populations, the base of aquatic food webs, are being significantly impacted by climate change. The growth, reproduction and survival of plankton are being altered by rising water temperatures, which frequently favor warm-tolerant species while decreasing cold-water varieties. The seasonal food supply for fish larvae and

other aquatic animals is being disrupted by numerous plankton blooms that are now happening earlier or becoming irregular, according to research. Additionally, stratification is increased by warmer surface waters, which restricts the upward flow of nutrients required for phytoplankton development and lowers production in some areas. In order to adapt to changing conditions, many plankton species are also moving toward deeper zones or colder polar waters. Because phytoplankton absorbs a lot of carbon dioxide through photosynthesis, these changes have the potential to reduce biodiversity, degrade fisheries, and affect the global carbon cycle. As a result, plankton are considered to be among the most sensitive markers of climate change and its ecological effects on freshwater and marine environments (Sarkar et al., 2025).

9. Conserving Aquatic Ecosystems through Biodiversity Protection

Clean water, fisheries, climate balance and ecological stability depend on the conservation of aquatic ecosystems through biodiversity protection. According to recent studies, one of the best strategies for restoring rivers, lakes, ponds, and wetlands is to reduce pollution from sewage, fertilizers, pesticides, plastics, and industrial waste. While chemical pollutants and microplastics impair aquatic food webs and biodiversity, excess nutrients frequently result in eutrophication and toxic algal blooms. By providing protection, breeding grounds and nutritional balance, protecting natural habitats including wetlands, riparian vegetation, spawning grounds and shallow littoral zones also benefits fish, plankton, aquatic plants and other organisms. Research also shows that sustainable land-use practices, routine monitoring of biodiversity and habitat restoration significantly increase the resilience of freshwater ecosystems to climate change. In order to preserve aquatic biodiversity and ensure the long-term health of ecosystems, pollution management and habitat protection are crucial strategies (Nogueira & Kane, 2025).

10. Conclusion:

Despite their tiny size, plankton may communicate important information about the condition of aquatic environments. Plankton diversity, abundance and seasonal dynamics are among the most accurate measures of water quality, nutrient balance, pollution stress and the effects of climate change in lakes, rivers, ponds, and oceans, according to recent studies. While polluted or disturbed environments frequently exhibit algal blooms, decreased diversity and the dominance of tolerant species, healthy waters typically support rich and balanced plankton populations. The health of plankton directly affects fisheries, biodiversity, and ecological stability since they are the base of aquatic food webs and play a major role in the creation of oxygen and the cycling of carbon. Thus, preventing pollution in water bodies, preserving habitats, and routinely observing plankton communities are crucial elements in managing aquatic ecosystems sustainably.

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Smart Livestock Health Management: Integration of AI, Big Data and Wearable Sensors for Early Disease Detection



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Abstract

The Livestock sector plays a crucial role in ensuring global food security, supporting rural Livelihoods and contributing to economic development. However, the sector faces persistent challenges due to infectious and non-infectious diseases, which significantly reduce productivity and increases economic losses. Traditional health monitoring methods, largely based on periodic observation and visual assessment, are often inadequate for the early detection of diseases. Recent advancements in precision livestock farming have introduced innovative solutions through the integration of artificial intelligence, big data analytics and wearable sensor technologies. Artificial intelligence enables the analysis of complex datasets for accurate disease prediction and decision support, while big data analytics integrates information from multiple sources, such as environmental conditions and farm records, to improve the reliability of predictions. Wearable sensors facilitate continuous, real-time monitoring of physiological and behavioral parameters, allowing early identification of health abnormalities and timely intervention. The integration of these technologies supports a shift from reactive to proactive and preventive health management, improving animal welfare, productivity and resources efficiency. Although challenges such as high costs, limited technical expertise, and infrastructure constraints exist, ongoing technological advancements are expected to enhance the adoption effectiveness of smart livestock systems.

Key words: AI, Data, Livestock, Management, Role

Introduction

The livestock sector plays a significant role in global food systems, contributing to nutritional security, economic development and livelihood support, particularly in developing countries (FAO, 2019). However, the productivity and sustainability of livestock farming are frequently challenged by the occurrence of infectious and non-infectious diseases, which lead to decreased production efficiency and increased financial losses (Pfeiffer *et al.*, 2021). Traditional livestock health monitoring systems are primarily based on periodic inspection and visual assessment, which are often subjective and may fail to detect early-stage health abnormalities (Rutten *et al.*, 2013).

In recent years, the concept of precision livestock farming has emerged as a promising solution to these challenges by incorporating advanced technologies for continuous monitoring and management of individual animals (Berckmans, D. 2017). Artificial intelligence has gained considerable attention due to its ability to process large datasets and identify patterns associated with disease development (Kamilaris & Prenafeta- Boldu, 2018). At the same time, wearable sensors provide real-time data on various physiological and behavioral parameters, enabling continuous health assessment (Neethirajan *et al.*, 2020). Furthermore, the integration of big data analytics allows for the aggregation and analysis of information from multiple sources, such as farm records, environmental conditions and sensor data, thereby improving the accuracy of predictive models (Coble *et al.*, 2018). This technological advancement facilitates a shift reactive disease management to proactive and preventive approaches, where early detection and timely intervention are possible (O' Grady & O' Hare, 2017).

Core Concepts:

1. **Artificial Intelligence in livestock Disease Prediction and Decision Support** – Artificial intelligence has emerged as a transformative technology in livestock health management by enabling the automated analysis of complex datasets and improving disease prediction accuracy (Liakos *et al.*, 2018). Machine learning algorithms can analyze historical as well as real-time data to identify patterns and correlations associated with diseases occurrence (Kamilaris & Prenafeta –Boldu, 2018). These predictive models are capable of

detecting early warning signs that may not be visible through conventional observation methods (Rutten *et al.*, 2013). For instance, slight variations in feeding behaviour, locomotion and body temperature can be interpreted by AI systems as potential indicators of diseases such as mastitis, lameness or metabolic disorders (Hogeveen *et al.*, 2010). Advanced deep learning techniques, including convolution neural networks are increasingly used for image and video analysis to identify physical abnormalities, lesions and behavioral changes in livestock (Tzounis *et al.*, 2017).

2. **Big Data Analytic in Livestock Health and Production Systems** – Big data analytic plays a crucial role in managing the vast amount of information generated in modern livestock farms, including data from sensors, environmental monitoring systems and farm management records (Wolfert *et al.*, 2017). The ability to process and analyze these large datasets enables the identification of trends and patterns that can support effective decision- making (Spanaki *et al.*, 2021). The intergration of multiple data sources enhances the accuracy of disease prediction models by providing a comprehensive understanding of animal health and environmental influences (Coble *et al.*, 2018). For example, combining climatic data such as temperature and humidity with animal physiological data can help predict heat stress and its associated health risks (Rojas-Dowing *et al.*, 2017). Big data analytics also supports optimization of feeding strategies, breeding programs and overall farm management by providing actionable insights based on predictive modelling and data mining techniques ((Kamilaris & Prenafeta –Boldu, 2018). This contribute to improved productivity, resources efficiency and sustainability in livestock production systems.
3. **Wearable Sensors for Continuous Monitoring of Animal Health** – Wearable sensor technologies have revolutionized livestock health monitoring by enabling continuous, real-time and non-invasive data collection (Neethirajan *et al.*, 2020). These devices, including smart collars, ear tags and implantable sensors, are capable of measuring various physiological and behavioral parameters such as body temperature, heart rate, activity levels and rumination patterns (Rutten *et al.*, 2013).
Changes in these parameters can serve as early indicators of disease or stress conditions in animals (Hogeveen *et al.*, 2010). For example reduced activity and feed intake may indicate illness while increased body temperature may signal infection or inflammation (Berckmans, D. 2017). Similarly, abnormal rumination patterns can be associated with digestive disorders or metabolic imbalances (Neethirajan *et al.*, 2020).
4. **Integrated Smart Systems for Precision Livestock Farming** – The integration of artificial intelligence, big data analytics and wearable sensors forms the backbone of smart livestock health management systems (Wolfert *et al.*, 2017). Wearable devices continuously generate data, which is stored and processed using big data platforms, while AI algorithms analyze this data to detect anomalies and predict diseases risks (O’ Grady & O’ Hare, 2017).
5. **Challenges, Limitations and future prospects** – Despite the numerous advantages the adoption of smart livestock technologies is associated with several challenges, including high initial investment costs and lack of technical expertise among farmers (Coble *et al.*, 2018). Data privacy and security concerns also pose significant challenges in the implementation of digital farming systems (Spanaki *et al.*, 2021). In addition, limited infrastructure and internet connectivity in rural areas can hinder the effective use of these technologies (Rojas-Downing *et al.*, 2017). However, ongoing advancement in sensor technology, artificial intelligence and cloud computing are expected to address these limitations (Kamilaris & Prenafeta-Boldu, 2018).
Future developments may include the integration of Internet of Things (IoT), blockchain technology for secure data sharing and more cost- effective solutions for small- scale farmers (Tzounis *et al.*, 2017). These innovations will further enhance the efficiency and accessibility of smart livestock health management systems.

Conclusion

In conclusion, the integration of intelligence, big data analytics, and wearable sensors has the potential to transform livestock health management by enabling early diseases detection and informed decision- making. Despite challenges such as cost and infrastructure limitations, continuous technological advancements are expected to improve accessibility, thereby enhancing productivity, animal welfare, and the overall sustainability of livestock production systems.

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Fungi Unleashed: Decoding the Silent Destruction of Stored Food Commodities



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Abstract

Fungal contamination of stored food commodities represents a major global challenge affecting food safety, public health, and economic stability. Storage fungi such as *Aspergillus*, *Fusarium*, and *Penicillium* proliferate under favourable environmental conditions, producing toxic metabolites known as mycotoxins. These toxins are heat-stable and pose severe health risks, including carcinogenic, nephrotoxic, and immunosuppressive effects. This paper examines the ecological factors influencing fungal growth, the health and economic consequences of mycotoxins, and current detection and prevention strategies. The study emphasizes the need for integrated approaches combining improved storage systems, advanced detection technologies, and policy interventions to reduce post-harvest losses.

Keywords: fungal contamination, mycotoxins, food storage, post-harvest losses, food safety

1. Introduction

Post-harvest losses significantly threaten global food security, particularly in developing countries. Among the various causes, fungal contamination is one of the most critical due to its combined impact on food quality and safety. Storage fungi such as *Aspergillus*, *Fusarium*, and *Penicillium* species are major contributors to spoilage and toxin production (Kumar et al., 2019).

Mycotoxins produced by these fungi are highly toxic and resistant to thermal processing, making them persistent contaminants in the food chain (Williams et al., 2004). It is estimated that approximately 25% of global food crops are contaminated with mycotoxins annually (Food and Agriculture Organization, 2011).

2. Fungal Ecology in Stored Commodities

Fungal growth in stored food is influenced by environmental and storage conditions.

2.1 Environmental Factors

Moisture content is the most critical factor; grain moisture levels above 13–15% significantly increase susceptibility to fungal growth (Kumar et al., 2019). Temperature also plays a key role, with optimal fungal growth occurring between 20°C and 35°C (Medina et al., 2020). High relative humidity and poor ventilation further accelerate fungal colonization.

2.2 Common Storage Fungi

- *Aspergillus* species – associated with aflatoxin production
- *Fusarium* species – produces fumonisins and trichothecenes
- *Penicillium* species – linked to ochratoxin contamination

These fungi may infect crops before or after harvest, but improper storage conditions significantly enhance their growth (Kumar et al., 2019).

3. Mycotoxins and Health Implications

Mycotoxins are toxic secondary metabolites that pose serious health risks even at low concentrations.

3.1 Major Mycotoxins

- **Aflatoxins** – potent liver carcinogens
- **Ochratoxin A** – causes kidney damage
- **Fumonisin** – associated with neurological disorders and cancer

Aflatoxin B1 is one of the most potent naturally occurring carcinogens known (Williams et al., 2004).

3.2 Health Effects

Chronic exposure to mycotoxins can lead to liver cancer, immune suppression, kidney damage, and impaired growth in children (Kumar et al., 2019; Williams et al., 2004). These toxins remain stable during cooking and processing, making contamination difficult to eliminate.

4. Economic Impact

Fungal contamination contributes significantly to global post-harvest losses and economic damage.

Post-harvest losses in developing countries can reach 30–40%, with fungal contamination being a major factor (Food and Agriculture Organization, 2011). These losses reduce farmer income, increase food prices, and lead to rejection of exports due to safety regulations (Medina et al., 2020).

5. Detection Methods

Early detection is essential for controlling fungal contamination.

Traditional methods such as visual inspection and culture-based techniques are slow and less reliable. Advanced detection methods, including Polymerase Chain Reaction (PCR) and Enzyme-Linked Immunosorbent Assay (ELISA), provide faster and more accurate identification of fungi and mycotoxins (Zhang et al., 2021).

Recent developments in biosensor technology allow real-time detection of toxins at very low concentrations, improving monitoring efficiency (Zhang et al., 2021).

6. Prevention and Control Strategies

Preventive measures are the most effective way to manage fungal contamination.

6.1 Storage Practices

- Drying grains to safe moisture levels (below 13%)
- Maintaining low humidity and temperature
- Ensuring proper ventilation

6.2 Hermetic Storage

Hermetic storage systems reduce fungal growth and mycotoxin production by limiting oxygen availability (Baributsa et al., 2017).

6.3 Biological Control

The use of natural antifungal compounds and non-toxigenic fungal strains offers sustainable alternatives for controlling contamination (Medina et al., 2020).

7. Climate Change and Future Risks

Climate change is increasing the risk of fungal contamination by creating favourable conditions for fungal growth. Rising temperatures and irregular rainfall patterns are expected to expand the distribution of mycotoxin-producing fungi globally (Medina et al., 2020).

8. Conclusion

Fungal contamination of stored food commodities is a critical issue with significant implications for food safety, public health, and economic stability. The persistence and toxicity of mycotoxins make early detection and prevention essential. While advancements in storage and detection technologies offer promising solutions, their widespread adoption remains limited. A coordinated effort involving improved infrastructure, scientific innovation, and increased awareness is necessary to reduce the silent destruction caused by fungi.

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Cordia dichotoma: An Underutilized Indigenous Fruit with Expanding Applications in the Food Industry – A Review



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Abstract

The increasing demand for natural, functional, and sustainable food ingredients has renewed interest in underutilized plant resources. *Cordia dichotoma* G. Forst., commonly known as lasora or Indian cherry, is an indigenous fruit tree traditionally consumed in South Asia. The fruit is rich in mucilage, dietary fiber, minerals and bioactive compounds, making it a promising candidate for food industrial applications. This review summarizes the botanical characteristics, nutritional composition, functional properties and traditional uses of *Cordia dichotoma*, with particular emphasis on its applications as a natural thickener, stabilizer, functional ingredient, and biodegradable packaging material. The challenges related to large-scale utilization and future research prospects are also discussed. The review highlights the potential of *Cordia dichotoma* as a sustainable and value added ingredient in modern food systems.

Keywords: *Cordia dichotoma*, mucilage, functional foods, natural hydrocolloid, food industry, underutilized fruit

1. Introduction

The modern food industry is undergoing a paradigm shift toward the use of natural, plant-based, and clean-label ingredients driven by growing consumer awareness of health, sustainability, and environmental concerns. Synthetic additives such as artificial stabilizers, thickeners and preservatives are increasingly being replaced by naturally derived alternatives. In this context, indigenous and underutilized plant species are gaining scientific and commercial attention due to their functional properties and nutritional benefits (Kumar et al., 2019).



Cordia dichotoma G. Forst., a member of the family Boraginaceae, is one such underexploited fruit-bearing tree. Although it has been traditionally used as food and medicine for centuries, its industrial applications remain limited. Recent studies have identified its mucilage-rich pulp as a potential natural hydrocolloid, positioning *C. dichotoma* as a promising ingredient for food processing and functional food development (Patel & Rao, 2020). This review aims to consolidate available knowledge on *Cordia dichotoma* and explore its potential role in the food industry.

2. Botanical Description and Distribution

Cordia dichotoma is a medium-sized deciduous tree, reaching heights of 10–15 m and is widely distributed throughout India, Sri Lanka, Pakistan, Nepal, and parts of Southeast Asia and Australia. The tree is drought-tolerant and capable of growing in poor and marginal soils, making it suitable for agroforestry systems and sustainable agriculture (Singh et al., 2018).

The fruit is a globose drupe, green when unripe and yellowish-brown upon ripening. The pulp becomes soft and mucilaginous at maturity, which is responsible for its distinctive sticky texture and functional behaviour in food systems.

3. Traditional and Ethnobotanical Uses

Traditionally, *C. dichotoma* fruits have been consumed in both unripe and ripe forms. The unripe fruits are commonly used as vegetables and pickled, while ripe fruits are eaten fresh or dried. In Indian traditional medicine, the fruit pulp is used as a demulcent, laxative, and digestive aid (Warrier et al., 2017).

The widespread ethnobotanical use of *Cordia dichotoma* suggests its safety for human consumption and provides a strong foundation for its incorporation into modern food products.

4. Nutritional Composition and Phytochemical Profile

The fruit of *Cordia dichotoma* contains carbohydrates, dietary fiber, and essential minerals such as calcium, potassium, iron, and magnesium. The high soluble fiber content contributes to its beneficial effects on digestion and gut health (Sharma et al., 2021).

Phytochemical studies have revealed the presence of flavonoids, phenolic compounds, and other bioactive constituents with antioxidant activity. These compounds play an important role in reducing oxidative stress and enhancing the functional value of *Cordia* based food products (Rao et al., 2019).

5. Functional Properties of Cordia Mucilage

Mucilage extracted from *Cordia dichotoma* pulp is a complex polysaccharide with high water-holding capacity and viscosity-enhancing properties. It exhibits swelling, emulsifying, and stabilizing behaviour, which are essential characteristics for food hydrocolloids (Patel & Kulkarni, 2020).

The rheological properties of *Cordia* mucilage indicate its potential as a natural thickener and texture modifier, comparable to commercially used gums such as guar gum and xanthan gum.

6. Applications in the Food Industry

6.1 Natural Thickener and Stabilizer

Cordia mucilage can be used as a thickening and stabilizing agent in soups, sauces, gravies and ready-to-eat foods. Its ability to improve mouthfeel and prevent phase separation makes it suitable for convenience food formulations, while supporting clean-label claims (Kumar et al., 2019).

6.2 Pickles, Fermented Foods, and Condiments

The firm texture and flavour absorbing capacity of unripe *C. dichotoma* fruits make them ideal for pickles and fermented products. Industrial production of *Cordia*-based pickles offers opportunities for value addition and export of ethnic foods (Singh et al., 2018).

6.3 Bakery, Confectionery, and Snack Products

In bakery and confectionery products, *Cordia* mucilage acts as a natural binder and humectant, improving moisture retention and shelf life. Its application in fruit bars, traditional sweets, and fiber-enriched snacks has been reported (Sharma et al., 2021).

6.4 Functional Foods and Nutraceuticals

Due to its soluble fiber and antioxidant content, *Cordia dichotoma* can be incorporated into functional foods aimed at digestive health, cholesterol reduction, and glycemic control. The fruit shows strong potential for nutraceutical product development (Rao et al., 2019).

7. Emerging Applications in Edible Films and Packaging

Recent research has explored the use of *Cordia* mucilage in the development of edible films and biodegradable coatings. These films exhibit good film-forming ability and can reduce moisture loss and microbial spoilage in food products, contributing to sustainable packaging solutions (Patel & Rao, 2020).

8. Challenges and Limitations

Despite its potential, large-scale utilization of *Cordia dichotoma* faces challenges such as seasonal availability, lack of standardized extraction protocols, limited commercial cultivation, and insufficient regulatory data. Addressing these constraints is essential for industrial adoption.

9. Future Prospects and Research Directions

Future research should focus on optimizing cultivation practices, developing efficient mucilage extraction techniques, and conducting clinical and toxicological studies to support regulatory approval. Integration of *Cordia dichotoma* into food supply chains can enhance rural livelihoods and promote sustainable food systems.

10. Conclusion

Cordia dichotoma is a nutritionally rich and functionally versatile fruit with significant potential for food industrial applications. Its mucilage, dietary fiber and bioactive compounds make it suitable for use in processed foods, functional products, and biodegradable packaging. Systematic research and technological advancements can transform this underutilized fruit into a valuable ingredient for the modern food industry.

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Trapped in the Web: Navigating Digital Addiction in the Silver Generation



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Abstract

Rapid expansion of digital access has reshaped the lives of older adults, transforming technology into a key medium for communication, information, and daily functioning. However, alongside these benefits, a pattern of excessive and dependency-driven use has begun to surface among the elderly population. This article examines the emerging issue of digital addiction in later life by integrating recent national reports and clinical findings. It highlights how psychological vulnerabilities—such as loneliness, reduced social roles, and health-related limitations—interact with persuasive digital environments to foster compulsive usage. The discussion further outlines the wide-ranging consequences of this behaviour, including cognitive decline, sleep disturbances, sedentary lifestyles, and emotional distress. Emphasis is placed on practical and policy-level interventions that encourage balanced digital engagement, promote awareness of healthy usage patterns, and support overall well-being in aging populations.

Keywords: Digital addiction, older adults, retirement, silver generation.

Introduction

In numerous countries around the world, using the internet has become an integral part of everyday life. Older adults are increasingly using digital technologies, even though their use was formerly mostly restricted to younger people. Retired individuals frequently utilize the internet for a variety of reasons, such as enjoyment, financial management, communication with friends and family, information seeking, and assistance in daily tasks. This change is a result of easier access to technology and the expanding role that digital tools play in fostering independence and social engagement in old age. Retirement is a significant life shift that may have an impact on how people use the internet. Coping strategies in older life can be impacted by changes like the loss of regular daily routines, less social interaction, more leisure time, bereavement, and deteriorating physical health.

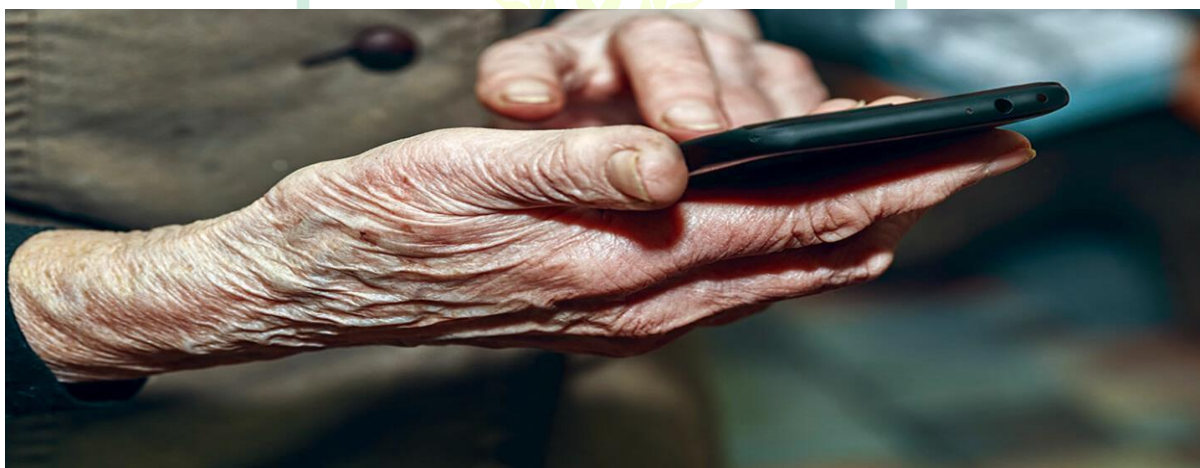
In this situation, the internet may develop into a significant source of company, emotional support, or diversion, influencing retirees' usage habits. However, studies show that older persons utilize the internet in a variety of ways. Depending on personal vulnerability and circumstances, digital participation may be advantageous in certain situations while being harmful in others. The conversation around digital behaviours in later life has been further broadened by concerns about smartphone use among older adults, highlighting the necessity of looking beyond traditional internet access alone. All age groups in India now have more access to the internet due to the country's rapid digital growth. Evidence at the national level indicates that internet addiction is a developing public health issue in the nation. Elderly people, notably those who live in socioeconomically deprived environments, also have problematic internet use, according to community-based study. In addition to sociodemographic characteristics, psychological considerations play a major role in determining an individual's risk of developing problematic internet use. (Aravindh et al., 2026)

For decades, the "digital divide" was the primary concern for policymakers, focusing on getting seniors online. However, as of 2026, data suggests the pendulum has swung. According to the **Economic Survey 2025–26**, digital addiction has moved beyond youth demographics to become a critical public health concern for all ages. In many regions, smartphone penetration among those aged 65+ now exceeds 85%, yet this access comes with a cost. Unlike younger users who may use devices for productivity, the elderly often falls into "passive consumption" loops—compulsive scrolling of short videos and news feeds—that can lead to behavioural dependency.

Statistical Data & Insights:

While comprehensive national surveys specifically for "elderly digital addiction" are evolving, data from the **National Institute of Mental Health and Neurosciences (NIMHANS)** and recent public health reports provide a clear picture:

- **Prevalence:** Research indicates that approximately **15% to 20% of urban elderly smartphone users** show signs of "problematic digital use," characterized by sleep disruption and neglect of physical health (NIMHANS, 2024).
- **Usage Patterns:** Government-backed studies show that 34% of digitally active seniors spend **3 to 7 hours daily** on their smartphones, primarily for social media and news consumption.
- **The "Information Cocoon":** Reports from the Ministry of Health suggest that compulsive consumption of short-form videos creates an "information cocoon" effect, leading to a significant increase in **late-life anxiety** and emotional dependency.



Source: <https://share.google/YOyisNiD6yBwTFtqu>

The Complex Roots: 8 Causes of Digital Addiction in the Elderly

Digital addiction in later life is rarely about the technology itself; it is an intersection of psychological needs and predatory design.

1. **Emotional Compensation for Loneliness:** Driven by the "empty nest" syndrome or loss of a spouse, many seniors use digital platforms to fill emotional voids, leading to a voluntary but compulsive reliance on virtual interactions.
2. **Algorithmic "Incentive" Structures:** Modern platforms use "preferential incentives" (profit-seeking psychology) that target the "silver economy." Algorithms are specifically tuned to keep seniors engaged through repetitive, high-resonance content.
3. **Low Digital Literacy & Manipulative Design:** Many older adults lack the "digital skepticism" to recognize dark patterns—UI designs intended to keep users scrolling. This makes them more susceptible to "infinite scroll" features and clickbait.
4. **The "Information Cocoon" Effect:** Compulsive consumption of short videos creates a feedback loop where the user is isolated within a narrow set of viewpoints, providing a false sense of security and engagement.

5. **Escape from Physical Chronic Pain:** Digital devices serve as a cognitive distraction from age-related physical discomfort, creating a "numbing" effect that reinforces prolonged use.
6. **Cognitive "Feedback" loops:** Interactive games and social likes provide immediate dopamine hits that may be lacking in a retired, sedentary lifestyle.
7. **Social Displacement:** As real-world social circles shrink due to mobility issues, the smartphone becomes the *only* portal to the outside world, leading to an "all-or-nothing" dependency.
8. **Structural Exclusion:** A lack of physical community spaces for the elderly in urban environments forces them into the "digital square" as a default rather than a choice.

Impacts on Health:

The health consequences of digital addiction in the elderly are often more severe than in younger cohorts due to lower physiological resilience.

- **Accelerated Cognitive Decline:** While moderate use can help, *excessive* and passive screen time (like watching 3.5+ hours of TV/tablet daily) is linked to declines in verbal memory and hippocampal-related deficits.
- **Severe Sleep Fragmentation:** Blue light exposure inhibits melatonin production, but more critically, "compulsive checking" interrupts the deep sleep cycles necessary for brain "cleansing" in seniors, potentially accelerating dementia risks.
- **The "Sedentary Syndrome":** Prolonged sitting leads to musculoskeletal disorders, specifically chronic neck pain and lower back stiffness, and increases the risk of cardiovascular events and metabolic dysfunction.
- **Psychological Distress and Depression:** High levels of smartphone addiction, particularly when displacing real-world social interaction, are central predictors of late-life depression.
- **Visual Fatigue and "Dry Eye" problem:** Age-related vision changes make seniors more prone to digital eye strain, which can lead to headaches and a further reduction in physical mobility due to dizziness.
- **Cardiovascular Risks:** Lack of physical movement combined with the stress of "doom scrolling" or online arguments can lead to increased blood pressure and heart rate variability issues.
- **Ocular Strain and "Tech Neck":** Older eyes are more prone to strain. Excessive use exacerbates cataracts and macular degeneration, while poor posture during device use leads to chronic cervical spine pain.

How can you stop a phone addiction?

To stop a phone addiction, set certain goals.



1 Limit the time spent on your phone.		6 Find alternatives to phone use.	
2 Apps that help track time.		7 Create habits that contribute to mental health.	
3 Set time limits for specific apps.		8 Set specific times for phone use.	
4 Features that limit access to certain apps.		9 Seek professional support if needed.	
5 Turn off notifications to reduce the urge to check.			

Source: <https://share.google/FREVEWt7Wv7UukdYe>

Management Strategies for Digital Wellness

Managing digital intake in the elderly requires empathy rather than "infantilizing" restrictions.

1. **Notification Hygiene:** Caregivers should help seniors disable non-essential "push" notifications, reducing the "external triggers" that prompt compulsive checking.
2. **Transition to "Active" Usage:** Encourage moving from passive scrolling to active engagement, such as video calling family or using cognitive training apps, which have shown positive correlations with memory.
3. **The "20-20-20" Rule for Physical Health:** For every 20 minutes of screen time, look at something 20 feet away for 20 seconds, and incorporate a "standing lap" around the room to break sedentary patterns.
4. **Predictable "Phone-Free" Zones:** Establishing strict digital-free periods during meals and two hours before bed helps reset the circadian rhythm and fosters real-world connection.
5. **Digital Literacy Training:** Educational programs that explain how algorithms work can empower seniors to recognize when they are being "manipulated" by an app, shifting them from victims to informed users.
6. **Community-Based Interventions:** Encouraging participation in local physical groups (as recommended by the **WHO ICOPE guidelines**) can reduce the loneliness that drives digital addiction in the first place.

Government Initiatives to Cure and Manage Addiction

The Government of India has integrated digital wellness into its broader mental health and aging frameworks:

1. **SHUT Clinic (NIMHANS):** The **Service for Healthy Use of Technology (SHUT)** clinic at NIMHANS, Bengaluru—a premier government institute—is the first of its kind to offer specialized counselling and de-addiction protocols for all age groups, including the elderly.
2. **National Mental Health Programme (NMHP):** The government has expanded the **District Mental Health Programme** to include "digital hygiene" awareness, specifically targeting senior citizen centres to promote physical activities over screen time.
3. **Tele-MANAS:** The 24/7 tele-mental health service through a national toll-free helpline number (14416) provides immediate counselling for behavioural addictions, including compulsive internet use, making support accessible to homebound seniors.

Conclusion:

The growing dependence on digital technologies among older adults presents a complex public health challenge that extends beyond mere access to responsible use. While digital tools can enhance independence and social inclusion, unchecked and habitual engagement may adversely affect both physical health and psychological stability in later years. Evidence suggests that sustainable solutions must move beyond restriction and instead focus on empowerment through digital literacy, structured routines, and community-based support systems. Public health initiatives and family involvement play a crucial role in guiding seniors toward meaningful and moderated technology use. Ultimately, fostering a balanced relationship with digital media is essential to ensure that technological advancement contributes positively to healthy and dignified aging rather than undermining it.

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Hydroponics and Aeroponics in Urban Floriculture for Water-Efficient Flower Production



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Abstract

Water is becoming one of the most precious resources on our planet, and traditional agriculture — including flower farming — is one of its biggest consumers. As cities grow and green spaces shrink, the demand for locally produced, beautiful flowers continues to rise. This creates a real tension: how do we keep producing flowers without draining the water supplies that communities depend on?

This article explores two innovative growing methods — hydroponics and aeroponics — and how they are reshaping urban floriculture. Both systems allow flowers to grow without soil, using significantly less water than conventional farming. From rose farms in city warehouses to vertical gardens on rooftops, these technologies are giving urban growers a smarter, cleaner, and more sustainable way to bring flowers to people. The article walks through how these systems work, why water efficiency matters, what flowers thrive in these setups, and what the future looks like for water-smart flower production in cities around the world.

1. Introduction

Walk into any flower shop in a busy city, and you will find beautiful blooms — roses, tulips, gerberas, lilies — often flown in from farms thousands of miles away. What most people do not think about is how much water went into growing those flowers. Traditional flower farming is a thirsty business. Growing one rose using conventional soil methods can require anywhere from seven to thirteen litres of water. Multiply that by the billions of flowers traded globally every year, and the numbers become staggering.

At the same time, the world is facing a growing water crisis. Many major cities are dealing with water scarcity, and climate change is making things worse. So the question becomes very practical: can we keep growing flowers — something that brings joy, marks celebrations, and supports millions of livelihoods — without being so reckless with water?

The answer, it turns out, is yes. And two technologies are leading the way: hydroponics and aeroponics. These soil-free growing methods are finding a natural home in urban environments, where land is limited, water is expensive, and people are hungry for locally grown, sustainable products. This article takes a close look at what these systems are, how they work, and why they might just be the future of flower farming in cities.

2. What Is Urban Floriculture?

Floriculture simply means the cultivation of flowering plants — for decoration, sale, ceremonies, and personal use. Urban floriculture takes this practice into city environments: rooftops, warehouses, basements, old factories, greenhouses attached to apartment buildings, or any available indoor space in a densely populated area.

It is a growing movement, driven by a few key trends. First, consumers increasingly want to know where their products come from. A locally grown flower, sold at a neighborhood market, carries a very different story than one that was flown in from Ecuador or Kenya. Second, cities are looking for ways to green their spaces and reduce their carbon footprints. Growing flowers locally reduces transport emissions significantly. Third, urban farming in general has proven that food — and flowers — can be produced in surprising places with the right technology. However, urban floriculture comes with real challenges. Space is limited and expensive. Outdoor conditions are often unpredictable. Soil quality in cities is poor. And water access, especially in water-stressed regions, can be both expensive and restricted. This is exactly where hydroponics and aeroponics enter the picture — not just as interesting ideas, but as practical, working solutions.

3. Understanding Hydroponics — The Basics

Hydroponics sounds technical, but the core idea is simple: instead of growing plants in soil, you grow them directly in water that contains all the nutrients the plant needs. The roots are submerged or exposed to this nutrient-rich solution, and the plant takes up what it needs directly, without having to search through soil for it.

There are several variations of hydroponic systems:

Nutrient Film Technique (NFT): A thin stream of nutrient solution flows continuously over the roots, which are suspended in a shallow channel. The roots get both water and oxygen this way.

Deep Water Culture (DWC): Plant roots are suspended in a tank of nutrient solution. An air pump keeps the water oxygenated so roots do not drown.

Ebb and Flow (Flood and Drain): The root zone is periodically flooded with nutrient solution and then drained. This gives roots regular access to both water and air.

For floriculture specifically, hydroponics has proven particularly effective. Flowers like roses, gerberas, tulips, chrysanthemums, and carnations all grow well in hydroponic systems. Because nutrients are delivered directly and consistently, plants often grow faster and produce more uniform, high-quality blooms. A rose that might take several weeks in soil can reach harvest-ready quality more quickly in a well-managed hydroponic setup.

4. Understanding Aeroponics — Taking It a Step Further

If hydroponics is impressive, aeroponics takes the concept even further. In an aeroponic system, plant roots hang in the air — in a chamber or chamber-like structure — and are misted with a fine spray of nutrient solution at regular intervals. The roots are exposed to both the mist and plenty of oxygen in between spray cycles.

This might sound futuristic, and in some ways it is. But the principle behind it is sound: roots need nutrients, water, and oxygen to thrive. In soil, getting all three in the right balance is difficult. In hydroponics, water and nutrients are well-managed but oxygen can sometimes be limiting. In aeroponics, all three are optimized simultaneously.

The result is remarkable. Plants in aeroponic systems often grow faster than in any other method. Their roots are more developed and active. And crucially, from a water efficiency standpoint, aeroponics uses dramatically less water — studies and farm-level data suggest up to 95% less water compared to conventional soil farming. For urban flower production, aeroponics is especially exciting because these systems can be stacked vertically, making use of building height rather than floor space. Flowers that do particularly well in aeroponic conditions include orchids, anthuriums, and certain varieties of roses. The level of control over root environment allows growers to experiment with nutrient formulas that enhance colour, fragrance, and vase life.

5. Water Efficiency — The Core Advantage

Let us talk numbers, because the water savings in these systems are genuinely remarkable. Conventional soil-based flower farming uses a large volume of water per square meter per growing cycle. Much of this water is lost — it evaporates from the soil surface, drains away underground, or is taken up by weeds rather than the target plant. Irrigation systems in traditional farms are improving, but even well-managed drip irrigation loses a significant portion of the water applied.

Hydroponic systems, by comparison, operate in a closed or semi-closed loop. Water that is not immediately absorbed by plant roots stays in the reservoir and is used again. The system is recirculating — the same water goes around and around, refreshed with nutrients as needed. Water loss occurs mainly through plant transpiration and some evaporation. Compared to soil farming, a well-run hydroponic system typically uses around 70 to 80% less water.

Aeroponic systems push this even further. Because only a fine mist is delivered — rather than flooding roots in water — and because that mist is contained in a chamber where excess can be collected, the efficiency is extraordinary. These systems can achieve water savings of up to 95% over traditional farming. For cities facing water restrictions or high water costs, this is not just an environmental benefit — it is a direct economic advantage.

6. Benefits Beyond Water Saving

Water efficiency is the headline advantage, but hydroponics and aeroponics offer a range of other benefits that make them compelling for urban flower production.

Faster Growth Cycles: Because nutrients are delivered directly and the growing environment is controlled, plants often mature faster than they would in soil. This means more flower harvests per year from the same space.

Year-Round Production: A hydroponic or aeroponic setup indoors, with controlled lighting and temperature, can produce flowers every single month of the year. This consistency is hugely valuable for florists and event planners who need reliable supply regardless of the time of year.

Reduced Pesticide Use: Soil is home to many pests and diseases that attack plants. When you remove soil from the equation, many of these threats disappear. Hydroponic and aeroponic flowers typically require far fewer pesticides.

Space Efficiency: Both systems can be implemented vertically, stacking growing layers upward rather than spreading across large flat areas. A single warehouse in the middle of a city can produce a substantial quantity of flowers using vertical racks and efficient lighting.

Higher Quality Blooms: Consistent nutrient delivery and a stable, controlled environment means flowers often have better color, more uniform sizes, and longer vase life — a competitive advantage in the cut flower market.

7. Challenges and Limitations

It would be unfair to discuss these technologies without acknowledging their real challenges. Hydroponics and aeroponics are not a perfect solution for everyone, and there are legitimate reasons why they have not yet replaced conventional farming entirely.

High Initial Investment: Setting up a hydroponic or aeroponic system — with tanks, pumps, misting nozzles, sensors, grow lights, and climate controls — requires significant upfront capital. For small-scale growers or those in lower-income regions, this cost can be a serious barrier.

Technical Knowledge: These systems require understanding of plant nutrition, pH management, water chemistry, and mechanical maintenance. A pump failure or nutrient imbalance can wipe out an entire crop quickly if not caught early.

Energy Consumption: Indoor systems, particularly those with artificial lighting and climate control, consume electricity. If that electricity comes from fossil fuels, the environmental benefit of water savings may be partially offset by carbon emissions.

Species Adaptability: Not all flower species adapt easily to soil-free systems. Some prefer soil or have root structures that do not suit these methods. Growers need to carefully select varieties suited to their chosen system.

8. Real-World Applications and Examples

These are not just theoretical ideas. Urban hydroponic and aeroponic flower farming is already happening at scale in several parts of the world. The Netherlands, long considered the capital of global flower production, has been integrating hydroponic greenhouse technology for decades. Dutch growers have refined nutrient systems and climate controls to produce extraordinary volumes of high-quality flowers with minimal water waste.

In Japan and Singapore, where land is extremely limited and expensive, vertical farming operations for flowers have emerged in repurposed urban buildings. These farms supply local florists and supermarkets with fresh-cut flowers without the long transport chains that traditionally connect consumers to distant farms.

In the UAE and other parts of the Middle East — where water scarcity is an existential issue — aeroponic systems are being explored as a way to produce flowers locally that would otherwise be impossible to grow given the desert climate. At a smaller scale, urban entrepreneurs are setting up rooftop hydroponic flower gardens in cities like New York, London, Mumbai, and Nairobi.

9. The Future of Water-Efficient Urban Floriculture

The future of urban flower farming looks genuinely exciting. Several trends are converging to make these systems more accessible, more efficient, and more widespread.

Smart Technology Integration: Sensors, artificial intelligence, and IoT devices are being integrated into modern hydroponic and aeroponic systems. These tools monitor pH, nutrient levels, humidity, temperature, and plant health in real time — automatically adjusting conditions to keep plants in their ideal growing range.

Renewable Energy Pairing: As solar panels and battery storage become cheaper, more urban farms are powering their systems with clean energy. This addresses one of the biggest criticisms of indoor farming — its energy footprint.

Growing Consumer Demand: People increasingly want to buy flowers that are local, sustainable, and responsibly produced. This creates a strong market incentive for urban growers who can offer a greener alternative to imported blooms.

Policy Support: Governments in several countries are beginning to recognize urban agriculture — including floriculture — as part of broader food security and sustainability strategies. Grants, subsidies, and zoning changes are making it easier to set up urban farms in previously restricted spaces.

10. Conclusion

Flowers are not a luxury — they are part of how humans mark important moments, express care, and bring beauty into everyday life. But the way we produce them needs to change. Traditional flower farming's high water demands are increasingly difficult to justify in a world where freshwater is becoming scarcer and more contested. Hydroponics and aeroponics offer a different path. They prove that flowers can be grown beautifully, abundantly, and with far less water — right in the heart of cities, close to the people who love them. These are not perfect systems, and they come with real costs and challenges. But the trajectory is clear: smarter, water-efficient flower production is not only possible, it is already happening.

For cities, entrepreneurs, researchers, and policymakers, the invitation is open. Invest in these technologies, support the growers pioneering them, and help build a future where flowers continue to bloom — even as we learn to use water more wisely. The garden does not have to end where the city begins.

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Mendelian Era and Beyond: Implications for Cross-Pollinated Crop Breeding



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Abstract

The rediscovery of Mendelian principles transformed plant breeding into a genetics-driven discipline. Cross-pollinated crops, due to high heterozygosity, benefited significantly through hybrid breeding, quantitative genetics, and genomic tools. This manuscript reviews the evolution from Mendelian genetics to genomic selection and highlights implications for modern crop improvement.

Keywords

Mendelian genetics; heterosis; cross-pollinated crops; genomic selection; plant breeding

1. Introduction

Plant breeding has evolved from empirical selection to a science-based discipline following Mendel's laws. Cross-pollinated crops exhibit high variability and heterozygosity, making them ideal for hybrid breeding.

2. Mendelian Era

Mendel's laws of segregation and independent assortment laid the foundation for understanding inheritance in cross-pollinated crops, particularly explaining dominance and inbreeding depression.

3. Hybrid Breeding and Heterosis

Heterosis exploitation through inbred lines and hybrids revolutionized crops like maize, leading to yield gains and uniformity.

4. Quantitative Genetics

Quantitative traits governed by multiple genes require statistical approaches including GCA, SCA, and recurrent selection.

5. Molecular and Genomic Era

Modern tools such as MAS, QTL mapping, genomic selection, and CRISPR have accelerated breeding efficiency.

6. Implications

Cross-pollinated crops benefit from heterotic grouping, improved hybrid prediction, and climate-resilient breeding strategies.

7. Conclusion

The integration of Mendelian genetics with genomics continues to drive innovation in plant breeding.

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When Cows Wear Stripes: A Simple Japanese Innovation for Better Fly Management



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Abstract

Biting flies pose a significant challenge in cattle management by irritating cattle, causing stress, reducing feeding efficiency, and resulting in economic losses in livestock production systems. Conventional fly control strategies depend heavily on chemical insecticides, which may contribute to environmental contamination, insect resistance, and recurring financial burden for farmers. Inspired by the natural striping pattern of zebras, Japanese researchers investigated whether painting black-and-white stripes on cattle could reduce fly attacks. Their findings revealed that cows painted with high-contrast stripes experienced significantly fewer fly landings and displayed reduced fly-repelling behaviours compared to non-striped controls. The visual contrast created by stripes likely interferes with flies' landing mechanisms. This innovative, low-cost, and chemical-free strategy offers promising implications for sustainable livestock management, improved animal welfare, and reduced pesticide dependency. Although practical limitations such as durability and labour requirements exist, this nature-inspired approach highlights the potential of simple management innovations in modern dairy farming.

Keywords

Cattle management; Biting flies; Zebra stripes; Animal welfare; Sustainable livestock; Fly control; Visual disruption

Introduction

In livestock farming, small stressors often create large consequences. Among these stressors, biting flies represent one of the most persistent and underestimated problems in cattle production systems. During warm and humid seasons, cattle are constantly disturbed by stable flies, horseflies, and other biting insects. What appears as a minor irritation actually leads to significant physiological and economic impacts.

A cow under continuous fly attack spends more time flicking its tail, stamping its feet, shaking its head, and twitching its skin than grazing peacefully. Over time, this disturbance reduces feed intake, affects milk yield, lowers weight gain, and increases stress levels. Conventional fly management relies primarily on chemical insecticides and repellents. While effective, these methods have limitations, including environmental concerns, chemical residues, resistance development, and recurring expenses.

A remarkable study conducted in Japan introduced an unconventional yet practical alternative: painting cows with black-and-white stripes.

The Inspiration from Nature

Zebras have fascinated scientists for decades because of their distinctive stripes. One widely accepted hypothesis suggests that zebra stripes help deter biting flies. Flies rely heavily on visual signals to identify landing surfaces. High-contrast patterns may disrupt their depth perception and approach behaviour.

Inspired by this biological observation, Japanese researchers designed an experiment to determine whether artificial striping on cattle could produce similar benefits.

The Japanese Study and Its Findings

In the experiment, black-coated cattle were painted with white stripes, creating a zebra-like appearance. For comparison, researchers observed cattle without stripes and cattle painted with black stripes that blended into their natural coat.

The results were significant. Cattle with black-and-white stripes experienced a marked reduction in fly landings compared to non-striped animals. Furthermore, striped cows showed fewer fly-repelling behaviours such

as tail flicking, ear beating, head tossing, and skin twitching. These behavioural indicators clearly demonstrated reduced irritation and stress.

The study confirmed that strong visual contrast, rather than the presence of paint itself, was responsible for reducing fly attacks.

How Do Stripes Work?

Although research is ongoing, several mechanisms have been proposed:

1. Visual Disruption

The alternating dark and light bands create optical confusion for flies during landing attempts.

2. Distortion of Motion Perception

As cattle move, the shifting striped patterns may interfere with flies' ability to calculate landing trajectories.

3. Light Reflection Effects

Stripes may alter polarised light reflection, making the animal less attractive to certain fly species.

Regardless of the exact mechanism, the reduction in fly landings is consistently associated with high-contrast striping.

Implications for Cattle Management

Improved Animal Welfare

Reduced irritation means lower stress levels. Chronic stress negatively affects immunity, reproduction, and productivity. A calm cow is generally more productive and healthier.

Better Feed Utilisation

With fewer disturbances, cattle spend more time grazing and ruminating, thereby improving feed efficiency.

Reduced Chemical Usage

Striping offers a non-chemical alternative that may reduce reliance on insecticides, supporting environmentally sustainable farming.

Cost-Effective Innovation

Temporary painting or marking solutions are relatively inexpensive compared to repeated chemical treatments, making this approach accessible even to small-scale farmers.

Practical Challenges

Despite promising results, several factors must be considered before large-scale adoption:

- Paint durability under rain and mud conditions
- Labour required to apply stripes in large herds
- Variation in effectiveness across breeds and regions
- Need for long-lasting, animal-safe marking materials

Further research and field trials in different climatic conditions, including tropical regions, are necessary to evaluate long-term feasibility.

Relevance for Indian Dairy Farming

India has one of the largest dairy cattle populations globally. Fly infestation is a common problem, especially during the monsoon and summer seasons. Exploring non-chemical fly management strategies is crucial in the context of sustainable and residue-free milk production.

The striping approach could be tested in organised dairy farms, gaushalas, and research institutions. Even if adopted selectively during peak fly seasons, it may offer measurable benefits in animal comfort and productivity.

Conclusion

Sometimes innovation lies not in advanced technology, but in simple observation of nature. The Japanese striped cow experiment demonstrates how a creative, low-cost idea can contribute to improved animal welfare and sustainable livestock management.

By reducing fly attacks through visual disruption, black-and-white striping provides a promising alternative to chemical control methods. Although practical limitations remain, the concept encourages farmers, researchers, and veterinarians to think beyond conventional solutions.

In dairy farming, comfort directly influences productivity. And in this case, better management might just be a matter of painting in black and white.

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Transitioning Traditions: A Study of Evolving Sowing Patterns in Jhum Cultivation among the Garo Tribe of West Garo Hills, Meghalaya



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Abstract

Jhum cultivation is one of the indigenous cultivation technique practiced by tribal farmers in the Northeastern Hill Region of India. This research article investigates the significant shift in agricultural practices within the Garo farmer community specifically focusing on the Dalu, Gambegre and Rongram blocks of West Garo Hills District, Meghalaya. Traditionally, shifting cultivation (locally known as *Jhum* or *A-ba so-a*) followed a single annual sowing cycle initiated after forest clearing and burning of jungles in the month of March and April. However, contemporary findings revealed a transition toward double sowing patterns, where a second sowing occurs between September and October. This study explores the multifaceted drivers behind this transformation including climate variability, increasing market demand for seasonal crops, and the community's efforts toward livelihood sustainability and food security. The transition reflects a "dual strategy" where indigenous farmers adapt their traditional knowledge to meet modern socio-economic pressures.

Key words: *Jhum, Shifting, Cultivation, Sowing, Tribe, Sustainability*

Introduction

Jhum or *shifting* cultivation also known as *slash-and-burn* stands as one of the oldest tribal agricultural practices in the Northeastern Hill Region of India. *Jhuming* is the name given to the method of shifting agriculture, and *Jhumias* are the farmers who participate in it (Dam et al, 2022). In Meghalaya, this age-old farming practice remains deeply rooted in the socio-cultural and economic sustainability of indigenous communities, especially among the Garo tribes. It is an ancient and widespread system of cultivation by Garo tribe and they follow agrosilvipastoral system in their cultivation practices (Das et al., 2016). In West Garo Hills district, *jhum* cultivation transcends its identity as a mere agricultural activity, embodying traditional ecological wisdom, collective labour and an adaptation finely tuned to the challenging topography of the region.

The practice starts with the clearing of vegetation on hill slopes, drying the cut biomass, and subsequently burning it before the monsoon season sets in. The ash produced from the burning is rich in essential plant nutrients which enriches the soil fertility. Farmers cultivate mixed crops of cereals, pulses, vegetables, spices and tubers predominantly using local cultivars. This approach not only



guarantees food security but also minimizes risks and optimizes available resources. Yield of crops grown under shifting cultivation in the region generally remains low (Paul *et al*, 2020). After two to five years of cultivation, the land is traditionally left fallow for an extended period to allow and enable natural regeneration of vegetation and restoration of soil essential nutrients. However, with the ever increasing population, the traditional *jhum* cycle has shortened, adversely affecting soil fertility and overall farm productivity. Other factors like market expansion, crops demand, and exposure to modern agricultural techniques are reshaping traditional practices and influencing farmer decision making.

Study Area

The West Garo Hills district is characterized by an undulating terrain and a humid sub-tropical climate, with high annual rainfall that typically ranges from 2,000 to 4,500 mm. Agriculture remains the mainstay of the district's economy, with *shifting* cultivation covering approximately 39% of the landscape. This study specifically focuses on Dalu, Gambegre, and Rongram blocks of the district.

Rongram Block: A region where the overall Benefit-Cost (B:C) ratio for *jhum* farming indicates profitability despite variability in production techniques.

Dalu and Gambegre Block: Areas identified as moderately suitable for the expansion of specialized crops like horticultural crops, which are increasingly integrated into the *jhum* landscape to enhance yield.

The Shift in Sowing Patterns

This study highlights a shift from a single to a double sowing cycle. The local farmers of the mention blocks of the district cleared jungles during the post monsoon months of mid January- February followed by drying of biomass and burned from end of February to March months. The sowing of seeds starts during the end of March and early April, aligned with pre-monsoon rainfalls. During the period, it was observed that upland rice, maize, oilseed, pulses, tubers, chilli, brinjal, cowpea, and millets predominantly of local cultivars are grown. But a notable



transformation was observed in sowing patterns, that the farmers in the study areas are increasingly adopting a double sowing cycle rather than adhering to the traditional single sowing period from mid September to mid October. This evolution signifies an intensified land-use approach and a significant deviation from established *jhum* cultivation calendars. Several factors including climate variability, erratic rainfall, modified seasonal cycles are responsible for this change. Seeking to improve year round food security and income stability, farmers are increasingly cultivating their land more frequently and diversifying their crop choices. Despite its adaptive advantages, this change in *jhum* cultivation practices raises critical concerns about environmental sustainability and long-term feasibility. These changes underscore the resourcefulness and resilience of Garo farmers as they navigate evolving challenges while striving to meet their economic needs and adapt to climatic uncertainties to sustain their livelihood.

Drivers of Agricultural Transition

The move toward double sowing is propelled by several environmental and other critical factors-

- a. Climate Change and Variability:** Erratic rainfall patterns, delayed monsoons, and changes in temperature and relative humidity have influenced crop growth cycles and altered the delicate balance required for traditional crop production. Farmers have been forced to adopt staggered sowing to mitigate the risk of total crop failure due to extreme weather events. Increasing intensity of shifting of cultivation practices leads to low rainfall due to destruction of habitat which finally reduces biological diversity and causes extinction of previously undiscovered indigenous species too (Jeeva, 2006).

- b. Market Demand and Commercialization:** Increasing demand for seasonal crops and cash crops in local markets has encouraged farmers to utilize land more intensively. By sowing twice, *jhum* farmers capitalized on fluctuating commodity prices and provide a continuous supply of produce to local weekly markets.
- c. Livelihood Sustainability and Food Security:** With an average family size of seven in the region, there is a constant need for a steady food supply to their family. The second crop serves as a "safety net," ensuring food sovereignty throughout the year and reducing dependence on the market for basic nutrition.
- d. Rising Population Pressure and Land Constraints:** With the ever growing population, there is a need to maximize production from limited land. This also led to shorter fallow periods of *jhum* farming.
- e. Food Security and Livelihood Needs:** To ensure year-round food availability and income stability, farmers are diversifying cropping patterns and increasing the frequency of cultivation.
- f. Exposure to Development Programs:** Government scheme interventions, agricultural extension services, and exposure to improved practices have also influenced farmers to adopt multiple cropping systems from the limited availability of land.



Implications of the Changing Patterns

Positive Outcomes

- Increased cropping intensity and productivity
- Enhanced income opportunities
- Better utilization of available land
- Diversification of crops and diets

Challenges and Concerns

- Decline in soil fertility due to continuous cropping
- Reduced fallow periods affecting ecological regeneration
- Increased risk of pest and disease incidence
- Potential loss of traditional knowledge systems

Sustainability Considerations

While transforming towards double sowing in *jhum*, it raises critical questions about long-term sustainability. The characteristics of *jhumming* are changing over time reported by Trishna Moni Tamuli and Ashok K. Bora, 2022. Continuous cultivation without adequate soil management may lead to land degradation. Therefore, integrating sustainable practices such as agroforestry systems, use of organic manure and compost, crop rotation and intercropping, soil and water conservation measures can help to maintain ecological balance while supporting productivity.



Conclusion

The study clearly highlights that *jhum* cultivation in the West Garo Hills district of Meghalaya is undergoing a significant transformation from a traditional single sowing system to a more intensified double sowing pattern. The emergence of this dual sowing pattern describes how indigenous knowledge systems are not static but evolve dynamically to meet contemporary socio-economic challenges. While the transition has resulted in positive outcomes such as increased cropping intensity, enhanced income opportunities, and improved food security, it also raises serious ecological concerns. The shortening of fallow periods, continuous land use, and increased pressure on natural resources threaten soil fertility, biodiversity, and the long-term sustainability of the *jhum* ecosystem. Therefore, a balanced and integrated approach is essential. To ensure the long-term sustainability of this evolving system, it is recommended that policy interventions focus on *jhum* management rather than eradication. Future strategies should include improving road connectivity for market access, providing credit facilities for *jhum* farmers, and documenting indigenous nature conservation practices that allow this unique form of agriculture to thrive in harmony with the environment.

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Green Living with Smart Home Innovations



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Abstract

Green living has become an essential approach to address growing environmental challenges such as climate change, resource depletion and pollution. Smart home innovations play a significant role in promoting sustainable lifestyles by integrating advanced technologies that enhance energy efficiency, reduce waste and optimize resource utilization. This article explores the concept of green living through the adoption of smart home systems, including automated lighting, energy-efficient appliances, smart thermostats and water management systems. These technologies enable real-time monitoring and control, leading to reduced energy consumption and lower carbon footprints. Additionally, smart homes contribute to improved quality of life by offering convenience, safety, and cost savings. The study highlights the potential of combining eco-friendly practices with digital solutions to create sustainable living environments. It concludes that the widespread adoption of smart home innovations can significantly support environmental conservation efforts while promoting economic and social well-being.

Keywords: Green Living, Smart Homes, Sustainability, Energy Efficiency

Introduction: -

In recent decades, the world has been facing serious environmental challenges such as climate change, rapid depletion of natural resources and increasing levels of pollution. These issues have highlighted the urgent need for adopting sustainable lifestyles, commonly referred to as green living. Green living emphasizes the efficient use of resources, reduction of waste and adoption of environmentally responsible practices in daily life. At the same time, rapid advancements in digital technology have introduced innovative solutions that support sustainability. Among these, smart home innovations have emerged as a promising approach to achieving eco-friendly living.

Smart homes utilize advanced technologies such as the Internet of Things (IoT), automation systems and energy-efficient devices to monitor and manage household activities efficiently. These systems enable users to control lighting, heating, cooling and water usage remotely, thereby reducing unnecessary consumption of energy and resources. Residential buildings account for a significant share of global energy consumption, making them a crucial sector for implementing energy-efficient solutions (International Energy Agency, 2021). Furthermore, integrating technological innovations with sustainable practices is essential for achieving global environmental targets (United Nations Environment Programme, 2020).

Research has also demonstrated that smart home technologies can influence user behavior and improve energy efficiency. Feedback provided through smart systems can lead to reductions in household energy consumption (Darby, 2006). Similarly, smart home adoption has been found to enhance environmental performance as well as user comfort (Wilson et al., 2015).

Thus, the integration of green living principles with smart home innovations not only helps in reducing carbon footprints but also improves quality of life through enhanced convenience, efficiency and cost savings, representing a sustainable pathway toward the future.

Core Concepts of Green Living and Smart Home Technology

Green living refers to an eco-friendly lifestyle that emphasizes the conservation of natural resources, reduction of waste, and sustainable use of energy to minimize environmental impact. In contrast, smart home technology involves the use of advanced systems such as the Internet of Things (IoT), automation and energy-efficient devices to manage household functions like lighting, heating and water usage in an efficient and convenient manner. The link between the two lies in their shared goal of sustainability, as smart home technologies provide practical tools that support green living practices by reducing energy consumption, minimizing resource wastage and promoting responsible behavior. Thus, the integration of smart home innovations with green living creates a more efficient, sustainable and environmentally conscious way of life.

Key Components of Smart Homes and Their Role in Sustainability



Smart homes incorporate various technologies that directly support sustainable living. Smart lighting systems automatically adjust brightness or switch off when not in use, reducing unnecessary electricity consumption. Smart thermostats regulate indoor temperature based on occupancy and user habits, helping to save energy used in heating and cooling. Energy-efficient appliances are designed to consume less electricity and water while maintaining performance, thereby lowering overall resource use. Smart water management systems monitor usage, detect leaks and optimize water consumption, which helps in conserving this vital resource. Additionally, the integration of renewable energy

sources such as solar panels enables households to generate clean energy, reducing dependence on non-renewable sources and lowering carbon emissions. Together, these components contribute significantly to environmental sustainability by promoting efficient resource utilization and reducing waste.

Benefits of Smart Homes for Sustainable Living

- 1. Environmental Benefits:** Smart home technologies help in reducing energy consumption through automated lighting, smart thermostats and efficient appliances. They minimize wastage of electricity and water, which leads to a lower carbon footprint and supports environmental conservation.
- 2. Economic Benefits:** Although the initial cost of installing smart home systems may be high, they result in significant long-term savings. Reduced electricity and water bills, along with efficient resource utilization, make smart homes a cost-effective solution over time.
- 3. Social Benefits:** Smart homes improve the quality of life by offering comfort, convenience and safety. Users can control devices remotely, automate daily tasks and enjoy a more secure and modern lifestyle, leading to overall well-being.

Challenges and Limitations of Smart Homes

High Initial Cost: Installation of smart devices, automation systems and renewable energy solutions requires significant investment, making it less affordable for many households.

Lack of Awareness: Many people, especially in rural areas, have limited knowledge about smart home technologies and their benefits, which restricts adoption.

Technical Issues and Maintenance: Smart homes depend on internet connectivity, regular updates and proper functioning of devices; any malfunction or system failure can cause inconvenience and require expert support.

Solutions to Promote Smart Homes for Sustainable Living

Awareness Programs: Conduct educational campaigns, workshops and community outreach programs to inform people about the benefits, usage, and long-term advantages of smart home technologies, especially in rural and semi-urban areas.

Government Support and Subsidies: Governments can encourage adoption by providing financial incentives, subsidies, tax benefits and supportive policies for installing smart devices and renewable energy systems like solar panels.

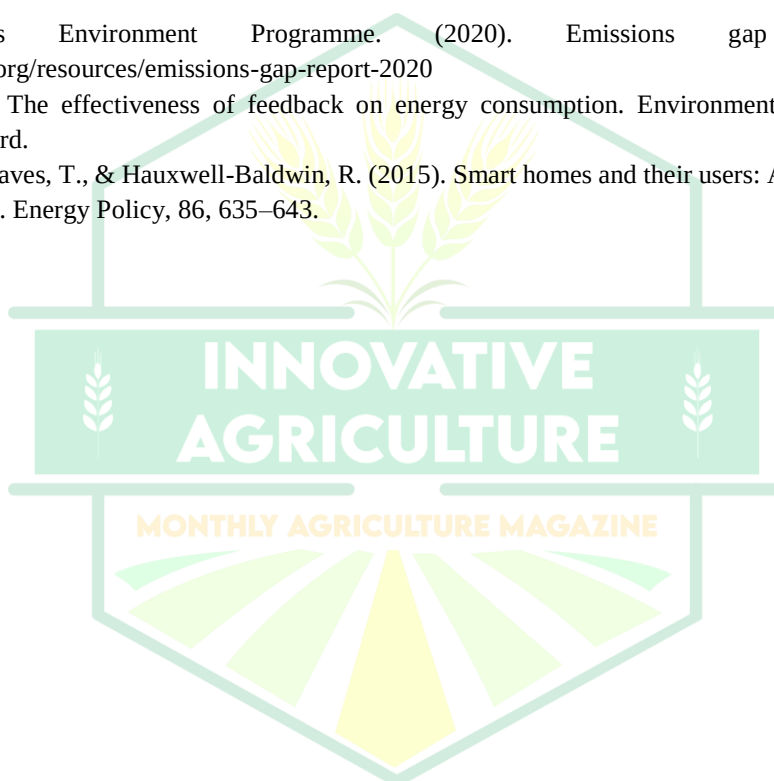
Affordable Technologies: Development and promotion of low-cost smart home devices and scalable solutions can make these technologies accessible to a wider population, ensuring inclusive and widespread adoption.

Conclusion

In conclusion, green living and smart home innovations together offer an effective approach to achieving sustainable development. Smart technologies such as automated lighting, temperature control systems, energy-efficient appliances and smart water management play a vital role in reducing resource consumption and minimizing environmental impact. These systems not only support environmental conservation but also provide economic benefits through long-term cost savings and social advantages by enhancing comfort and convenience. However, challenges like high initial cost, lack of awareness and technical issues must be addressed to ensure wider adoption. With increasing technological advancements, supportive government policies and growing environmental awareness, smart homes are expected to become an integral part of sustainable living in the future. Therefore, embracing smart home innovations can lead society toward a more efficient, eco-friendly, and sustainable lifestyle for future generations.

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Emerging Hybrid Approaches for Textile Dye Wastewater Treatment



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Abstract

Water is one of the most essential natural resources for sustaining life and maintaining ecological balance. The importance of good-quality, potable water to human existence cannot be overstated, and life would be practically impossible without safe drinking water. However, contamination of water bodies by textile industry effluents has emerged as a serious environmental concern. The discharge of untreated dye-containing wastewater into rivers, lakes, and other aquatic environments threatens both ecological integrity and human well-being. Synthetic dyes are particularly problematic because of their complex molecular structures, high stability, and resistance to natural degradation processes. As a result, these pollutants require proper treatment before wastewater is released into the environment. Conventional methods, including physical, chemical, and biological approaches, exhibit limitations such as high cost and incomplete removal. In recent years, integrated or hybrid treatment strategies have gained considerable attention as more sustainable alternatives. Approaches that combine adsorption, artificial intelligence-based process optimisation, and biodegradation have shown strong potential for efficient dye removal, decolorization of wastewater, and improved cost-effectiveness, making them promising solutions for textile wastewater management.

Keywords: Textile dyes, Remediation, Decolorization, Artificial intelligence, Wastewater management.

1. Introduction:

Clean and safe water is fundamental not only for human health but also for ecosystem integrity and sustainable development however, the rapid pace of industrialisation and urbanisation has severely compromised water quality through the discharge of various pollutants, with synthetic dyes being a major concern. The swift advancement of the global economy has enhanced human living conditions however, it has also accelerated the expansion of sectors like textiles and fashion which, despite their cultural significance, exert substantial ecological stress. A major contributor to this environmental burden is the extensive reliance on synthetic dyes in dyeing operations, processes that are notoriously difficult to regulate and environmentally unsustainable. The first synthetic organic dye, mauveine, was discovered by William Perkin in 1865. This discovery led to a revolution in the dyestuff industry and initiated global synthetic organic dye production. At the beginning of the 20th century, the global production of dyestuff was mainly located in Europe. Now the largest producers are China and India, which are also the main suppliers of fabrics worldwide (Chemical Economics Handbook, 2018). The projections suggest that the global market for these dyes could reach USD 14.8 billion by 2032, underscoring not only the sector's growth, but also the escalating environmental burden associated with dye discharge (Barciela *et al.*, 2023). The Indian dyes and pigments industry has attained a value of USD 65.70 billion in 2023 and is expected to reach USD 97.64 billion by 2032 with a CAGR of 4.5% during the period (<https://www.chemicalmarket.net>). Maharashtra and Gujarat account for 90% of dyestuff production in India due to the availability of raw materials and dominance of textile industry in these regions. A critical problem lies in the inefficiency of dye fixation processes. For example, several prominent studies have reported that the annual production of synthetic dyes worldwide is around 7×10^7 tonnes, of which the textile industry alone uses more than 10,000 tons of these dyes

for dyeing processes that are often inefficient, resulting in the discharge of between 15 and 50% of the dyes that do not bind to fibres into wastewater. Because synthetic dyes possess limitless structural variations, a vast range of dye types exists, each requiring its own specific manufacturing process.

Synthetic dyes are extensively used in industries such as textiles, food processing, leather tanning, paper, cosmetics, and pharmaceuticals. This coloured effluent not only changes the appearance of natural water bodies but also interferes with light penetration, thereby reducing photosynthetic activity in aquatic ecosystems (Chavan *et al.*, 2013). Gungordu *et al* (2013) demonstrated that textile dyes pose serious ecological risks to amphibians, with tadpoles of *Xenopus laevis* showing high sensitivity. Figure 1 illustrates dye-containing wastewater and its adverse effects on human health (El Messaoudi *et al.*, 2024). These contaminants may exhibit carcinogenic properties and are associated with skin irritation, allergic reactions, respiratory complications, hypersensitivity, central nervous system dysfunction, and an increased risk of cancer. Exposure to dye pollutants can also cause skin rashes along with symptoms such as sneezing, coughing, wheezing, and asthma (Jorge *et al.*, 2023; Mu *et al.*, 2023).

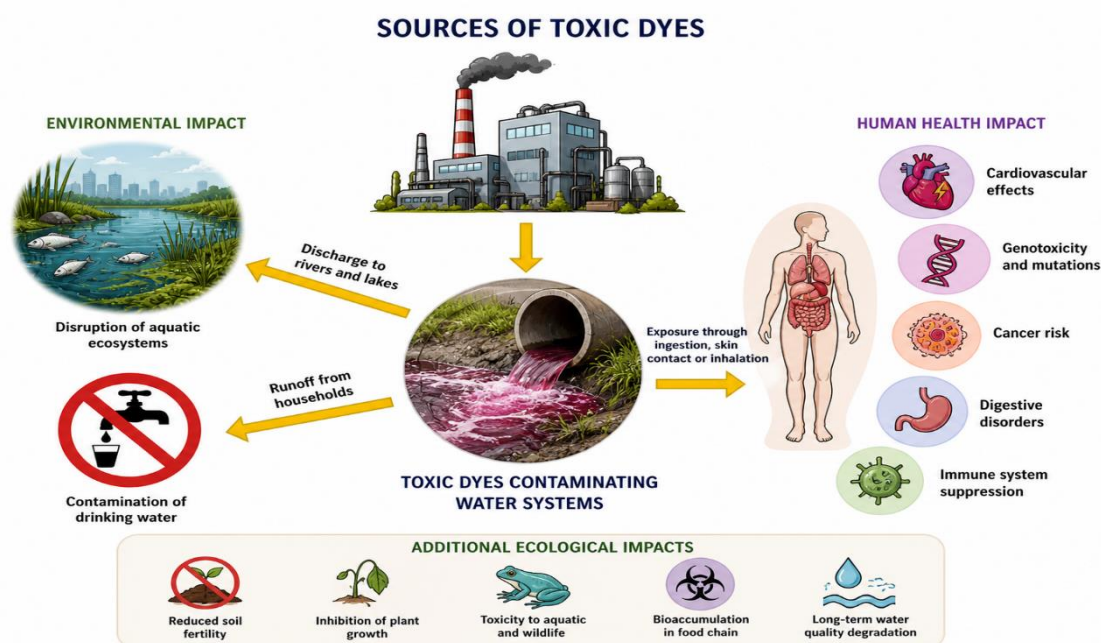


Figure 1. Effects of dyes on human health and the environment.

Synthetic dyes are used for their bright colors and stability, and they are mainly classified into azo, phenolic (triphenylmethane), disperse dyes, reactive dyes, sulphur dyes and other organic dyes. Azo dyes such as Congo Red, Methyl Orange, and Disperse Orange 1 are the most common, containing $-N=N-$ linkages that impart vivid shades. Phenolic dyes like Crystal Violet and Malachite Green produce intense colours but are often toxic and persistent. Other organic dyes, including Indigo, Rhodamine B, and Brilliant Blue, are used for various fibers and applications.

Traditionally, several conventional methods have been employed for dye removal from wastewater. These include physical processes such as adsorption, membrane filtration, and coagulation–flocculation, which primarily transfer dyes from the liquid phase to a solid phase. Bal and Thakur (2022) summarized key physicochemical methods for dye removal from wastewater. Fenton oxidation ($H_2O_2-Fe^{2+}$) is highly effective for decolourizing both soluble and insoluble dyes, though it produces considerable sludge. Ozonation achieves efficient oxidation without changing wastewater volume, but its short ozone half-life (~20 minutes) limits performance. Photochemical treatment using UV-based oxidation avoids sludge formation, yet may generate secondary by-products. Salt-based oxidation (e.g., NaCl) effectively cleaves azo bonds but can lead to the formation of hazardous aromatic amines. Electrochemical methods offer clean degradation into non-toxic products however; their application is constrained by high electricity costs. To overcome these limitation researchers now shifting towards combined and hybrid approaches to complete removal of dyes from waste water.

2. Hybrid approaches for dye remediation:

At the core of this transformation is the integration of physical, chemical, and biological methods into a single, cohesive treatment train (Ayub *et al.*, 2025). Rather than relying on a single mechanism, hybrid approaches utilize the strengths of each such as the rapid removal of bulk pollutants through physical filtration, followed by the molecular degradation capabilities of chemical oxidation, and the polishing effect of biological processes. This "multi-stage" architecture ensures that even complex, persistent dyes are effectively removed, resulting in higher quality effluent and a significant reduction in secondary waste generation.

The integration of AI and ML serves as an advanced intelligence layer in water treatment systems, improving prediction and optimization. Karishma *et al.* (2024) developed a novel mixed biomass (algae + manila tamarind seeds) for dye adsorption and applied ANN ([artificial neural network](#)) and ANFIS (adaptive neuro fuzzy interference) models for prediction. The hybrid ANN-PSO (particle swarm optimization) model showed excellent accuracy ($R^2 = 0.9999$ for EB and 0.9994 for BO). Maximum adsorption capacities were 79.95 mg/g (EB) and 102.4 mg/g (BO), indicating high efficiency. The Langmuir isotherm and pseudo-first-order kinetics best described the process, confirming monolayer adsorption dominated by physisorption. The distinctiveness of this study lies in the integration of mixed-biomass adsorption as a combined strategy to improve dye removal efficiency and adsorption performance. In addition, the regenerated mixed biomass retained its adsorption capability over five consecutive reuse cycles, demonstrating its practical applicability and operational stability. This feature distinguishes the study from earlier investigations that primarily focused on single-use biomass adsorbent systems.

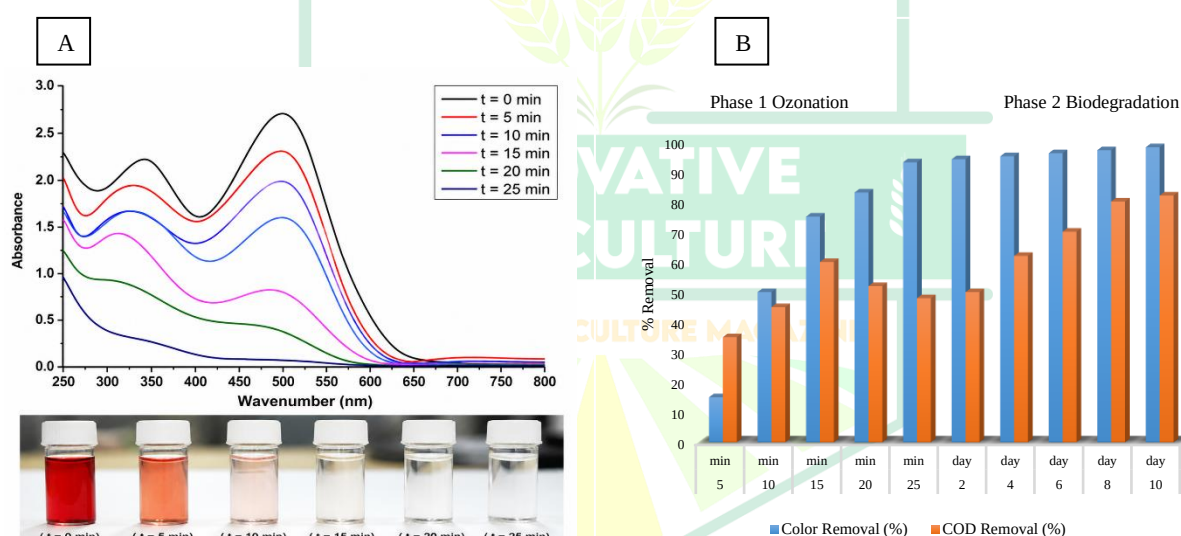


Figure 2.- A. Variation in the absorbance of the dye sample with the ozonation time (Initial dye concentration = 500 mg/L, Temperature = 35 °C, pH = 11.0). B. Combined color and COD removal plot for coupling process (ozonation and biodegradation).

Tripathi *et al.* (2023) reported that biological treatment is an economical and sustainable approach for removing organic pollutants from wastewater; however, its efficiency declines markedly when the wastewater contains recalcitrant compounds and exhibits low biodegradability ($BOD_5/COD < 0.2$). They synthesised a combined treatment approach for effective removal and mineralization of the recalcitrant Congo red dye from textile effluent. During ozonation, the solution pH decreased rapidly from alkaline to acidic conditions due to the formation of oxidation-derived acidic intermediates. Spectral analysis revealed substantial degradation of aromatic and azo chromophoric structures, evidenced by a marked reduction in absorbance in the 300–350 nm and 500–550 nm regions in Figure 2(A). After 15 min of ozonation, more than 80% color removal was achieved, whereas COD removal reached about 60%, confirming that chromophore destruction occurred faster than complete mineralization. Prolonged ozonation significantly enhanced the biodegradability of the wastewater, with the BOD_5/COD ratio increasing from 0.114 to 0.44 after 25 min, indicating the transformation of refractory

compounds into more biodegradable intermediates. Subsequent biological treatment, carried out after adjusting the ozonated effluent to pH 7.0, further improved treatment efficiency. In Figure 2(B) showing COD removal gradually increased during biodegradation and reached nearly 80% after 10 days, resulting in a final COD concentration of 179 mg L⁻¹, which complied with the discharge standards prescribed under the Environment (Protection) Rules.

Toxicity evaluation using *Daphnia magna* demonstrated that, at 500 ppm, the raw synthetic wastewater showed an EC₅₀ value of 14, the ozonated wastewater showed an EC₅₀ value of 17, and the biologically treated effluent was found to be non-toxic after 48 h exposure. These findings indicate that although ozonation generated intermediate oxidation products, the subsequent biological step effectively metabolized these compounds and reduced residual toxicity. These results confirm that integrating ozonation with biological treatment is an efficient and sustainable strategy for treating textile wastewater containing recalcitrant organic pollutants.

Kumar *et al.* (2026) developed an innovative bacterial consortium comprising *Pseudomonas aeruginosa* VITKSS5 and *Klebsiella pneumoniae* VITKSS6 for the effective degradation of the dye Brill Red 3BN (BR-3BN) at high concentrations. These strains were specifically chosen due to their strong biofilm-forming ability and high tolerance to dye levels up to 50,000 mg/L. The study reported a decolorization efficiency of 97.6% for 1000 mg/L of BR-3BN under microaerophilic conditions. This remarkable efficiency demonstrates the enhanced performance of the mixed consortium compared to individual bacterial strains, indicating a strong synergistic interaction. Environmental safety of the treated effluent was confirmed through phytotoxicity tests, which showed a 61.3% reduction in toxicity compared to untreated dye solutions. Additionally, plant growth parameters improved significantly: root elongation in *Lablab purpureus* increased by 31.3%, and seed germination in *Vigna radiata* rose from 50% to 85%.

Moreover, the bacterial strains exhibited key Plant Growth-Promoting Rhizobacteria (PGPR) characteristics, such as the production of indole acetic acid (IAA), ammonia, hydrogen cyanide (HCN), and the ability to solubilize phosphate. These results indicate that the treated wastewater is not only detoxified but may also serve as a nutrient-rich input for agricultural use. However, further large-scale field studies and ecological risk assessments are necessary before practical implementation.

3. Benefits of Hybrid or Combined Approaches:

- Higher dye removal performance: Combining different treatment technologies produces a synergistic effect, leading to very high dye removal efficiencies, often exceeding 95% decolorization.
- Reduces drawbacks of individual methods: Hybrid treatment systems, such as membrane bioreactors, can simultaneously remove both biodegradable and persistent non-biodegradable pollutants more effectively than single processes.
- More economical treatment: The integration of methods like Fenton oxidation with coagulation lowers chemical and energy requirements while enhancing COD reduction efficiency.
- Broader operating pH range: Advanced combined systems, particularly electro-Fenton processes, can work effectively under a wider range of pH conditions compared to traditional Fenton treatment.
- Enhanced degradation and detoxification: Integrated approaches promote complete breakdown of complex dye molecules and minimize the formation of harmful intermediate by-products.

4. Key Challenges of Hybrid Dye Removal Approaches:

- Integrated treatment systems can be expensive due to high energy demand, advanced equipment, and costly chemicals.
- Managing multiple treatment processes together requires careful control of operating conditions to maintain efficiency.
- Toxic intermediate compounds formed during chemical treatment may negatively affect subsequent biological treatment steps.

5. Conclusion:

Conventional methods have various limitations and opting a hybrid treatment system offers a very feasible and sustainable solution for the elimination and mineralization of dyes from waste water. In this case the complementary processes such as advanced oxidation, biological degradation and membrane or adsorption have

synergistic mechanism due to which limitations of individual methods is over committed and enhanced overall performances obtained. Future efforts, nevertheless, should concentrate on reducing costs and streamlining processes with large scale implementations to enable realistic industry usage.

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High Density Planting in Mango: Importance and Advantages



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Introduction

Mango is known as the “King of Fruits” and is one of the most important fruit crops cultivated in tropical and subtropical regions. In India, mango occupies a major place in horticulture because of its high nutritional value, delicious taste, and export potential. Traditionally, mango orchards are planted with wider spacing, which accommodates fewer trees per unit area. However, increasing land pressure, rising demand for fruits, and the need for higher productivity have encouraged farmers to adopt modern cultivation methods such as High Density Planting (HDP).

High Density Planting is a system in which mango trees are planted closer together than in conventional planting systems. Proper canopy management, pruning, irrigation, nutrient management, and use of dwarf or semi-dwarf varieties are important components of this technique. HDP helps farmers obtain higher yields and better economic returns from limited land resources.

What is High Density Planting?

High Density Planting refers to the cultivation of a larger number of mango plants per unit area by reducing the spacing between trees. In traditional orchards, mango trees are planted at wider spacing such as 10 m × 10 m, whereas in HDP systems spacing may range from 5 m × 5 m, 4 m × 2 m, or even closer depending on the variety and management practices. The main aim of HDP is to maximize productivity per hectare while maintaining plant health and fruit quality.

Importance of High Density Planting in Mango

1. Efficient Utilization of Land

Agricultural land is becoming limited due to urbanization and population growth. HDP enables farmers to cultivate more trees in the same area and utilize land resources efficiently.

2. Increased Mango Production

Since more plants are accommodated per hectare, total fruit production increases significantly compared to conventional planting systems.

3. Early Economic Returns

Trees in HDP systems come into bearing earlier due to better management practices. Farmers can obtain income within a shorter period after planting.

4. Suitable for Modern Orchard Management

HDP supports scientific orchard management practices such as drip irrigation, fertigation, pruning, and mechanized operations.

5. Improved Resource Use Efficiency

Water, fertilizers, sunlight, and nutrients are utilized more effectively under HDP systems, reducing wastage and improving productivity.

6. Enhances Farmers' Income

Higher yield and better fruit quality increase market value and profitability, thereby improving the economic condition of farmers.

Advantages of High Density Planting in Mango

1. Higher Yield per Unit Area

One of the major advantages of HDP is increased productivity. More trees per hectare result in greater fruit yield compared to traditional orchards.

2. Early Fruiting

Mango trees under HDP start bearing fruits earlier because of better canopy exposure and improved management practices.

3. Better Canopy Management

Regular pruning and training maintain optimum tree height and canopy structure, which improves sunlight penetration and air circulation.

4. Easy Intercultural Operations

Activities such as spraying, pruning, harvesting, weeding, and fertilizer application become easier and more efficient.

5. Efficient Irrigation and Fertigation

Drip irrigation and fertigation systems can be easily adopted in HDP orchards, saving water and fertilizers while improving nutrient uptake.

6. Improved Fruit Quality

Proper canopy management and balanced nutrition help produce fruits with better size, color, and quality.

7. Reduced Pest and Disease Incidence

Good ventilation and sunlight penetration reduce humidity within the canopy, thereby minimizing pest and disease occurrence.

8. Higher Profitability

Although the initial establishment cost may be high, the increased yield and early returns provide greater long-term profits.

9. Scope for Mechanization

Modern tools and machinery can be conveniently used in HDP orchards for pruning, spraying, and harvesting operations.

10. Sustainable Orchard System

HDP promotes scientific cultivation practices that improve resource efficiency and support sustainable horticultural production.



Management Practices in HDP Mango Orchards

Selection of Suitable Varieties

Dwarf and regular bearing varieties such as Amrapali, Mallika, Alphonso, and Totapuri are preferred for HDP systems.

Pruning and Training

Regular pruning is essential to control tree size and maintain proper canopy architecture.

Irrigation Management

Drip irrigation ensures efficient water supply directly to the root zone.

Nutrient Management

Balanced fertilizer application through fertigation improves growth and yield.

Pest and Disease Management

Integrated Pest Management (IPM) practices should be followed for effective control of pests and diseases.

Challenges in High Density Planting

Despite its advantages, HDP also has some challenges:

- Requires skilled management practices
- Higher initial investment
- Need for regular pruning and monitoring
- Risk of overcrowding if canopy management is neglected
- Increased competition for nutrients and water if not managed properly

Proper technical guidance and scientific orchard management are essential for the success of HDP systems.

Conclusion

High Density Planting in mango is an innovative and efficient cultivation technique that helps increase productivity, improve fruit quality, and enhance farmers' income. It ensures better utilization of land, water, nutrients, and sunlight while promoting scientific orchard management practices. Although the system requires careful management and higher initial investment, its long-term benefits outweigh the challenges. Adoption of HDP technology can play a major role in improving mango production and achieving sustainable horticultural development in India.

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Impact of Climate Change on Crop Diseases, Yield and Farm Economics: A Comprehensive Review



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Abstract

Climate change is significantly affecting agricultural productivity, crop health and farm economics worldwide. Rising temperatures, irregular rainfall, elevated atmospheric carbon dioxide and extreme weather events influence plant disease development, crop growth and yield stability. Climatic variability has increased the occurrence and spread of fungal, bacterial and viral diseases in major crops, resulting in substantial economic losses and food security concerns. Smallholder farmers are particularly vulnerable because of limited adaptive capacity and dependence on climate-sensitive agriculture. This review discusses the impact of climate change on crop diseases, agricultural productivity and farm economics while highlighting major adaptation and mitigation strategies such as climate-smart agriculture, integrated disease management, weather forecasting systems and digital agriculture. Interdisciplinary approaches integrating plant pathology, agrometeorology, agronomy and agricultural economics are essential for sustainable agricultural development under changing climatic conditions.

Keywords: Climate change; Plant diseases; Crop productivity; Farm economics; Food security; Climate-smart agriculture; Sustainable agriculture.

1. Introduction

Agriculture is one of the most climate-sensitive sectors and plays a vital role in global food security, employment and economic development. However, climate change has become a major challenge for sustainable agricultural production due to rising temperatures, irregular rainfall, prolonged droughts, floods and extreme weather events. These climatic changes directly influence crop growth, disease development and agricultural productivity. According to Malhi *et al.* (2021), climate change adversely affects soil health, water availability and crop physiology, resulting in reduced agricultural output worldwide. Yadav *et al.* (2021) also reported that increasing climatic variability threatens sustainable agricultural production systems and food security.

Plant diseases are among the most serious biological constraints affecting crop productivity. Environmental factors such as temperature, humidity and rainfall strongly influence pathogen survival, multiplication and spread. Singh *et al.* (2023) emphasized that climate change is accelerating the emergence and geographical expansion of plant pathogens, increasing the risk of disease outbreaks in major crops. Savary and Willocquet (2020) estimated that plant diseases are responsible for nearly 20–40% annual crop losses globally.

Climate change also creates severe economic consequences for farmers through reduced yields, increased production costs and unstable market conditions. Smallholder farmers are particularly vulnerable because of limited adaptive capacity and dependence on climate-sensitive farming systems. Therefore, understanding the combined impacts of climate change on crop diseases, yield and farm economics is essential for developing resilient agricultural systems.

2. Climate Change and Plant Disease Dynamics

Plant disease occurrence depends on the interaction among host plants, pathogens and environmental conditions, commonly known as the disease triangle. Climate change alters these interactions and creates favorable conditions for disease development. Rising temperatures, increased humidity and changing precipitation patterns significantly influence pathogen growth, survival, reproduction and dispersal.

Temperature is one of the most important climatic factors affecting disease development. Higher temperatures may accelerate pathogen life cycles and increase infection rates. Garrett *et al.* (2006) explained that climatic variability alters disease epidemiology by influencing host susceptibility and pathogen virulence. Bebbler (2015) further reported that warming temperatures have enabled many pests and pathogens to expand into new geographical regions.

Changes in rainfall and humidity also affect disease outbreaks. Excess rainfall and prolonged leaf wetness favor fungal diseases such as rusts, blights and downy mildew. Rosenzweig *et al.* (2001) observed that extreme rainfall events enhance pathogen survival and dispersal. Conversely, drought stress weakens plant defense systems, increasing crop susceptibility to opportunistic pathogens.

Elevated atmospheric carbon dioxide concentrations also influence plant-pathogen interactions by modifying crop physiology and canopy structure. Increased canopy humidity under elevated CO₂ conditions can create favorable environments for pathogen growth. Singh *et al.* (2023) reported that changing climatic conditions are contributing to the emergence and re-emergence of several economically important plant diseases.

3. Impact of Climate Change on Crop Productivity and Food Security

Climate change significantly affects crop productivity through heat stress, water scarcity, flooding and disease outbreaks. Rising temperatures negatively influence photosynthesis, flowering, pollination and grain formation, ultimately reducing crop yields. Wheeler and von Braun (2013) reported that climate change could substantially reduce the productivity of major food crops such as wheat, rice and maize.

Rice production is highly vulnerable to irregular rainfall and increasing temperatures. Diseases such as rice blast and bacterial blight become more severe under warm and humid conditions. Wheat crops are increasingly affected by rust diseases and terminal heat stress, while maize productivity is reduced by drought and fungal infections.

Erratic rainfall patterns further reduce water availability and nutrient uptake. Flooding damages root systems and promotes soil-borne diseases, whereas drought conditions reduce biomass accumulation and crop growth. Yang *et al.* (2024) stated that climate change intensifies environmental pressures on agricultural systems and threatens global food production.

Reduced agricultural productivity directly threatens food security. Declining yields and disease outbreaks contribute to food shortages, increased food prices and nutritional insecurity. Paudel *et al.* (2023) highlighted that climate change, conflicts and global crises collectively pose major challenges to food systems worldwide. Strange and Scott (2005) also identified plant diseases as a serious threat to global food security.

4. Economic Impacts of Climate Change on Agriculture

Climate change has major economic consequences for agriculture at farm and national levels. Reduced crop yields, increased disease incidence and climatic uncertainties lower farm profitability and increase production costs. Farmers are required to spend more on irrigation, disease management, pesticides and improved crop varieties. Smallholder farmers are particularly vulnerable because of limited financial resources and dependence on rainfed agriculture. Khan *et al.* (2021) reported that climate-induced hazards such as droughts and floods significantly increase farmers' vulnerability and economic instability.

Climate change also affects agricultural markets and supply chains. Reduced production often leads to food shortages, higher prices and market fluctuations. Raihan (2023) explained that climate change negatively affects socio-economic systems through declining agricultural productivity and increasing economic instability. Disease outbreaks further increase financial losses due to higher management costs and reduced product quality. Nelson *et al.* (2009) estimated that substantial investments will be required globally to adapt agriculture to future climate conditions.

5. Adaptation and Mitigation Strategies

Adapting agriculture to climate change is essential for ensuring food security and economic sustainability. Climate-smart agriculture (CSA) has emerged as an effective strategy for improving productivity, resilience and environmental sustainability. Practices such as conservation agriculture, crop diversification, efficient irrigation and integrated nutrient management help reduce climate-related risks (Bibi and Rahman, 2023).

Integrated disease management (IDM) is another important approach for controlling climate-induced disease outbreaks. IDM combines cultural, biological and chemical methods such as crop rotation, resistant varieties, biological control and judicious pesticide use. The development of climate-resilient and disease-resistant crop varieties is essential for maintaining agricultural productivity. Advances in plant breeding and biotechnology have improved the development of crops tolerant to heat, drought and pathogens.

Agrometeorological tools and weather-based forecasting systems also play an important role in climate adaptation. Early warning systems help farmers make timely decisions regarding disease management and crop protection. Digital agriculture technologies including remote sensing, drones, artificial intelligence (AI) and mobile advisory services are increasingly supporting sustainable farming. Balasundram *et al.* (2023) emphasized that digital agriculture improves precision farming, disease monitoring and climate risk management. Government support through climate policies, agricultural insurance, research investments and farmer training programs is equally important for strengthening agricultural resilience.

6. Conclusion

Climate change represents a major threat to global agriculture through its adverse effects on crop diseases, agricultural productivity and farm economics. Rising temperatures, altered precipitation patterns, elevated atmospheric carbon dioxide concentrations and extreme weather events have intensified plant disease outbreaks and reduced crop yields worldwide. These impacts threaten food security, rural livelihoods and economic sustainability, particularly in developing countries where agriculture remains highly climate-sensitive.

The interaction between climate variables and plant-pathogen systems has resulted in increased disease severity, geographical expansion of pathogens and emergence of new disease risks. Simultaneously, declining productivity and increasing management costs have negatively affected farm income and market stability. Addressing these complex challenges requires interdisciplinary collaboration among plant pathology, agrometeorology, agronomy and agricultural economics.

Climate-smart agriculture, integrated disease management, resistant crop varieties, digital agriculture technologies and weather-based forecasting systems offer promising solutions for enhancing agricultural resilience. Strong policy support, research investment and farmer awareness programs are also essential for sustainable adaptation and mitigation. Future agricultural strategies must integrate scientific innovation, socio-economic planning and environmental sustainability to ensure global food security under changing climatic conditions.

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From Lab to Field: How Genetic Research Improves Farmers' Lives



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Introduction

Modern agriculture is facing serious challenges—climate change, increasing pest attacks and declining soil fertility. Farmers today need crops that can survive these stresses while still giving good yields. This is where genetic research is playing a vital role, helping to develop improved crop varieties that directly benefit farmers in their fields.

What is Genetic Research in Agriculture?

Genetic research focuses on understanding the genetic material of plants to identify traits such as higher yield, tolerance to drought or heat and disease resistance. By selecting or modifying these traits, scientists develop improved varieties that perform better under real farming conditions. It also helps in identifying specific genes linked to important traits, allowing the breeders to make more informed and faster decisions compared to the traditional methods. Instead of waiting for full plant growth, desirable characteristics can be detected at early stages.

Another important aspect is that it supports the development of region-specific varieties, which are better adapted to local soil climate, and water availability, ensuring more consistent performance in farmers' fields.

From Lab to Field: How Technology Reaches Farmers

The journey begins in research laboratories where scientists identify useful traits. These traits are tested through field trials under different environments. Once proven successful, seeds are multiplied and distributed to farmers through agricultural universities and extension systems.

Technologies Making a Difference

1. Marker-Assisted Selection (MAS)

This technique helps scientists select plants with desirable traits using DNA markers, making breeding faster and more accurate and farmers benefit from early availability of improved varieties with better performance in the field. Unlike traditional breeding, MAS allows breeders to identify useful traits at the seedling stage itself, reducing the time required for variety development. It has been widely used for improving disease resistance, grain quality, and stress tolerance in crops like rice, wheat, and maize.

2. Genetic Engineering

Genetic engineering allows the introduction of specific traits into crops, e.g. Bt cotton in India has significantly reduced pest damage and pesticide use, leading to better yields and lower costs for farmers. This technology also helps in developing crops with enhanced nutritional quality and tolerance to environmental stresses. In many cases, genetically improved crops contribute to more stable production and reduced crop losses under difficult conditions.

3. CRISPR-Cas9 Technology

CRISPR is a modern gene-editing tool that allows precise changes in plant DNA. It has fundamentally transformed plant science by enabling precise, efficient, and scalable modification of plant genomes. Since it is adapted from prokaryotic adaptive immune systems, CRISPR–Cas9 has rapidly replaced earlier genome engineering technologies owing to its programmability, simplicity and broad applicability across diverse plant species. In plant research, CRISPR–Cas9 has been extensively applied to crop improvement, functional genomics, stress tolerance enhancement, yield optimization and disease resistance. The technology supports targeted gene insertion, knockout, and transcriptional regulation, significantly accelerating breeding programs while improving genetic precision.

Real-life Impact on Farmers

Genetic research has already shown results in Indian agriculture:

- **Improved rice varieties:** Better resistance to diseases like bacterial blight
- **Drought-tolerant wheat:** More stable production under water stress
- **Mustard (DMH-11):** A high-yield, herbicide-tolerant hybrid developed at the University of Delhi.
- **Brinjal (Bt Brinjal):** Engineered for resistance to fruit and borer pests.
- **Disease resistant high yielding hybrid:** HHB 67 improved- a high yielding pearl millet hybrid with improved resistance to downy mildew disease and 10% higher yield than the original developed by Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar in collaboration with International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Benefits for Farmers

Aspect	Benefit
Better quality produce	Improved grain size, taste, and higher market value
Reduced crop loss	Resistance to pests and diseases lowers damage
Efficient input use	Better utilization of water and fertilizers
Stable yield under stress	Consistent production under drought and heat
Reduced labor requirement	Less need for repeated pesticide applications
Improved shelf life	Longer storage life, reduced post-harvest losses
Climate adaptability	Performs better under changing weather conditions
Higher profitability	Increased income due to better yield and lower costs

What Should Farmers Do?

- Use certified seeds of improved varieties recommended for their region
- Stay updated with information provided by agricultural universities and extension services
- Participate in field demonstrations and farmer training programs
- Adopt new technologies gradually after understanding their benefits and suitability
- Combine improved crop varieties with good agronomic practices for maximum benefit

Conclusion

Genetic research is no longer confined to laboratories—it is actively transforming agriculture at the field level. It is strengthening the connection between science and agriculture by developing crops that are more productive, resilient, and suitable for modern farming challenges. From improving tolerance to climate stress to reducing crop losses caused by pests and diseases, these advancements are helping farmers improve their livelihoods.

As agricultural research continues to progress, the collaboration between scientists, extension workers, and farmers will become even more important. By adopting scientifically developed crop varieties and modern farming practices, farmers can move toward more profitable and sustainable agriculture.

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Reimagining Seafood Production through Floating Sea Cage Systems



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Abstract

The rising global demand for seafood, alongside the steady depletion of wild fish stocks, has made it necessary to rethink how we produce fish. Floating sea cage farming presents a practical and scalable alternative that uses natural water bodies without requiring additional land. In India, this approach is gradually gaining importance with support from institutions such as the National Fisheries Development Board (NFDB) and the Indian Council of Agricultural Research – Central Marine Fisheries Research Institute (ICAR-CMFRI), along with policy backing under the Pradhan Mantri Matsya Sampada Yojana (PMMSY). This article discusses the technical, economic, and institutional aspects of marine cage culture and its potential to strengthen food security, generate livelihoods, and contribute to the country's blue economy.

Introduction

For decades, seafood production has largely depended on capture fisheries, where fish are harvested directly from oceans and inland water bodies. While this method supported global consumption for a long time, it is now under strain due to overfishing, climate variability, and environmental degradation. Recent global assessments by the Food and Agriculture Organization (FAO) indicate that a significant portion of fish stocks are either fully exploited or overexploited, leaving limited scope for increasing catch from natural sources.

Traditional fishing systems are inherently uncertain. They depend on seasonal availability, weather conditions, and fluctuating fish populations. As a result, income for fishing communities remains unstable and productivity is difficult to scale.

In this context, aquaculture—and more specifically marine cage culture—offers a reliable alternative. By growing fish in controlled enclosures placed in natural water bodies, it becomes possible to ensure steady production while reducing pressure on wild resources. The shift toward cage culture is therefore not just a technological change but a necessary transition for ensuring long-term sustainability, improving export potential, and strengthening coastal livelihoods.

Cage Culture

Marine cage culture involves rearing fish in floating or anchored net enclosures installed in seas, reservoirs, or coastal waters. These cages allow free movement of water, ensuring a continuous supply of oxygen and natural removal of waste. Unlike pond-based systems, cage culture does not require land excavation or intensive infrastructure, making it both cost-effective and environmentally compatible.

Different cage designs are used depending on site conditions. These include fixed cages anchored to the seabed, floating cages supported by buoyant structures, and more advanced submersible or submerged cages used in deeper or high-energy waters. The choice of cage depends on depth, wave conditions, and species requirements.

Importance of Cage Culture

The importance of cage culture lies in its ability to address multiple challenges simultaneously. It helps increase seafood production without putting additional pressure on declining fish stocks. At the same time, it creates employment opportunities and generates income for coastal populations, particularly those with limited access to land resources.

Another significant advantage is efficiency. Natural water currents facilitate better growth conditions, leading to faster development of fish. Compared to traditional systems, cage culture also has a lower environmental footprint, as it utilizes existing ecosystems without major alterations.

Criteria for Site Selection for Marine Cage Culture

The success of cage farming depends heavily on selecting an appropriate site. The location should have adequate depth, generally between 6 and 10 meters, to allow sufficient water circulation beneath the cages. Moderate currents are essential to ensure oxygen replenishment and waste dispersion, but excessively strong currents can damage the structure.

Sites must be protected from extreme weather conditions such as strong winds and high waves. It is equally important to avoid areas near industrial discharge, sewage outlets, or agricultural runoff, as these can deteriorate water quality. Accessibility is another key factor, as farmers need to regularly monitor and manage the cages. In addition, the site should be free from navigation routes to prevent accidental damage and should have stable environmental conditions to reduce operational risks.

Water Quality Parameters

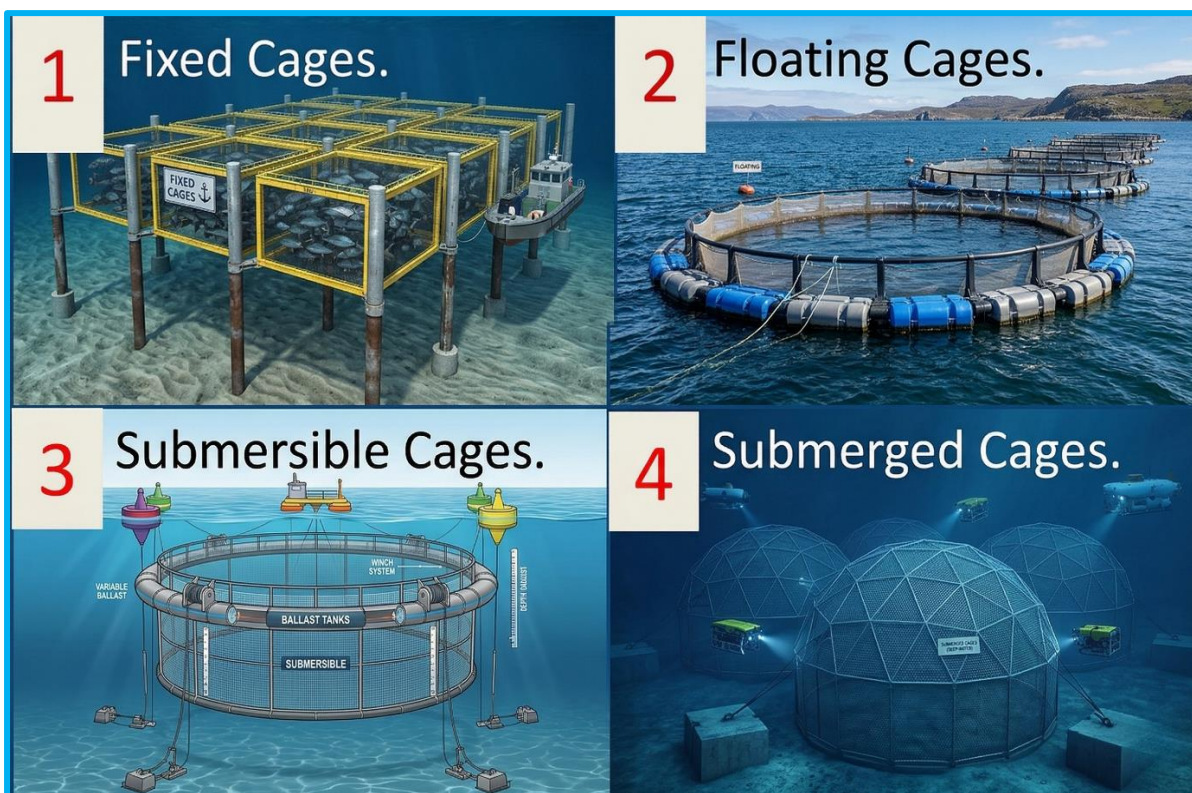
S.No.	Environmental Factors	Optimal Range
1	Temperature (°C)	27 – 31
2	Salinity (ppt)	< 25 – 40
3	Dissolved oxygen (DO)	5 ppm or more
4	pH	7.8 to 8.5
5	Maximum permissible wind velocity limit	10 knots for floating cage
6	Optimum transparency (Secchi disk)	< 5 m
7	Depth	6 – 10 m during low tide
8	Maximum limit of wave height	1 m for floating cage
9	Maximum limit of wave height	1 m for floating cage
10	Permissible current velocity range	0.05 to 1 m/sec

Maintaining good water quality is fundamental to the success of marine cage farming, whether culturing species like seabass, grouper, or snapper. Since fish are highly sensitive to environmental changes and have limited ability to cope with stress or regulate their body temperature, consistent and clean water conditions are essential. Proper water quality helps in minimizing disease risks, supports healthy growth, and prevents large-scale mortality.

Types of Cage Culture

Over time, cage aquaculture systems have evolved significantly, resulting in a range of designs suited to different environmental and operational conditions. Based on standard classification, four primary types of cage systems are commonly recognized:

1. **Fixed Cage:** These cages are permanently anchored to the seabed and are typically installed in deep, sheltered waters. Due to their stability and durability, they are widely used and suitable for cultivating a broad range of fish species.
2. **Floating Cage:** Floating cages are positioned on the water surface and supported by buoyant structures. They are generally deployed in relatively shallow and open waters. Although easier to install and manage, they tend to be less stable compared to fixed cages and may not be ideal for all species.
3. **Submersible Cage:** Submersible cages are designed to move vertically within the water column. They can be lowered below the surface during rough weather or raised when conditions are favourable. This flexibility makes them highly adaptable, though they involve higher costs and technical complexity.
4. **Submerged Cage:** These cages remain fully below the water surface and are typically used in deeper areas with strong currents. While they reduce surface disturbances, they are less commonly used due to operational difficulties and maintenance challenges.



Species to be Cultured

The selection of species is guided by market demand, growth performance, and adaptability to cage conditions. Species such as seabass (*Lates calcarifer*), cobia (*Rachycentron canadum*), pompano (*Trachinotus blochii*), and grouper (*Epinephelus* species) are commonly cultivated due to their high market value and export potential.

Ideal species should be able to tolerate crowding, adapt to artificial feeding, and grow rapidly. Availability of quality seed and resistance to diseases are also important considerations, as these factors directly influence productivity and profitability.

Major Differences Between Traditional and Cage Farming

Aspect	Traditional Fishing	Cage Culture
Source	Wild capture	Controlled farming
Productivity	Uncertain	High and predictable
Sustainability	Declining stocks	Sustainable
Employment	Seasonal	Continuous
Scalability	Limited	High

Economics, Resources and Infrastructure

Cage culture is economically attractive due to its relatively low infrastructure cost and high production efficiency. Feed and seed together account for the majority of operational expenses, typically ranging between 60% and 85%. Infrastructure costs remain comparatively low, often below 10%, as cages are simple to construct and maintain.

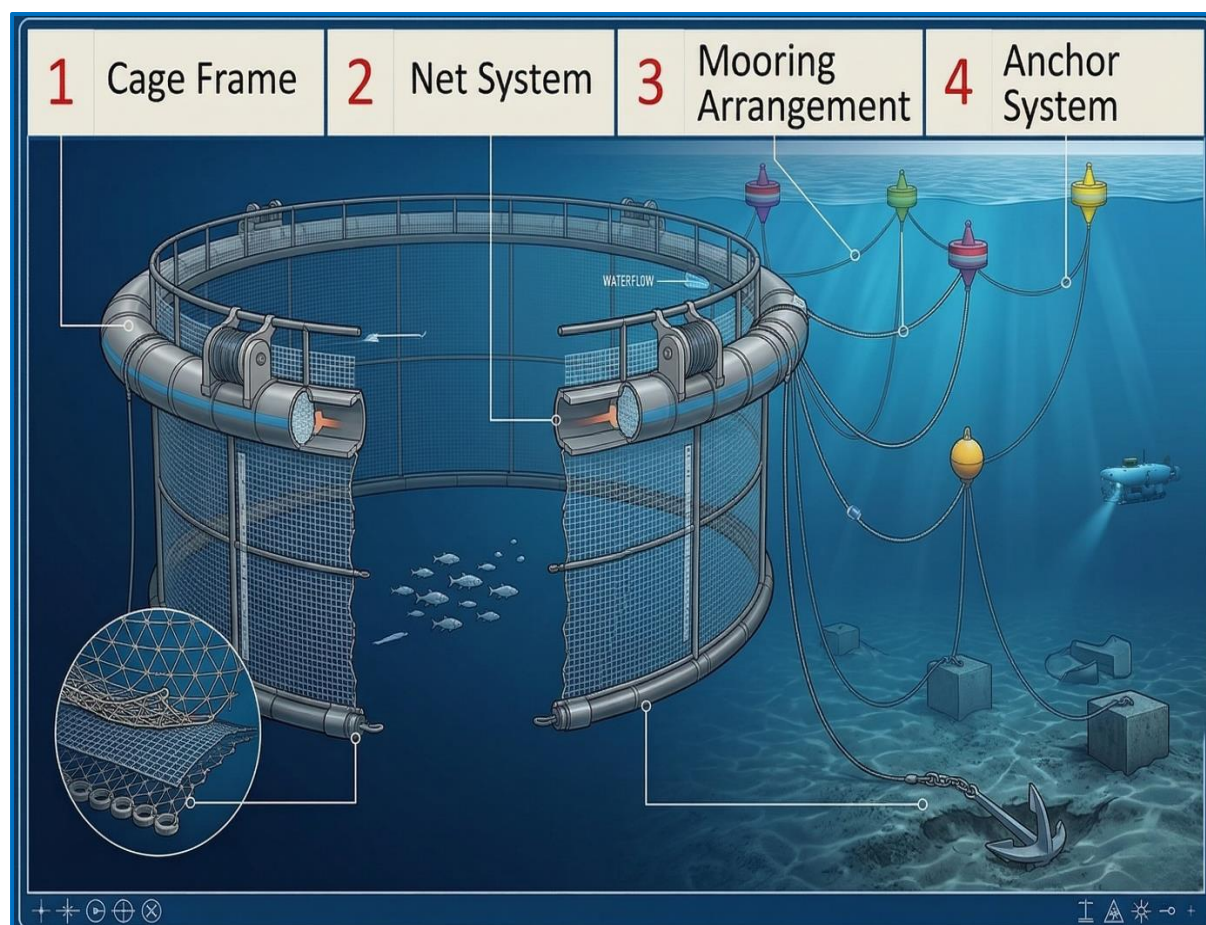
India has significant potential for expanding cage farming. With a long coastline, vast brackish water resources, and identified suitable zones, the country is well positioned to scale up production. States such as Andhra Pradesh, Gujarat, and Tamil Nadu have already demonstrated strong potential.

Components and Operations of Cage System

1) Cage Frame

The cage frame serves as the main structural support of the sea cage system. High Density Polyethylene (HDPE) pipes are commonly used due to their strength, durability, and resistance to harsh marine conditions. These pipes

help maintain the cage's shape and provide buoyancy, enabling it to float steadily on the water surface. Sea cages with diameters of 6 m and 15 m are generally used for grow-out operations, with the 6 m size being more preferred due to its ease of handling and efficient management in coastal environments.



2) Cage Net

The cage net functions as a protective enclosure that retains the fish while allowing continuous water exchange. It prevents fish from escaping and shields them from predators. The net is designed as a suspended bag, kept in position by weights at the bottom to maintain its shape. HDPE braided or twisted nets are widely used because of their durability and long service life, often lasting several seasons with proper care. Net depth varies based on the culture stage, typically ranging from 2–4 meters for nursery rearing and 5–6 meters for grow-out culture.

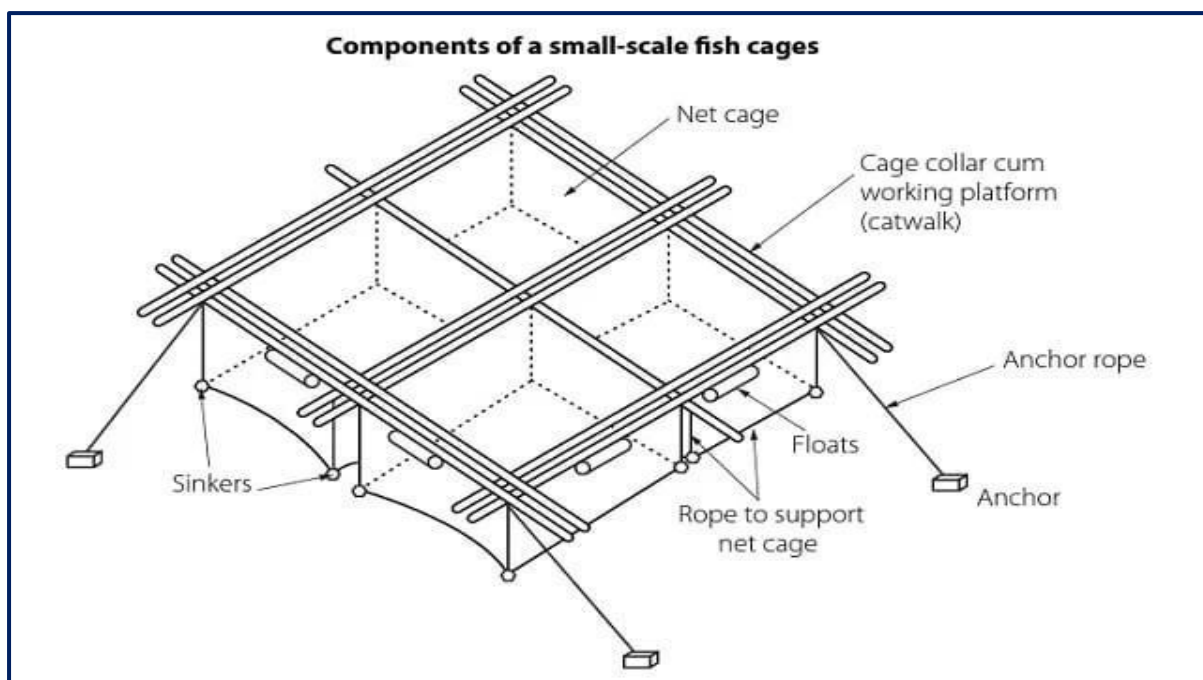
3) Mooring System

The mooring system ensures that the cage remains securely positioned in the water. It stabilizes the structure by counteracting currents, tides, and wind forces while maintaining its alignment. Constructed using strong materials such as steel chains, ropes, and connectors, the mooring arrangement provides durability and prevents drifting or structural damage under varying marine conditions.

4) Anchor System

The anchor system secures the cage to the seabed through the mooring arrangement, ensuring it stays fixed at the desired location. In India, concrete block anchors are commonly used due to their reliability and stability. These anchors, often weighing around 200 kg or more, are connected using heavy-duty chains and ropes. Typically, multiple anchors (around 3 tonnes total weight) are deployed to provide sufficient strength and resistance against environmental forces.

Operations within the cage involve maintaining optimal stocking density, monitoring environmental conditions, and ensuring proper fish health.



Feeding, Maintenance and Harvesting Practices

Feeding is carried out based on the growth stage of fish. Juveniles require higher feeding rates, which are gradually reduced as fish grow. Feeding is usually done multiple times a day to ensure efficient utilization and minimize waste.

Regular maintenance includes cleaning of nets to remove biofouling and inspection of cage structures. Regular assessment of fish health is critical to avoid the occurrence and spread of diseases.

Harvesting can be partial or complete, depending on market demand. This flexibility allows farmers to maintain steady income and efficient production cycles.

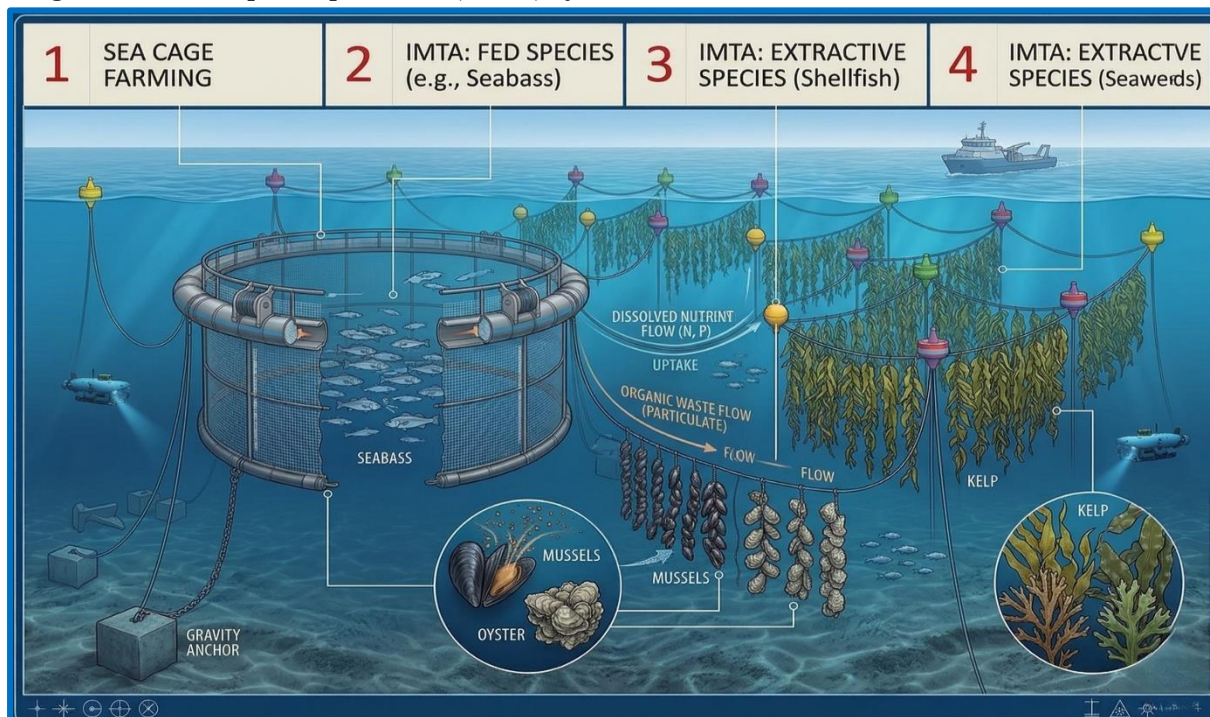
Advantages of Cage Culture

- Cage farming systems are relatively simple to construct and require less complex infrastructure compared to conventional aquaculture methods.
- They offer higher productivity per unit volume, making them more efficient than many land-based systems.
- Fish stock can be easily observed and managed, which simplifies feeding, monitoring, and routine operations.
- Fish grown in cages generally exhibit better quality, appearance, and taste due to natural water conditions.
- Since cage culture utilizes existing water bodies, it is especially beneficial for coastal communities and fishermen who do not own land, providing them with an alternative and stable source of income.
- It creates additional employment opportunities in coastal regions, including activities such as cage installation, feeding, maintenance, and marketing.
- Harvesting is comparatively easier and requires less labour, reducing operational effort and cost.
- The net enclosure acts as a barrier, protecting fish from many natural predators and competitors.

Challenges in Cage Culture

- Fish may develop skin injuries by rubbing against the cage net, which can lead to stress and increase the risk of disease.
- The accumulation of algae, barnacles, and other organisms on cage surfaces can restrict water flow and affect oxygen availability.
- Strong currents, high waves, or extreme weather conditions can damage or deform cage structures.
- Cages may attract predators and other aquatic organisms, including birds, fish, and marine animals, which can disturb the system.
- Risks of theft, poaching, and vandalism remain a concern in open water aquaculture systems.

Integrated Multi-Trophic Aquaculture (IMTA) System



The Integrated Multi-Trophic Aquaculture (IMTA) approach can be effectively linked with sea cage farming by combining different aquatic species within and around cage systems. Like polyculture, IMTA involves cultivating multiple species together, but in a more structured and ecologically balanced manner where the waste generated by one species becomes a resource for another.

In the context of sea cages, fed species such as finfish (for example seabass or cobia) are cultured inside the cages, where they produce organic waste and excess nutrients. Surrounding these cages, extractive species such as shellfish or herbivorous fish utilize organic waste particles, while seaweeds absorb dissolved nutrients like nitrogen and phosphorus. This creates a natural recycling system within the farming environment.

By integrating sea cage culture with IMTA, farmers can improve resource efficiency, reduce environmental impact, and maintain better water quality. This system not only supports ecological balance through bio-mitigation but also provides additional income streams by producing multiple marketable species. As a result, IMTA-based sea cage farming enhances sustainability from environmental, social, and economic perspectives while reducing risks associated with single-species aquaculture.

Government Support and Institutional Framework

The **Pradhan Mantri Matsya Sampada Yojana (PMMSY)** is the Government of India's flagship initiative aimed at accelerating the development of the fisheries and aquaculture sector, including marine cage farming. With a substantial allocation of around ₹2,500 crore in the Union Budget 2026–27, the scheme reflects a strong policy focus on expanding sustainable seafood production and strengthening the blue economy.

PMMSY provides financial assistance for key inputs such as cage installation, seed, feed, and related infrastructure. Beneficiaries can avail subsidies of up to 40%, which are further enhanced to 60% for women, Scheduled Castes, and Scheduled Tribes, ensuring inclusive participation in aquaculture development.

The implementation and technical support framework are strengthened by institutions such as the **National Fisheries Development Board (NFDB)**, State Fisheries Departments, and the **Indian Council of Agricultural Research – Central Marine Fisheries Research Institute (ICAR-CMFRI)**. While NFDB and state agencies facilitate funding, training, and regulatory approvals including Coastal Regulation Zone (CRZ) clearances, ICAR-CMFRI plays a critical role in research, site identification, species selection, and dissemination of cage culture

technologies. It has also developed standardized cage designs and operational guidelines, enabling scientific and efficient adoption of sea cage farming across coastal regions.

Additionally, the **Fisheries and Aquaculture Infrastructure Development Fund (FIDF)** complements PMMSY by supporting the creation of modern fisheries infrastructure, cold chain systems, and capacity-building initiatives.

Role of Financial Institutions

Financial institutions play a crucial enabling role in the expansion of sea cage aquaculture by bridging the financing gap and supporting small and medium fish farmers.

- **Infrastructure Financing:** Provide term loans for setting up sea cages, including purchase of cage structures, nets, mooring systems, and allied equipment.
- **Working Capital Support:** Extend short-term credit for recurring expenses such as seed stocking, feed procurement, labour, and maintenance.
- **Priority Sector Lending:** Classifying fisheries under priority sector lending ensures easier access to credit at affordable interest rates, encouraging adoption of cage culture.
- **Linkage with Government Schemes:** Facilitate credit integration with schemes like the **Pradhan Mantri Matsya Sampada Yojana (PMMSY)**, enabling beneficiaries to avail subsidies along with institutional finance.
- **Promotion of Group-Based Financing:** Support financing through **Self-Help Groups (SHGs)** and **Joint Liability Groups (JLGs)**, which improves credit access for small-scale and marginal fishers.
- **Financial Inclusion and Risk Reduction:** Encourage participation of coastal communities by reducing entry barriers, offering flexible repayment options, and supporting insurance linkages.
- **Support to Blue Economy Growth:** By financing aquaculture activities, institutions like SBI contribute to income generation, employment creation, and sustainable development in coastal regions.

Conclusion

Floating sea cage farming represents a practical solution to the growing seafood crisis. It combines efficient resource use with economic viability, making it suitable for large-scale adoption. With strong institutional support, technological advancements, and financial backing from banks, cage culture has the potential to transform India's fisheries sector. Integrating sustainable practices such as the **Integrated Multi-Trophic Aquaculture (IMTA)** system will further ensure long-term environmental and economic benefits, supporting both food security and coastal development.

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PADDY FIELDS IN THE CLIMATE CRISIS: UNDERSTANDING AND REDUCING METHANE FROM RICE CULTIVATION



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Abstract:

Rice paddies feed over half the world's population, yet they are among the most significant anthropogenic sources of methane (CH₄), a greenhouse gas with a global warming potential 25–28 times that of carbon dioxide over a 100-year horizon. This article synthesises current scientific knowledge on the biogeochemical mechanisms of CH₄ production, transportation, and oxidation in paddy soils; reviews the principal methodologies used to measure emissions at field and landscape scales; and evaluates the most promising mitigation strategies from water management innovations to cultivar selection and novel soil amendments.

Keywords: Methane, paddy fields, methanogenesis, global warming, alternate wetting and drying, biochar, mitigation

1. Introduction

Rice is the staple food crop of more than 3.5 billion people, cultivated on roughly 167 million hectares worldwide. Yet this essential crop carries a hidden climate cost: the waterlogged soils beneath flooded paddies produce enormous quantities of methane. Atmospheric CH₄ has increased nearly threefold since pre-industrial times, reaching 1,853 ppb in 2016 and rising at approximately 6.8 ppb per year (Rahman & Yamamoto, 2020). Rice cultivation accounts for 10–11% of all anthropogenic CH₄ emissions, with irrigated paddies—just 60% of total rice area—producing 78% of emissions from rice-growing regions. Annual emissions from rice fields are estimated at 24–31 Tg of CH₄ (Rajendran *et al.*, 2024). During the production of 1 kg of rice grain, paddy fields release approximately 100 g of CH₄ into the atmosphere (Rahman & Yamamoto, 2020). Southeast Asia contributes roughly 90% of the global rice CH₄ budget. As population and rice demand continue to grow, emissions are set to intensify. Understanding and reducing this footprint has therefore become an urgent scientific and policy priority.

Methane production in paddy soils is a microbial process. When fields are flooded, oxygen is excluded from the soil, triggering anaerobic fermentation of organic matter. Specialised archaea called methanogens thrive only in oxygen-free environments, which convert the breakdown products of this fermentation into CH₄ as a metabolic end product. Two main biochemical pathways are the acetoclastic pathway (contributing ~80% of CH₄), which involves methanogens cleaving acetate produced by fermentation of organic matter—into CH₄ and CO₂. The hydrogenotrophic pathway (10–30%) uses H₂ and CO₂ as substrates. A particularly active group, the Rice Cluster I methanogens, colonises rice roots and taps into photosynthetically derived carbon; research shows that more than 50% of total CH₄ emissions originate from compounds fixed by the rice plant itself (Rahman & Yamamoto, 2020). CH₄ reaches the atmosphere via three pathways. Plant-mediated transport through aerenchyma - hollow gas channels that rice develops to supply roots with oxygen (accounts for approximately 90% of total emissions). CH₄ dissolves into soil water near roots, diffuses into these internal channels, and is vented from leaf nodes and stem bases. Bubble ebullition (rapid escape of gas bubbles when dissolved CH₄ exceeds saturation) contributes around 10%, while slow molecular diffusion through the water column adds a further ~1%. Methane's global

warming potential is 25–28 times that of CO₂ over 100 years. Paddy rice cultivation is responsible for more than 20 % of global agricultural CH₄ emissions, which in turn account for approximately 20 % of the total global warming effect of greenhouse gases.

2. Factors affecting CH₄ production

- **Temperature:** Optimal CH₄ production occurs at around 40–45°C. Rising global temperatures drives more methane, which drives more warming (Rajendran *et al.*, 2024).
- **Soil pH and redox:** Methanogens are sensitive to acidity; optimal activity occurs near pH 7.0. Waterlogged, oxygen-depleted (low redox) conditions strongly promote methanogenesis.
- **Organic matter inputs:** Rice straw incorporation, organic fertilizers and root exudates all supply readily fermentable carbon, amplifying CH₄ production. Emissions peak at the reproductive and maturity stages when root exudate supply is highest.
- **Water management:** Continuous flooding is the master driver. The default emission factor under continuous flooding is 1.3 kg CH₄ ha⁻¹ day⁻¹ (IPCC, 2006). Introducing any period of soil aeration dramatically curtails methanogenesis.

3. Measuring Methane Emissions

3.1. Closed Chamber Method

The most widely used field technique involves placing a sealed transparent chamber (typically 50 × 50 × 100 cm) over the crop canopy. Gas samples are drawn by syringe at 0, 5, 10, 20 and 30 minutes after closure, then analysed in the laboratory by gas chromatography. Sampling between 07:00 and 10:00 hours (when temperatures match the daily mean) gives the best estimate of the daily average flux. The method is low-cost and sensitive but covers only a small area.

3.2 Eddy Covariance Method

For landscape-scale measurement, the eddy covariance technique correlates high-frequency vertical wind speed data (from a sonic anemometer) with real-time CH₄ concentrations (from an open-path LI-7700 analyser) at 10 Hz. Processing over 30-minute intervals yields integrated fluxes across hundreds of metres of paddy, capturing spatial variability invisible to chambers. The approach is expensive and technically demanding but provides the most realistic picture of ecosystem-level emissions (Rahman & Yamamoto, 2020).

4. Mitigation Strategies

4.1. Water Management

Since flooding creates the anaerobic conditions that drive methanogenesis, managing water is the most powerful tool available. Three approaches stand out:

- **Alternate Wetting and Drying (AWD):** Fields are deliberately cycled between flooding and controlled drying throughout the season. A global meta-analysis shows AWD reduces the combined global warming potential of CH₄ and N₂O by approximately 46.9% compared with continuous flooding. AWD technique remarkably reduced CH₄ emission by 57.4 % compared to puddled transplanted rice (Sandeep *et al.*, 2025). It also improves water use efficiency and improves grain yields.
- **Mid-season drainage:** A single drainage event during tillering can cut seasonal CH₄ by approximately 50%. Combined with pre-harvest drainage, emissions reductions are compounded further.
- **System of Rice Intensification (SRI):** Combining intermittent irrigation with young seedling transplanting at wider spacings reduces CH₄ by up to 32% while saving 28–40% of irrigation water across trials in India, Japan, Iraq and Indonesia (Rahman & Yamamoto, 2020).

6.2 Biochar and Soil Amendments

Biochar reduces CH₄ emissions by suppressing methanogen activity and stimulating methanotrophic oxidation. Rice-straw biochar amendment has reduced seasonal CH₄ emissions by 39.5% under both ambient and elevated temperature CO₂ conditions. When biochar is combined with mild AWD, the effects are synergistic: field trials in 2023–2024 recorded 9–10% yield gains over continuous flooding while achieving significant emission reductions (Li *et al.*, 2024). Biochar also improves soil water retention, a practical advantage under AWD in water-scarce regions.

6.3 Cultivar Selection

Rice varieties differ substantially in their emission profiles, driven by differences in root architecture, exudate chemistry and aerenchyma structure. Deeper, more oxidising root systems suppress rhizospheric methanogenesis. Short-duration varieties ranked as the top mitigation strategy in an Egyptian multi-criteria assessment, reducing CH₄ by 25% and water use by 20% without yield loss (Hasan, 2013). Molecular breeding programmes now target low-emission traits directly, with heat-tolerant varieties offering an additional co-benefit as temperatures rise (Rajendran *et al.*, 2024).

6.4 Fertiliser and Residue Management

Composted rather than fresh organic fertilizers produce substantially lower CH₄ because composting depletes the rapidly fermentable carbon fractions that fuel methanogenesis. Controlled-release nitrogen fertilisers under AWD reduce both CH₄ and N₂O emissions while improving nitrogen use efficiency. Avoiding the open burning of rice straw eliminates a significant secondary source of CH₄ and other greenhouse gases.

Conclusion

Paddy rice feeds billions, yet the anaerobic conditions essential to its cultivation silently pump methane into an already warming atmosphere. The mechanisms are well understood: methanogenic archaea, activated by flooding and organic matter, produce CH₄ that travels to the atmosphere primarily through the rice plant itself. The good news is that a toolkit of proven, complementary interventions such as AWD, biochar, improved cultivars and smarter fertilization can reduce emissions by 30–50% without jeopardising food security. The challenge now is scaling these solutions across the hundreds of millions of smallholder farms that collectively shape the global methane budget, supported by carbon markets, policy incentives and continued investment in breeding and agronomic innovation.

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DIGITAL MARKETING IN AGRICULTURE



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INTRODUCTION

India is often described as a country of villages, and the progress of these rural communities plays a crucial role in the nation's overall development. Recognizing this, the government has introduced several initiatives to strengthen rural livelihoods and improve market access. Among these, the promotion of digital marketing stands out as a transformative step, enabling farmers and rural entrepreneurs to sell their products directly through online platforms without relying on traditional intermediaries. This shift not only enhances transparency and profitability but also empowers rural producers to reach wider consumer bases. According to a Global Data report, the digital marketing sector recorded an impressive growth rate of 30% in 2023, reflecting its expanding role in shaping modern markets. As rural India steadily embraces digital tools, digital marketing continues to emerge as a powerful driver of inclusive and sustainable rural development.

The launch of the Digital India movement on 1st July 2015 marked a turning point in the nation's journey toward building a digitally empowered society and knowledge-driven economy. This initiative played a significant role in extending digital infrastructure and services to rural areas, thereby opening new avenues for economic participation. Following the movement, many industries began shifting toward digital platforms to market and sell their products, taking advantage of improved connectivity and consumer reach. In the agricultural sector, this transformation has been particularly impactful, encouraging young agriculturalists to adopt digital marketing tools to promote their produce globally. By leveraging online marketplaces, social media, and digital communication channels, young farmers are not only expanding their market access but are also contributing to the modernization and competitiveness of rural agriculture.

The global agricultural landscape is undergoing a rapid, technology-driven transformation, moving beyond traditional farm-to-market channels into the dynamic world of digital marketing. For today's farmers and agribusinesses, success is increasingly tied not just to the yield of their crops, but to their online reach. This digital revolution, as highlighted by various industry reports, hinges on several key factors: adopting accessible platforms like social media and e-commerce to bypass intermediaries and connect directly with consumers; leveraging data and analytics for smarter marketing and pricing strategies; and, crucially, mastering the art of digital storytelling to build trust and brand identity around their produce. By embracing these tools, from mobile-based communication to targeted online advertising, agri-entrepreneurs can significantly increase their profitability, gain real-time market insights, and ensure their high-quality products reach a wider, more appreciative audience, truly cultivating a successful digital harvest.

DIGITAL MARKETING- DEFINITION

Digital marketing is the practice of using digital channels to market products and services to reach consumers.

Key Digital Channels

The core channels involved in digital marketing include:

- **Websites:** The foundational online presence for information, transactions, and branding.
- **Mobile devices:** Using apps, SMS, and mobile-optimized websites to reach users on the go.
- **Social media:** Platforms like Facebook, Instagram, and X (Twitter) for engagement, brand building, and targeted advertising.
- **Search engines:** Optimizing content (SEO) and running ads (SEM) to be found when consumers search for relevant products or information.
- **Other similar channels:** This includes email marketing, digital display advertising, and video platforms.



SOCIAL MEDIA MARKETING

Digital marketing is defined as the use of digital channels-such as websites, mobile devices, social media, and search engines-to market products and services and reach target consumers. This strategy is rapidly transforming the agricultural sector, where a 2018 FAO report identified three critical factors fueling its growth: first, the widespread increase in the use of internet, mobile devices, and social networks among farmers and extension officers; second, the essential need to develop digital skills within the rural population; and third, the necessity of fostering a culture that encourages digital agripreneurship and innovation. The use of social media marketing (also known as e-marketing) is a key component, allowing companies to leverage platforms where users build social networks and share information to quickly build brand awareness, increase sales, and drive website traffic. Together, these elements are empowering farmers to connect directly with consumers and thrive in the modern digital economy.

CONTENT MARKETING

Content marketing is a strategic approach focused on creating and distributing valuable, relevant, and consistent content to attract and retain a clearly defined audience-and, ultimately, to drive profitable customer action.

This strategy utilizes various formats to engage current and prospective customers at every stage of their journey. Key examples of this distributed content include:

- **Blog posts** (for in-depth articles and helpful tips)
- **Emails and Newsletters** (for direct communication and regular updates)
- **Social media posts** (for bite-sized, frequent engagement)
- **Videos** (for demonstrations, storytelling, and visual learning)
- **Podcasts** (for convenient, audio-based consumption)
- **E-books and White Papers** (for comprehensive, lead-generating resources)

EMAIL MARKETING

Email marketing is a type of direct digital marketing method that uses emails to engage with a business's audiences. It involves sending promotional or informational content. Email marketing is typically used to create product or brand awareness and generate leads or sales.

PAY PER CLICK ADVERTISING

Pay-per-click (PPC) is a form of internet marketing where advertisers pay a fee each time one of their ads is clicked. Simply put, you only pay for advertising if your ad is actually clicked on by a user. It is essentially a method of "buying" visits to your site, which complements the process of driving website visits organically through search engine optimization or content creation.

SEARCH ENGINE OPTIMIZATION

SEO marketing is a subset of digital marketing that involves the optimization of websites and web pages for major search engines, such as Google. As these search engines became the predominant way for users to find virtually

anything online, various practices have emerged to help organizations improve the visibility of their digital assets in search results.

MOBILE MARKETING

Mobile marketing is defined as the set of practices that enable organizations to communicate and engage with their audience in an interactive and relevant manner through any mobile device or network. More specifically, it encompasses any advertising activity that promotes products and services via mobile devices, such as tablets and smartphones. A key component of modern mobile marketing is its ability to utilize features of mobile technology, including location services, to tailor campaigns based on an individual's geographical position.

NEED FOR DIGITAL MARKETING IN AGRICULTURE

The number of internet users in India is expected to grow over 900 million by 2025, demonstrating a tremendous increase in the population of internet users. This increased adoption of digital platforms offers a great opportunity, particularly for farmers, to connect directly with their customers. This is especially important for smallholder farmers who sell their goods directly. By removing the middleman's commission, digital platforms can help farmers increase their profits and display a wide range of fresh produce to direct buyers, such as consumers, restaurants, and chefs. Furthermore, digital marketing offers a crucial chance to receive feedback from buyers and discover what the target audience genuinely requires. Recognizing the need and importance of digitalization and digital marketing in the agricultural sector, the Government of India has introduced innovative initiatives like Digital India and the online portal, e-NAM, specifically for the trade of agricultural produce.

IMPORTANCE OF DIGITAL MARKETING IN AGRICULTURE

Digital marketing offers significant advantages for farmers by enabling direct communication with consumers. This direct relationship helps farmers increase their profits by removing middlemen, allowing them to retain a greater share of the sale price. Furthermore, digital platforms offer a valuable opportunity to receive direct feedback from buyers, which in turn helps farmers discover more about what the target audience genuinely requires in terms of produce quality, quantity, and variety.

DIGITAL MARKETING IN INDIAN AGRICULTURE: DIFFERENT ONLINE PORTALS

Electronic-National Agricultural Market (e-NAM)

It is Launched on 14 April, 2016 by Ministry of Agriculture, Govt. of India. It is a pan-India electronic trading portal which networks the existing APMC mandis to create a unified national market for agricultural commodities. It is Managed by SFAC.

Services:

1. Transparent online bidding and trading.
2. Real time price discovery.
3. Better price realization of products.

Rashtriya electronic Market Services (ReMS)

The Unified Market Platform (UMP) was established in 2014 as a joint venture created by the Government of Karnataka and the NCDEX (National Commodity & Derivatives Exchange Limited). This platform successfully unifies 162 main and 354 sub-APMCs (Agricultural Produce Market Committees) and covers a total of 92 commodities. The UMP is a specialized electronic trading platform that offers a range of services, including online bidding and auction facilities, the dissemination of real-time market information through SMS, online payments, and an efficient price discovery mechanism.

AgMarknet: Connecting Farmers to the Market

The AgMarknet (Agricultural Marketing Information Network) is a crucial project for connecting farmers directly to the market, launched in March 2000 by the Ministry of Agriculture, Government of India. This extensive project has covered 3,413 markets across the country. The core of the service is a portal that provides farmers with easy access to daily price and arrival information, broken down by commodity and variety, covering more than 2,000 varieties and about 300 commodities. The price information is effectively disseminated through information linkages provided to the Farmer's portal, m kisan portal, and others. The network covers a wide spectrum of information essential for farmers, including:

- **Market-related information**

- **Price-related information**
- **Infrastructure-related information**
- **Market requirement-related information**

Digital Marketing in Indian Agriculture

Digital marketing is crucial for the future of Indian agriculture, particularly as the number of internet users in India is projected to exceed 900 million by 2025. This digital leap provides a massive opportunity for farmers to connect directly with customers, including consumers, restaurants, and chefs. By removing the middleman's commission, this direct selling helps smallholder farmers increase their profits and provides a platform to receive immediate feedback from buyers, helping them align their produce with market demand. The Government of India has supported this transition with innovative initiatives like Digital India and the agricultural trading portal, e-NAM.

E-CHOUPAL

e-Choupal was launched in June 2000 by ITC Limited and is a powerful initiative that directly links rural farmers via the Internet for the procurement of agricultural and aquaculture products like soybean, wheat, coffee, shrimp, and prawns. The platform offers farmers up-to-date marketing and agricultural information, and allows them to directly negotiate the sale of their products with ITC Limited. Currently, there are 6,100 e-Choupals in operation across 35,000 villages in 10 states, covering 4 million farmers in Andhra Pradesh, Haryana, Madhya Pradesh, Uttarakhand, Uttar Pradesh, Rajasthan, Karnataka, Kerala, Maharashtra, and Tamil Nadu.

TOOLS USED FOR DIGITAL MARKETING

1. Social Media for Marketing

The landscape of social media is diverse, with each platform offering unique opportunities for businesses to engage with their audience and industry partners.

- **Twitter** is a fast-paced platform best suited for sharing state-of-the-art developments and tackling contemporary events, allowing businesses to stay relevant and current.
- **Instagram**, with over 1 billion monthly active users, is a highly visual platform that provides an excellent opportunity to showcase a business's personality and product aesthetics.
- **LinkedIn** is the primary social networking platform for professionals, making it the top choice for B2B social media marketing. Businesses use it to update customers, connect with industry partners, and recruit new team members.
- **Pinterest** is another visual platform that allows a business to visually showcase product offerings, before-and-after images, and curated pin-boards, which is effective for driving traffic and product discovery.

2. Managing Social Media Updates

- **Hootsuite** is a comprehensive social media management platform that allows users to manage multiple social media channels and delegate tasks, making it ideal for team collaboration.
- **Buffer** is a focused content publishing platform used to help businesses efficiently publish and schedule content across various social networks.

3. Reviewing Brand Mentions and Industry Developments

- **Google Alerts** is a free notification service that summarizes search activity around specified terms and emails the reports to subscribers.
- **Talk walker** is a robust listening and analytics tool that delivers social insights to help brands build growth, measure their impact, and gain key consumer insights.
- **Feedly** is a robust feed reader that aggregates information from around the web (news, blogs, RSS feeds, etc.) into one convenient place for easy updates on any topic.

4. Understanding Customer Search Behavior

- **Google Trends** is a free data exploration tool that helps businesses learn what their users are interested in in real time, showing how interest in a topic changes and when it peaks annually.

- **Uber suggest** is a free Chrome extension and a powerful SEO tool that provides insightful data on keywords, including monthly search volume, CPC, and competition data, not just for Google but also for platforms like YouTube and Amazon.

5. Understanding Overall Online Marketing Effectiveness

- **Google Analytics** offers free tools to analyze business data in one place, enabling users to rapidly process large amounts of data, shareable reports, and empower collaboration with an easy-to-use interface. It also provides secure, accurate data across sites and apps with built-in technical support.

BENEFITS OF DIGITAL MARKETING CHANNELS FOR AGRIBUSINESS

Digital Marketing allow to explore new markets and reach a global marketplace. It requires less money than traditional marketing methods. It enables to track and measure the marketing efforts. It helps to build a relationship with the customers which in turn helps in building customer loyalty. It allows to personalize the website with offers and coupons with the help of the customer database. It Provides access to modern farming methods and techniques. Digital marketing technologies allow the Consumers to stay updated with products or services. With digital marketing, consumers can engage with the company's various activities. Customers can visit company's site, examine data approximately of the items or administrations, and make buys online and give feedback. Through digital marketing, consumers get clear information about the products or services. Available online for product information, customer can carefully take informed decision. Through digital Marketing most of the companies are promoting their products, hence, it is becoming the greatest advantage for the customer in terms that they can make comparison among products or services by different suppliers in cost and time friendly way.

CONCLUSION

Digital Marketing has changed the way to connect with people, communicating the idea behind the product and services, explaining the value and usages of the product and services, it is a matter of one second to explore the offering with people but for that one can have a great plan and strategy to get success in that. With the increasing literacy in rural areas and growth in the agricultural infrastructure, it is observed that the agribusiness sector is gradually moving to the digital platform as well. The agripreneurs and Agri startups are seen effectively using the Digital Marketing to reach the desired customers. In the process, they are better able to convey the company values to their customers and other stakeholders. Various free/paid tools and techniques are making it further convenient for them. In a time to come, one can get great results linking digital marketing with agriculture. Even Central and State Governments are using the Digital marketing to reach to farmers, agripreneurs and other departments to effectively share the information on schemes, projects, beneficiaries etc.

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GREEN MANURING – A SUSTAINABLE WAY TO ENHANCE SOIL FERTILITY



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Introduction

Soil may be a fundamental component of life on Earth and acts as a storehouse of nutrients that give humans the majority of their food and nourishment. Two significant factors contributing to soil nitrogen loss are erosion and denitrification. Thus, crop quality and soil quality are negatively impacted by nutrient loss and productivity as well. Our nation's soil fertility is declining daily as a result of overuse of fertilizers to maintain high food production for food security. In situ green manuring has significant potential for weed reduction in addition to being an efficient way to supply organic manures

Types of Green Manuring

There are two different types of green manuring. They are

1. Green Manuring *In Situ*

This approach involves growing short-duration (~45 to 60 days) green manure crops and incorporating them into the soil at the same location, either as an intercrop with the primary crop or as a pure crop. Later on, the green manure is planted in between the rows and is very well suited to circumstances requiring the most intense usage of the soil.



2. Green Leaf Manuring

Green leaf manuring is the process of turning into the soil green leaves and tender green twigs collected from shrubs and trees grown on bunds, wastelands, and adjacent forest areas. Depending on the tenderness of the foliage or plant parts. *Gliricidia maculata*, *Pongamia pinnata*, *Sesbania speciosa*, *Leucaena leucocephala*, *Azadirachta indica*, *Delonix regia* and *Peltophorum pterocarpum* are used for green manuring.

Green Leaf Manure Crops



Peltophorum ferrugenum

Azadiracta indica

Effect of green manuring on crop production:

Green manuring's beneficial effects on agricultural production have been recognized since antiquity. The necessity for sustainable agricultural systems, the high expense of chemical fertilizers and the rising risk of environmental pollution have all contributed to the growing importance of this soil-improving technique in recent years. Crop yields can be increased by using green manuring to enhance the physical, chemical and biological characteristics of the soil. Additionally, lower fertilizer N requirements for subsequent crops and a decreased danger of nitrate (NO_3^-) leaching are potential advantages of green manuring. Its impact, however, may differ depending on the soil, crop, environmental factors, type of green manure crop utilized and how it is managed. The benefits of green manuring in agricultural productivity should be assessed in conjunction with chemical fertilizers rather than separately.

Effect of green manuring on soil:

Green manuring is an arable farming technique that involves adding undecomposed green material to the soil (either in situ or harvested elsewhere) to boost crop output. When the crop is ready to flower, which is typically 7–8 weeks after sowing, green manure should be added to the soil. Continuous application of green manures increases the soil's organic matter content and adds to its nutrient pool, improving its physical, chemical and biological qualities. It gives the soil microbes nutrient-rich organic matter, which readily transforms organically bonded nutrients in plant wastes into a form that the crop can easily access.



Incorporation of Green Manures in Soil

Need for Green manuring:

The current trend of declining crop production or stagnating crop yields in India is a result of the cumulative effects of abundant soil and its accompanying constraints. Documents of low crop yields include acceptance of inappropriate methods of soil management, widespread use of crop residues, non-judicious adoption of agronomic practices and asymmetric nutrient management. Additionally, depletion of soil organics amount with accretion agricultural practices are the above causes of low crop yield per unit area of land. The documentation of low crop yields is the adoption of improper soil management techniques, generally crop residues, uneven nutrient management, and careless use of agronomic technique. Crop production per unit area of land can also be reduced by poor management, inadequate usage of organic and biofertilizer, and depletion of soil organic matter. Low crop productivity and soil abundance depletion are caused by inappropriate farming practices and the depletion of soil organics, which may be considered a significant issue.

Conclusion:

Green manuring can play a crucial role because it has the ability to improve the physical and biological superiority of the soil and appropriately enhance soil fertility. It also fixes atmospheric nitrogen in the soil if legumes are taken into consideration. Finally, it is benign in managing weeds, diseases, and insect pests. The deterioration of land caused by humans is truly terrible because of the numerous accidents of soil fertility caused by tainted agronomic methods. Green manures can have a significant impact on the soil's physical, actinic, and biological qualities as well as its fertility. In addition to improving soil quality on its own, green manuring fixes atmospheric nitrogen in the soil when legumes are taken into account. By adding green foliage to the soil, botheration soils can also be improved.

Pig Farming – High Profits with Low Investment



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Pig farming is emerging as one of the most profitable livestock enterprises that can generate high income with relatively low investment and within a short period. In recent years, unemployed youth, particularly in tribal and peri-urban areas, have been showing increasing interest in commercial pig farming.

Pigs are fast-growing animals with high reproductive efficiency and excellent feed conversion ability. They can efficiently utilize a wide range of feed materials, making them an economically attractive option for farmers. There is a growing demand for pork not only within India but also in international markets. Hotels, meat processing industries, and urban consumers are contributing to the increasing market demand for pork products. With proper scientific management practices, pig farming can become a highly profitable enterprise.

Selection of Suitable Breeds– The stepping stone to Profitability

Choosing the right breed is one of the most important factors for successful pig farming. Along with indigenous pigs, several exotic breeds like Large White Yorkshire, Landrace, Duroc, Hampshire pigs known for better growth and meat production are widely preferred.

While purchasing piglets, farmers should ensure that the animals:

- Are healthy and active
- Have bright eyes
- Free from skin wounds, disease signs or lesions and lameness
- Show good appetite and alertness

Housing Management– The foundation to Profitability

Pigs require clean, well-ventilated housing with proper drainage facilities.

The pig shed should:

- Be constructed on elevated land to avoid water stagnation
- Have cement flooring for easy cleaning
- Contain proper slope for removal of urine and waste
- Remain cool during summer and warm during winter
- Provide continuous access to rooting, foraging and clean drinking water

Pigs naturally prefer wallowing in mud to regulate body temperature. Therefore, during summer, sprinkling water or providing cooling arrangements like fans, foggers and sprinklers helps reduce heat stress.

Nutritional Management – The Key to Profitability

Feed accounts for nearly 70 percent of the total production cost in pig farming. Therefore, efficient feeding and balanced nutrition play a major role in determining profitability. Pigs are popularly known as “waste-to-wealth converters” because they can efficiently convert many low-cost agricultural and food wastes into valuable meat. Their excellent feed conversion efficiency enables them to gain body weight rapidly with comparatively less feed when compared to many other livestock species. One of the major advantages of pig farming is the ability of pigs to utilize a wide variety of feed resources such as hotel and hostel kitchen waste, household food leftovers, vegetable market waste, crop residues and agro-industrial by-products. This makes pig farming especially suitable near urban and peri-urban areas where such feed materials are readily available at low cost.

However, spoiled feed, rotten meat products, decaying waste, garbage contaminated with plastic, glass, metal objects, toxic chemicals, detergents, excessive oil and non-edible materials should never be fed to pigs, as

it can lead to serious health problems and reduced growth performance. To improve food safety, collected food waste fresh, screen and segregate the leftovers then heat-treat before feeding.

Apart from kitchen leftovers and vegetable waste, scientifically prepared concentrate feed is highly useful for achieving faster growth, better feed efficiency, improved reproduction, and higher profitability in pig farming. Concentrate feed is usually prepared using ingredients such as maize, wheat bran, rice bran, soybean meal, groundnut cake, mineral mixture, salt, and vitamin supplements. According to the age and physiological stage of pigs require 50–250 g Creep feed per suckling piglet per day; 0.5–1.0 kg/day Starter feed for weaned piglets; 1.5–2.0 kg/day Grower feed for growing pigs; 2.0–3.0 kg/day Finisher feed for pigs nearing market weight; 2.0–2.5 kg/day Gestation feed for pregnant sows; 3.0–5.0 kg/day Lactation feed for nursing sows depending on litter size and milk production; 2.0–2.5 kg/day Boar ration for breeding males. Providing balanced concentrate feed according to the age and physiological stage of pigs helps improve growth rate, reproductive performance, disease resistance, and overall productivity. It also enables pigs to attain market weight at an earlier age, thereby increasing economic returns to farmers.

Reproductive Management– The essence for Profitability

Female pigs generally attain puberty at 8–10 months of age. The gestation period in pigs is approximately 114 days. With proper breeding management a sow can produce 8–12 piglets per litter and two litters per year are possible.

Before farrowing, a clean and hygienic farrowing pen should be prepared. Newborn piglets must receive colostrum immediately after birth for better immunity and survival. Newborn piglets are highly delicate and require special attention. Important Piglet management practices include: Protecting piglets from cold stress, administering iron injections, teeth clipping and tail docking when necessary. These procedures should be carried out at the appropriate time under proper veterinary supervision.

Disease Prevention and Health Care

Diseases can spread rapidly in pig farms; therefore, hygiene and biosecurity are extremely important. Regular deworming with different drugs, timely vaccination and preventive measures should be followed against diseases such as Classical Swine Fever, Foot and Mouth Disease and Parasitic diseases. The sheds should be cleaned regularly, and newly purchased pigs should be kept separately for a quarantine period before mixing with the existing stock.

Marketing Opportunities

Pigs weighing around 70–100 kg at 6–8 months of age fetch good market prices. Major marketing channels include: Hotels, Meat processing units and Local meat markets. In addition to pork, pig farming also generates additional income through sale of pig fat and pig manure.

Conclusion

Due to low investment requirements, rapid growth, and high reproductive efficiency, pig farming is becoming an attractive livelihood option for farmers and rural youth. By adopting scientific management practices such as proper breed selection, balanced feeding, hygienic housing, and timely health care, farmers can achieve excellent profits and long-term success in pig farming.

Cordyceps militaris - Biology, Production Technology, and Its Potential Medicinal Value for Modern Healthcare



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ABSTRACT

Cordyceps, a genus of entomopathogenic fungi, has long been valued in traditional medicine for its diverse therapeutic properties and bioactive compounds. Among its species, *Cordyceps sinensis* and *Cordyceps militaris* are widely recognized for their medicinal significance due to the presence of compounds such as cordycepin, polysaccharides, ergosterol, and mannitol, which exhibit antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory activities. Historically discovered in the Himalayan regions, *Cordyceps* gained prominence because of its unique parasitic life cycle involving insect hosts and its reputed ability to promote health and vitality. Medicinal mushrooms, including *Cordyceps*, Lion's Mane, Reishi, Turkey Tail, Shiitake, and Chaga, are also rich sources of proteins, carbohydrates, dietary fiber, vitamins, and essential minerals, contributing to their nutritional and pharmacological importance. Recent advances in cultivation technologies have enabled large-scale production of *C. militaris* using artificial substrates and controlled environmental conditions, thereby reducing reliance on wild resources. Optimal cultivation parameters, including temperature, humidity, light, and nutrient availability, play a critical role in enhancing stroma development and bioactive compound production. Owing to its therapeutic potential and expanding commercial applications, *Cordyceps* has emerged as an important component in functional foods, nutraceuticals, and pharmaceutical products, highlighting its growing significance in modern healthcare and biotechnology.

Key words: *Cordyceps militaris*, cordycepin, cultivation technology, entomopathogenic fungi, medicinal mushrooms

INTRODUCTION

Cordyceps is a genus of entomopathogenic fungi that parasitizes insects and has been known since around 2000 B.C. It is regarded as one of the most important traditional Chinese medicinal fungi. Among the species, *Cordyceps militaris* has gained considerable attention because of its medicinal properties and rich content of bioactive compounds such as cordycepin, polysaccharides, ergosterol, and mannitol. These compounds exhibit various physiological and pharmacological activities, leading to the extensive use of *Cordyceps* in traditional and modern medicine (Holliday *et al.*, 2005).

Mushrooms are widely recognized for their nutritional and therapeutic importance, with more than 2,500 species cultivated worldwide. The medicinal fungus popularly known as “Dong Chong Xia Cao,” belonging to the genus *Cordyceps*, has been highly valued for health promotion and the treatment of several ailments. Consumption of medicinal mushrooms is believed to provide health benefits due to their antioxidant, antimicrobial, anti-inflammatory, and immunomodulatory properties (Zhou *et al.*, 2009). Consequently, *Cordyceps* has emerged as an important component in functional foods, dietary supplements, and pharmaceutical industries.

HISTORY OF MEDICINAL MUSHROOMS

Medicinal fungi have been closely associated with human culture and civilization for centuries, and species of the genus *Cordyceps* are especially valued for their therapeutic significance. Most species of *Cordyceps* are parasitic on insects and other arthropods and are naturally distributed in the Himalayan and Tibetan regions. The discovery of *Cordyceps* is linked to Nepalese and Tibetan herders who observed unusual behavior in yaks and goats grazing in high mountain pastures during spring. After consuming this unusual fungus, the animals became more energetic and active, which led to the recognition of its medicinal and vitality-enhancing properties (Das, A., & Chatterjee, S., 2018).

The fungus was first scientifically described in 1843 by the British mycologist Berkeley as *Sphaeria sinensis* Berk. Later, in 1878, Saccardo renamed it as *Cordyceps sinensis*. The scientific name *Cordyceps sinensis* (Berk.) Sacc. refers to the fruiting body of the fungus that emerges from the dead body of a caterpillar. Among the various species, *Cordyceps sinensis* has traditionally been regarded as the most valuable for medicinal purposes. Since then, extensive research has been conducted to determine its chemical composition, therapeutic properties, toxicity, and other biological activities.

VARIOUS TYPES OF MEDICINAL MUSHROOMS

Medicinal mushrooms are nutrient-dense fungi that contain a wide range of bioactive compounds such as polysaccharides, β -glucans, triterpenes, phenolic compounds, vitamins, and minerals. These compounds contribute to several health benefits, including enhancement of immunity, improvement of cognitive function, antioxidant activity, anti-inflammatory effects, and protection against various diseases (Das, S. K., & Masuda, M., 2010). Due to their therapeutic potential, medicinal mushrooms are widely utilized in traditional medicine, functional foods, nutraceuticals, and pharmaceutical products. Some of the important medicinal mushrooms are described below:

1. Cordyceps (*Cordyceps sinensis*)

Cordyceps sinensis is a well-known entomopathogenic medicinal fungus traditionally used in Chinese and Tibetan medicine. It contains important bioactive compounds such as cordycepin, polysaccharides, ergosterol, and mannitol (Paterson, R. R. M., 2008). *Cordyceps* is valued for its immunomodulatory, antioxidant, anti-inflammatory, and energy-enhancing properties. It is commonly used to improve stamina, respiratory health, kidney function, and overall vitality.

2. Lion's Mane (*Hericium erinaceus*)

Hericium erinaceus, commonly known as Lion's Mane mushroom, is recognized for its neuroprotective and cognitive-enhancing properties. It contains compounds such as hericenones and erinacines that stimulate nerve growth factor (NGF) synthesis. Lion's Mane is widely used to support brain health, improve memory and concentration, and reduce symptoms of anxiety and depression.

3. Reishi (*Ganoderma lucidum*)

Ganoderma lucidum, commonly called Reishi or the "Mushroom of Immortality," has been used in traditional medicine for centuries. It is rich in triterpenoids, polysaccharides, and peptidoglycans. Reishi exhibits immunomodulatory, anticancer, hepatoprotective, and anti-inflammatory activities. It is also known to reduce stress, improve sleep quality, and support cardiovascular health (Yue *et al.*, 2013).

4. Turkey Tail (*Trametes versicolor*)

Trametes versicolor, commonly known as Turkey Tail mushroom, is notable for its colorful fan-shaped appearance. It contains biologically active compounds such as polysaccharopeptides (PSP) and polysaccharide-K (PSK), which are known for their immune-boosting and anticancer properties. Turkey Tail is widely studied for its role in supporting cancer therapy and maintaining gut health.

5. Shiitake (*Lentinula edodes*)

Lentinula edodes, commonly referred to as Shiitake mushroom, is both a popular edible and medicinal mushroom. It is rich in lentinan, vitamins, minerals, and dietary fiber. Shiitake possesses antimicrobial, cholesterol-lowering, immune-enhancing, and antioxidant properties. Regular consumption is associated with improved cardiovascular health and enhanced immune response.

6. Chaga (*Inonotus obliquus*)

Inonotus obliquus, commonly known as Chaga mushroom, grows mainly on birch trees in cold climates. It is rich in antioxidants, melanins, and polysaccharides. Chaga is valued for its anti-inflammatory, antioxidant, antiviral, and immune-supporting properties. It is traditionally used to enhance overall health and protect against oxidative stress-related diseases.

PRODUCTION TECHNOLOGY OF *Cordyceps militaris*

The cultivation of medicinal mushrooms ranges from primitive farming practices to highly advanced industrial production systems. Since many medicinal mushrooms are scarce in nature, artificial cultivation techniques have been developed to ensure sustainable production. Traditionally, fruiting bodies were cultivated on wooden logs,

a practice that has been followed for centuries. Over time, cultivation methods have been improved, diversified, and modified to increase yield and quality.

At present, medicinal mushrooms are cultivated on a variety of lignocellulosic substrates using trays, beds, bags, bottles, and substrate blocks. Species such as *Pleurotus* spp. and *Agrocybe aegerita* are commonly grown on prepared substrates, while some fungi such as *Anthrodia cinnamomea* are cultivated on large wood pieces. Certain medicinal mushrooms, including Chaga (*Inonotus obliquus*), may also develop naturally on living tree trunks. In addition to fruiting body production, fungal mycelia can be mass-produced using submerged liquid fermentation and solid-state fermentation techniques in bioreactors. Successful cultivation requires a combination of practical expertise and scientific knowledge regarding nutrition, environmental conditions, and contamination management.

NUTRITIONAL REQUIREMENTS FOR STROMA PRODUCTION

INSECT-BASED SUBSTRATES

Artificial cultivation and stroma production of *Cordyceps militaris* have been extensively studied using different insect larvae and pupae. The silkworm, *Bombyx mori*, is the most commonly used host because it supports effective infection and stroma development. Studies have shown that silkworm pupae produce better stroma formation than larvae. Among different silkworm varieties, the Daeseungjam variety has been identified as highly suitable for *C. militaris* cultivation (Li *et al.*, 2006).

Apart from silkworms, other insects used for artificial stroma production include *Antheraea pernyi*, *Mamestra brassicae*, *Tenebrio molitor*, *Ostrinia nubilalis*, *Heliothis virescens*, *Spodoptera frugiperda*, *Andraca bipunctata*, *Philosamia cynthia*, *Spodoptera litura*, and *Clanis bilineata*. Although insect substrates provide favorable nutrition, they are expensive, difficult to handle, and highly prone to microbial contamination.

NATURAL ORGANIC SUBSTRATES

Due to the limitations associated with insect substrates, alternative organic materials have been explored for commercial cultivation. Cereals supplemented with organic nutrients have proven to be effective substitutes. Rice is the most commonly used substrate for the cultivation of *C. militaris* stromata and has been widely adopted since it was first reported for stroma production in 1941. Other substrates such as maize, millet, and mixed cereal media are also utilized for commercial production. Rice-based substrates are preferred because they are economical, easily available, and capable of supporting good stroma formation and bioactive compound production (Wang *et al.*, 2012).

HORMONES AND MINERAL COMPONENTS OF MEDIA

Plant growth regulators and mineral nutrients play an important role in enhancing stroma production. Chemicals such as 2,4-D, citric acid triamine, and colchicine have been reported to stimulate stroma development in *C. militaris*. Similarly, mineral salts containing potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) at low concentrations improve fruiting body yield. Certain trace elements may also enhance the synthesis of bioactive compounds such as cordycepin and polysaccharides. Production technology of *Cordyceps militaris* is clearly illustrated in Fig. 1.

DURATION OF STROMA PRODUCTION

The duration required for commercial production of *C. militaris* stromata generally ranges from 35 to 70 days, depending on the substrate and environmental conditions. On rice substrates, stromata are usually produced within 35–45 days, whereas cultivation on maize, millet, and other substrates may require 40–70 days.

EFFECTS OF ENVIRONMENTAL FACTORS

Environmental conditions play a major role in the successful cultivation of *C. militaris*. Unlike plant tissue culture, where hormones regulate development, fungal morphogenesis and stroma formation are mainly controlled by environmental factors such as temperature, light, humidity, and air exchange.

TEMPERATURE

Temperature significantly influences mycelial growth and stroma production. Higher temperatures around 25°C favor rapid mycelial growth, whereas lower temperatures are essential for induction and maintenance of stromata. The optimal temperature range for stroma production is reported to be 18–22°C (Yamaguchi, Y., 2014).

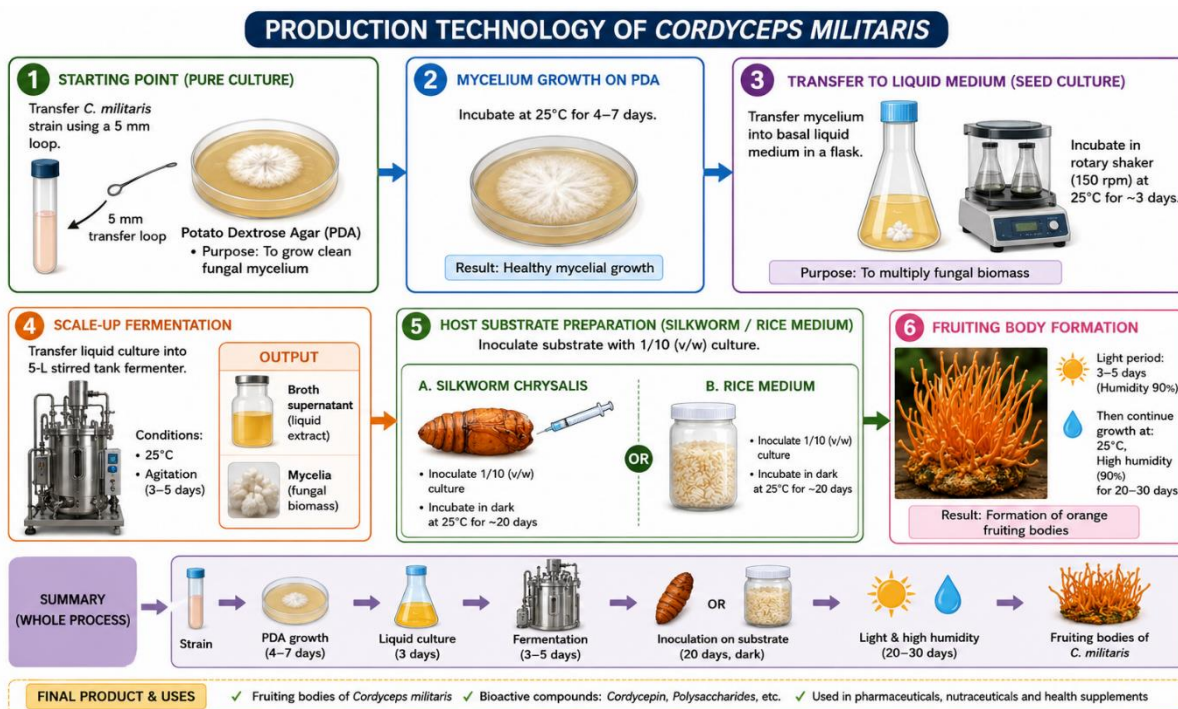


Fig. 1 Production technology of *Cordyceps militaris*

LIGHT

Light is one of the most critical environmental factors for stroma formation. Stromata are not produced under complete darkness. A light intensity of 500–1,000 lux with a 12-hour light and dark cycle is considered optimal for cultivation. Adequate light exposure promotes proper pigmentation, development, and maturation of stromata.

AIR EXCHANGE AND HUMIDITY

Proper air exchange enhances mycelial growth, primordia formation, and overall biomass production. High relative humidity of about 70–90% is essential for successful stroma development because low humidity causes rapid drying of the substrate. In indoor cultivation systems, humidifiers are often required to maintain suitable moisture levels.

INOCULUM PREPARATION

For efficient cultivation of *C. militaris*, liquid inoculum is commonly used. The liquid culture contains conidia, hyphal fragments, and mycelial pellets. Culture media generally consist of simple carbon sources such as carbohydrates along with organic or inorganic nitrogen and mineral salts. The optimum temperature and pH for liquid culture are 20–25°C and pH 6.0–8.0, respectively. In solid media exposed to light, the fungus produces yellowish-white to orange pigments, whereas liquid cultures generally remain colorless.

Uses of *Cordyceps militaris*

The fruiting bodies of *C. militaris* are widely consumed as food and medicinal products. They are commonly used in soups, teas, stewed chicken, stewed duck, hot pots, and other traditional dishes, especially in Southeast Asian countries such as China, Hong Kong, and Taiwan. Consumption below 2.5 g/kg body weight is considered safe (Kapoor, R., & Sharma, S., 2017). In addition to direct consumption, *C. militaris* is widely used in the preparation of health products and pharmaceutical formulations. Commercial products include capsules, oral liquids, medicinal wines, teas, yogurt, vinegar, and soy sauce enriched with Cordyceps extracts.

CONCLUSION

Cordyceps, particularly *Cordyceps militaris*, represents an important group of medicinal fungi with a long history of use in traditional medicine. Its rich composition of bioactive compounds, including cordycepin, polysaccharides, ergosterol, and mannitol, contributes to diverse therapeutic activities such as antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory effects. Advances in cultivation technology have enabled

large-scale production using artificial substrates and controlled environmental conditions, thereby reducing dependence on wild harvesting.

Modern production technologies ensure sustainable cultivation, improved quality, and affordability of Cordyceps products while supporting their growing use in functional foods, nutraceuticals, and pharmaceuticals. Although *Cordyceps sinensis* and *C. militaris* show promising medicinal benefits, further scientific studies are still required to validate their therapeutic efficacy and safety. Overall, Cordyceps continues to be recognized as a valuable natural resource in both traditional and modern healthcare systems

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Integrated Farming Systems for Sustainable Agriculture



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Integrated farming systems (IFS) is on farming method what combines different agricultural enterprises. such as crops, livestock's, poultry, fisheries, dairy, horticulture and agroforestry on a single farm. All these components are carefully named so that the out of one becomes the input for another ensuring efficient use of resources.

Core Components of Integrated Farming Systems

- **Crop Production:** Main crops, intercropping, and mixed cropping to ensure food supply.
- **Livestock Rearing:** Cattle, dairy, sheep, or goats for milk, meat, and manure.
- **Aquaculture:** Fish farming in ponds, often paired with dyke cropping.
- **Poultry/Duck Farming:** Poultry droppings provide high-quality fertilizer for fish ponds or crops.
- **Agroforestry/Horticulture:** Growing trees or fruits on farm boundaries or specialized plots.
- **Apiculture & Mushroom Culture:** Beekeeping for honey and mushrooms for added income.

Models of Integrated Farming Systems in Andhra Pradesh

Multi-Tier Natural Farming

- **The Setup:** The All-Time Money (ATM) or 5-layer model integrates 15 to 20 different crop varieties continuously on a single plot. It features multi-tier canopies (e.g., creepers, vegetables, and fruit trees) combined with livestock.
- **Year-Round Cycle:** The borders are used as permanent, green-leafy fences (agri-horticulture), while 2-3 indigenous cows and ram lambs are integrated to maintain steady nutrient cycling.
- **Benefits:** It provides daily and weekly income rather than relying on seasonal crop sales.

Tree-Crop-Livestock-Poultry

- **The Setup:** Practiced in regions like Visakhapatnam, this model uses about 1 hectare of land combining agriculture with coconut/mango trees, dairy cattle, and backyard poultry.
- **Year-Round Cycle:** Fodder crops and vegetables are grown in the under-story of tree plantations, and dairy waste is composted and used to support fish ponds or vegetable beds.
- **Benefits:** Protects farmers against single-crop failures by offering milk, eggs, meat, and vegetables consistently throughout the year.

Importance of Integrated Farming Systems:

Integrated farming plays a crucial role in achieving sustainable agriculture with rising input costs, climate change, and small farm sizes. IFS helps farmers make better use of available land, water and labour, It enhances food security ensures steady income and support environmental protection. IFS is especially important for small and marginal farmers as it reduces dependency on a single crop and minimizes financial risks.

Strategies of Integrated Farming Systems:

- Diversification of farm activities such as combining crops with dairy, poultry or fish farming.
- Recycling of farm waste, where crop residues are used as animal feed and animal waste is converted into organic manure.

- Efficient water management including the use of pond water for irrigation.
- Crop livestock irrigation which improves soil fertility and productivity.
- Adoption of eco-friendly practices like vermi composting green manuring and integrated pest management.

Benefits of Integrated Farming System:

- Higher and stable income through multiple sources.
- Reduced risks due to diversification of enterprises.
- Improved soil fertility through organic recycling.
- Efficient use of resources like water, land and labour.
- Employment generation throughout the year.
- Environmental sustainability by reducing chemical inputs and pollution.



Nanotechnology in Plant Disease Management - Current Advances and Future Prospects



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ABSTRACT

Nanotechnology has emerged as a promising and innovative approach in plant pathology, offering advanced solutions for the detection, diagnosis, and management of phytopathogenic diseases. Nanoparticles (NPs), typically ranging below 100 nm, possess unique physicochemical, optical, and antimicrobial properties that make them highly effective in agricultural applications. Metal nanoparticles such as silver, gold, zinc oxide, copper oxide, and titanium-based particles are widely explored as diagnostic probes, biosensors, and antimicrobial agents for rapid and sensitive detection of plant pathogens. Nanosensors and quantum dots enable real-time, on-site disease monitoring, facilitating early intervention and precise disease management. In addition, nanoparticle-based delivery systems enhance the efficiency of agrochemicals by improving solubility, stability, and targeted action, thereby reducing chemical usage and environmental impact. Nanoparticles also play a significant role in plant growth promotion and disease suppression through induction of systemic resistance and interaction with microbial communities. Furthermore, nanoparticle-mediated gene transfer and CRISPR/Cas9 delivery provide a novel molecular approach for developing disease-resistant crop varieties without traditional tissue culture methods. However, concerns regarding phytotoxicity and genotoxicity highlight the need for careful optimization of nanoparticle concentration and formulation. Overall, nanotechnology offers a sustainable and efficient platform for integrated plant disease management, combining rapid diagnostics, targeted control, and genetic improvement strategies to enhance global agricultural productivity.

Key words: Nanotechnology, Nanoparticles, Metal nanoparticles, Quantum dots, Phytotoxicity, Sustainable agriculture.

INTRODUCTION

Nanomaterials possess unique physicochemical, optical, mechanical, and magnetic properties that make them highly valuable across diverse fields such as electronics, textiles, medicine, agriculture, and environmental science. Nanoparticles, typically smaller than 100 nm, are engineered from various metal ions and can exist in different shapes including spheres, rods, and triangles. These distinctive features make them highly versatile for modern applications (Gogos *et al.*, 2012).

In agriculture, particularly in plant pathology, nanotechnology is emerging as a promising tool for plant disease management. It plays a dual role both as a diagnostic system for early disease detection and as a delivery system for targeted treatment of plant pathogens. By enabling controlled release of functional molecules, nanotechnology improves the efficiency and precision of plant protection strategies. For example, encapsulation of herbicides can enhance their performance; sulfonylurea herbicides used against *Orobanche* species often require repeated applications, but nano-formulations can improve their stability and effectiveness, reducing the need for multiple sprays (Rai *et al.*, 2015).

Applications of Nanotechnology in Plant Pathology

Nanotechnology offers several innovative approaches in plant disease control, including, Use of nano-biosensors, quantum dots, and nanoparticles for rapid and sensitive detection of plant pathogens. Application of nanoparticles as antimicrobial agents to suppress plant diseases caused by bacteria, fungi, and other pathogens.

Nanotechnology as a Disease Diagnostic Tool

Plant pathogens often overcome host resistance mechanisms, making disease prediction and management challenging. Nanotechnology addresses this issue by enabling early and accurate detection of pathogens. Nano-based diagnostic tools can identify infections at an initial stage, allowing timely intervention and reducing the risk of large-scale crop loss. In addition, nano-encapsulation technologies can be used to deliver fertilizers, pesticides, and other agrochemicals in a more stable, biodegradable, and efficient form, improving field-level disease management (Servin, A., & White, J. C., 2016).

Nanotechnology as a Disease Management Tool

Nanoparticles can protect plants through two main approaches: either by directly exhibiting antimicrobial activity or by acting as carriers for pesticides and other bioactive compounds such as double-stranded RNA (dsRNA). These nano-carriers can be applied through seed treatment, foliar spray, or root drenching.

The advantages of nanoparticle-based delivery systems include improved shelf life of active compounds, enhanced solubility of poorly water-soluble pesticides, reduced toxicity to non-target organisms, and better targeted uptake at infection sites (Khot, *et al.*, 2012). Together, these benefits make nanotechnology a powerful and sustainable approach for modern plant disease management.

Nanotechnology: Detection and Applications in Plant Pathology

Nanotechnology is transforming plant pathology by enabling highly sensitive disease detection, rapid diagnostics, and innovative disease management strategies. Engineered nanomaterials such as metal nanoparticles, biosensors, quantum dots, and nanofabricated devices provide powerful tools for identifying pathogens and controlling plant diseases at an early stage.

Metal Nanoparticles as Diagnostic Probes

Metal nanoparticles (NPs) such as silver (Ag), gold (Au), zinc oxide (ZnO), and copper oxide (CuO) are widely used as advanced diagnostic probes in plant disease detection. These nanoscale materials (1–100 nm) function as nanosensors, lab-on-a-chip platforms, and imaging agents capable of detecting pathogen biomarkers with high sensitivity and specificity. In addition to diagnosis, many metal nanoparticles also exhibit direct antimicrobial activity and can stimulate plant defense responses, making them dual-purpose tools in plant protection (Mishra *et al.*, 2017). For example, fluorescent silica nanoprobe linked with antibodies (such as goat anti-rabbit IgG) have been successfully used to detect *Xanthomonas axonopodis* pv. *vesicatoria*, the causal agent of bacterial spot in solanaceous crops.

Nanoscale Biosensors (Nanobiosensors)

Nanobiosensors integrate nanomaterials such as gold nanoparticles, carbon nanotubes, and quantum dots to detect plant pathogens, toxins, and environmental stress factors with exceptional sensitivity. These devices enable early, on-site, and real-time disease detection, overcoming the limitations of conventional laboratory-based diagnostic methods. Microfabricated biosensors, including uncoated and gold-coated silicon cantilevers functionalized with proteins such as concanavalin A, fibronectin, or immunoglobulin G, have been used to detect fungal spores of *Aspergillus niger* and *Saccharomyces cerevisiae*. These biosensors are capable of detecting pathogens at concentrations ranging from 10^3 to 10^6 CFU mL⁻¹, demonstrating their high efficiency in early diagnosis (Prasad *et al.*, 2017).

Quantum Dots in Plant Disease Management

Quantum dots (QDs) are nanoscale semiconductor particles, typically 2–10 nm in size, that exhibit unique optical and electronic properties (Jo *et al.*, 2009). They are emerging as powerful tools in plant pathology due to their ability to provide ultra-sensitive, real-time pathogen detection. Beyond diagnostics, quantum dots also show potential in targeted antimicrobial applications and plant immune stimulation. Their precision and efficiency make them a promising alternative to conventional chemical pesticides, supporting more sustainable agricultural practices.

Nanofabrication in Plant Disease Control

Nanofabrication refers to the precise engineering of nanomaterials designed for targeted applications in plant disease management. These engineered nanostructures, including silver (Ag-NPs) and zinc oxide nanoparticles (ZnO-NPs), help reduce disease incidence by damaging pathogen cell membranes or enhancing plant immune

responses (Elmer, W., & White, J. C. , 2018). Such technologies can significantly reduce the dependency on chemical pesticides while improving crop protection efficiency. Role Nanotechnology in Plant Disease Management is clearly illustrated in Fig. 1

Relevance to Host–Pathogen Interactions

Nanotechnology also contributes to understanding host–pathogen interactions. Studies involving pathogens such as *Colletotrichum graminicola* (causing anthracnose in maize) and *Xylella fastidiosa* (responsible for Pierce’s disease in grapevine) provide valuable insights into plant resistance mechanisms (Khan *et al.*, 2017). This knowledge is particularly useful for plant breeders aiming to develop resistant varieties by targeting traits such as stomatal architecture (to block pathogen entry), leaf surface characteristics (to prevent fungal appressorium formation), and vascular traits (to restrict systemic pathogen movement). List of nano-materials and its application in plant disease management is listed in Table 1.

Table 1. List of nano-materials and its application in Plant disease management

Nanomaterial	Application	Functions
Nano particles Thiamine di-lauryl sulfate (TDS) (258.6 nm)	<i>Xanthomonas campestris</i> pv. <i>campestris</i> (cabbage black rot in pot)	Nanosilver against <i>X. Campestris</i> pv. <i>campestris</i> revealed a considerable decrease in cabbage black rot.
Chitosan nanoparticles (CS NPs)	<i>Fusarium oxysporum</i> – causes wilt disease <i>Alternaria solani</i> – causes early blight <i>Magnaporthe oryzae</i> – causes rice blast <i>Rhizoctonia solani</i> – causes damping-off and root rot	CS NPs at a concentration of 0.6% (w/v) significantly delayed mycelial sp., growth of <i>Magnaporthe</i> , <i>Fusarium</i> <i>Colletotrichum capsici</i> , <i>C. gloeosporioides</i> and <i>Aspergillus niger</i> when compared with control.
Nano copper	<i>Xanthomonas</i> pv. <i>axonopodis</i> <i>Punicae</i> (pomegranate bacterial blight)	<i>X. axonopodis</i> pv. <i>punicae</i> growth was reduced by nanocopper @ 0.2 ppm (which is >10,000 times lower than what is typically recommended for Cu-oxychloride)
Copper nanoparticles (11–55 nm)	Cu-based NPs were tested on tomato against <i>Phytophthora infestans</i> for their antifungal activity.	Synthesised Cu-based the NPs outperformed the commercial agro-chemicals and significantly decreased the active ingredient rate. On plants that had been treated, the particles.

Nanoparticles in Plant Systems: Growth Promotion, Toxicity, and Microbial Interactions

Nanoparticles (NPs) are increasingly being explored in plant pathology and agriculture due to their unique ability to influence plant growth, interact with pathogens, and modify plant–microbe relationships. However, their effects can be both beneficial and potentially harmful depending on concentration, type, and exposure conditions.

NP-Induced Plant Growth Enhancement

Several studies have demonstrated that nanoparticles can stimulate plant growth and development when applied at optimal concentrations. Silver nanoparticles (AgNPs), for instance, have been shown to enhance root length in crops such as maize, cabbage, and barley. They also promote increased leaf number, leaf area, and overall plant height in species like borage, along with improved chlorophyll content in asparagus. Similarly, other types of nanoparticles can positively influence plant physiology. Metal oxide nanoparticles, for example, have been reported to support tomato plant growth by suppressing *Verticillium* wilt, a major soil-borne fungal disease. Carbon-based nanoparticles are also of interest due to their unique thermal, electrical, and chemical properties, which may contribute to improved plant performance and stress tolerance (Kumari *et al.*, 2019).

NP-Induced Phytotoxicity

Despite their benefits, nanoparticle–plant interactions remain a relatively underexplored area, and many mechanisms are still not fully understood. Nanoparticles may interact with plants through dissolution, direct contact with tissues, or co-transport with other environmental compounds. These interactions can lead to both

positive and negative physiological responses. For example, in *Zea mays* (maize), exposure to magnetic iron oxide (Fe_3O_4) nanoparticles has shown a dose-dependent effect. At lower concentrations (10–50 $\mu\text{L/L}$), there was stimulation in the production of chlorophyll a, chlorophyll b, and carotenoids. However, at higher concentrations, these effects were inhibited, leading to reduced photosynthetic efficiency. This highlights the importance of dosage optimization in nanoparticle applications.

NP-Induced Genotoxicity

While nanoparticles offer promising applications in plant disease management, concerns regarding their potential genotoxic effects cannot be overlooked. Genotoxicity refers to damage inflicted on the genetic material (DNA), which may lead to mutations, chromosomal abnormalities, or disruptions in the cell cycle. Metal nanoparticles such as silver (Ag), zinc oxide (ZnO), and copper (Cu) are widely recognized for their antimicrobial properties, but excessive or prolonged exposure may induce DNA damage in plants. Such effects raise important biosafety considerations for their large-scale agricultural use and highlight the need for careful regulation and risk assessment.

Nanoparticle Interaction with Microorganisms

Nanoparticles play a significant role in plant disease management by directly interacting with plant-associated microorganisms. Metallic nanoparticles, including silver and copper, as well as green-synthesized nanoparticles, exhibit strong antimicrobial activity by disrupting microbial cell walls, generating reactive oxygen species (ROS), and interfering with essential metabolic processes. In addition to their direct antimicrobial effects, nanoparticles can also enhance plant defense responses and act as targeted delivery systems for bioactive compounds. This dual functionality makes them valuable tools for precise and sustainable disease management strategies in agriculture.

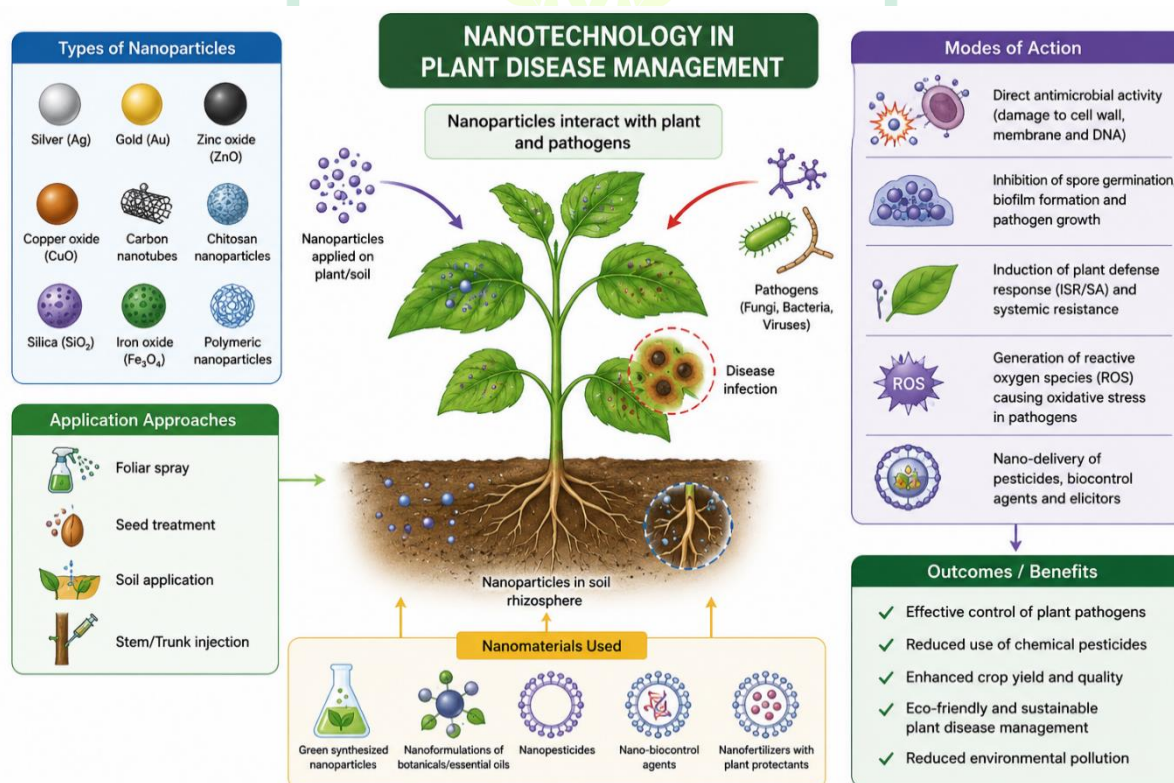


Fig.1. Role Nanotechnology in Plant Disease Management

Mechanisms of Nanoparticles in Controlling Phytopathogenic Diseases

Nanoparticles (NPs) play a multifaceted role in the management of phytopathogenic diseases through both direct antimicrobial activity and indirect enhancement of plant defense mechanisms. The biological and engineered systems used in nanoparticle synthesis can act through several mechanisms, including antibiosis, competition for nutrients and ecological space, and the induction of systemic resistance in plants. Biogenic nanoparticles, in

particular, can be tailored in terms of size, shape, and surface properties to improve their specificity and efficiency against target phytopathogens. This tunability allows for more precise and selective disease control compared to conventional chemical approaches. Among the most extensively studied metallic nanoparticles are silver (Ag), gold (Au), manganese (Mn), zinc (Zn), copper (Cu), and titanium (Ti), each demonstrating varying degrees of antimicrobial and plant-protective activity.

Nanoparticle-Mediated Gene Transfer and Crop Protection: A Molecular Approach

Nanoparticle-mediated gene delivery represents an emerging frontier in plant biotechnology and disease management. In this approach, ultrafine nanoparticles (<100 nm) are used as carriers to transport genetic material such as DNA, RNA interference (RNAi), or other functional nucleic acids into plant cells. This strategy provides a precise and minimally invasive alternative to traditional genetic modification techniques. By efficiently bypassing the rigid plant cell wall, nanoparticles facilitate targeted delivery of genetic constructs that enhance crop immunity and suppress pathogen-specific genes, thereby improving disease resistance. Furthermore, nanoparticle-based delivery systems enable efficient introduction of CRISPR/Cas9 components directly into intact plant cells. This advancement allows for rapid genome editing without the need for tissue culture or complex regeneration procedures, significantly accelerating the development of disease-resistant crop varieties.

Conclusion

Nanotechnology has emerged as a transformative approach in plant pathology, offering innovative solutions for the detection, diagnosis, and management of phytopathogenic diseases. The unique physicochemical properties of nanoparticles enable their use as diagnostic probes, biosensors, antimicrobial agents, and efficient delivery systems for agrochemicals and genetic materials. Metal nanoparticles, quantum dots, and nanosensors provide rapid and sensitive pathogen detection, while also contributing to disease suppression through direct antimicrobial activity and induction of plant defense responses. Despite these advantages, concerns regarding phytotoxicity and genotoxicity highlight the need for careful optimization of dosage and formulation to ensure environmental and biological safety. Overall, nanotechnology holds significant potential to revolutionize sustainable crop protection by integrating precision, efficiency, and eco-friendly approaches. Continued research is essential to better understand nanoparticle–plant–microbe interactions and to translate laboratory findings into safe, large-scale agricultural applications.

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From Scouting to Spraying: The Expanding Role of Drones in Pest Management



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Abstract

Modern agriculture is rapidly transitioning toward precision-based technologies to improve productivity, sustainability, and input use efficiency. Among these innovations, drones or Unmanned Aerial Vehicles (UAVs) are emerging as transformative tools in pest management. Equipped with advanced technologies such as multispectral imaging, thermal sensors, artificial intelligence (AI), GPS-guided navigation, and precision spraying systems, drones are revolutionizing the way pests are monitored and controlled in agricultural ecosystems. From early pest scouting and crop health assessment to site specific pesticide application, drones enable timely and data-driven interventions that minimize chemical use, reduce labour dependency, and improve operational efficiency. Unlike conventional blanket spraying methods, drone-assisted pest management supports precision agriculture by targeting only affected zones, thereby reducing environmental contamination and conserving beneficial organisms. Recent advancements in AI-integrated autonomous drones, real-time data analytics, and improved spray technologies are further enhancing the effectiveness of drone-based crop protection systems. In India, increasing labour shortages, rising input costs, and government support for “Kisan Drones” are accelerating the adoption of UAV technologies in agriculture. Although challenges such as high initial cost, limited battery life, spray drift, and regulatory constraints still exist, drones hold immense potential for the future of sustainable and climate-smart agriculture. This article explores the evolving role of drones from crop scouting to precision spraying and highlights their growing significance in modern pest management strategies.

Keywords: Agricultural drones, UAV, precision pest management, AI, remote sensing, pesticide spraying, crop scouting, precision agriculture

Introduction

Agriculture today stands at the crossroads of rising food demand, shrinking natural resources, labour shortages, and increasing environmental concerns. As the global population continues to expand, ensuring food security while maintaining ecological sustainability has become one of the greatest challenges of modern agriculture. Traditional farming practices alone are no longer sufficient to meet these growing demands. Consequently, precision agriculture is emerging as a smarter and more sustainable approach to crop production. Among the many technological innovations reshaping agriculture, drones or Unmanned Aerial Vehicles (UAVs) have gained tremendous attention in recent years. Once associated mainly with military surveillance and aerial photography, drones are now becoming valuable tools in crop monitoring, nutrient management, irrigation planning, disease detection, and particularly in precision pest management (Velusamy et al., 2022).

Pest management has traditionally relied on manual field scouting and blanket pesticide applications. Farmers often spray pesticides uniformly across entire fields irrespective of the actual pest distribution. Such practices increase production costs, promote pesticide resistance, contaminate the environment, and negatively affect beneficial organisms. In reality, most insect pests are not evenly distributed throughout fields. Instead, they occur in localized hotspots or patches. Aphids, for instance, often concentrate near field boundaries, while brown planthoppers tend to aggregate around the lower stem regions of rice plants near the waterline (Saini et al., 2024). This spatial variability forms the basis of precision pest management, where interventions are applied only where and when needed. Drones are playing a crucial role in making this approach practical and efficient (Rajabpour and Yarahmadi, 2024; Venegas et al., 2018).

With advanced imaging technologies, AI-driven analytics, and GPS-guided spraying systems, drones are transforming crop protection from a labour-intensive activity into a data driven precision operation. Their growing importance is especially evident in countries like India, where labour scarcity, increasing input costs, and the need for sustainable farming solutions are accelerating the adoption of smart agricultural technologies (Guebsi et al., 2024).

Table 1. Major Applications of Drones in Precision Pest Management

Application	Purpose	Major Benefit
Crop scouting	Detection of pest hotspots	Early intervention
Remote sensing	Monitoring crop stress	Real-time field analysis
Precision spraying	Site-specific pesticide application	Reduced chemical use
AI-assisted diagnosis	Automated pest identification	Faster decision making
Biological control release	Release of natural enemies	Eco-friendly pest control
Weed mapping	Identification of weed patches	Targeted herbicide application

Drones as the Eye in the Sky

One of the greatest strengths of drones lies in their ability to monitor crops quickly, accurately, and repeatedly over large agricultural areas. Modern agricultural drones are equipped with high resolution RGB cameras, multispectral sensors, hyperspectral imaging systems, thermal sensors, and GPS-based navigation technologies that allow real-time crop surveillance with exceptional precision (García-Munguía et al., 2024).

Unlike traditional crop scouting methods, which are labour intensive and time consuming, drones can rapidly capture detailed aerial images of entire fields within minutes. These images help identify crop stress caused by insect pests, diseases, nutrient deficiencies, or water stress long before visible symptoms become apparent to the human eye (Subramanian et al., 2021).

Multispectral and thermal imaging systems are particularly important in pest management. Insect feeding often alters plant physiology, leading to subtle changes in canopy temperature, chlorophyll content, and reflectance patterns. Drones equipped with these sensors can detect such abnormalities early and generate precise crop health maps for targeted interventions (Avhale et al., 2025).

Compared to satellite imagery, drones provide much higher spatial and temporal resolution. Satellite-based monitoring systems may take several days to revisit the same field, whereas drones can monitor crops repeatedly during critical growth stages and generate real-time information for rapid decision-making (Velusamy et al., 2022).

This ability to identify pest hotspots accurately enables farmers to shift from blanket pesticide application to site specific pest management, thereby improving efficiency and sustainability.

Artificial Intelligence and Smart Pest Detection

The integration of artificial intelligence (AI) with drone technology is pushing precision pest management into a new era of smart agriculture. AI-powered drones are capable of processing enormous volumes of field data collected through sensors and cameras and converting them into actionable insights for farmers (Rahman et al., 2026; Adetunji et al., 2023).

Machine learning, deep learning, and computer vision technologies enable drones to identify pest infestations, classify pest species, distinguish healthy and damaged plants, and even predict pest spread patterns in real time (Li et al., 2024).

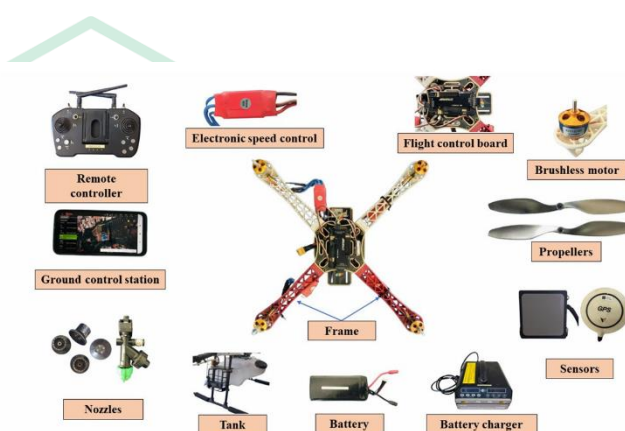


Figure 1. Structural components of an agricultural spraying drone used for precision pest management.

AI-assisted drones can analyse:

- Leaf discoloration and feeding damage
- Crop canopy temperature variations
- Wilting and stress symptoms
- Growth abnormalities
- Pest movement patterns

This level of intelligent analysis allows early pest detection before severe outbreaks occur. Early intervention is critical because delayed pest management often leads to major yield losses and increased pesticide dependence.

Autonomous navigation systems further improve drone efficiency. AI-powered drones can automatically adjust flight paths, avoid obstacles, optimize coverage, and operate with minimal human intervention. Swarm drone technology, where multiple drones operate together simultaneously, is also being explored for large-scale agricultural operations (Verma, 2025).

The future of agriculture may soon witness fully autonomous pest management systems where drones independently scout fields, identify pest infestations, make decisions, and perform targeted spraying operations (Saini et al., 2024).

Precision Spraying: A New Era of Crop Protection

While crop scouting represents the surveillance aspect of drones, precision spraying is perhaps their most visible and rapidly expanding application in agriculture.

Conventional pesticide spraying methods often suffer from uneven coverage, excessive chemical use, operator exposure to pesticides, and high labour requirements. Drone-based spraying addresses many of these limitations by enabling uniform, targeted, and efficient pesticide application (Meng et al., 2018).

Agricultural drones are capable of spraying pesticides precisely over affected crop zones while maintaining optimized droplet distribution and canopy penetration. Their ability to operate in difficult terrain, waterlogged fields, and dense crop canopies makes them especially valuable in crops like rice, cotton, sugarcane, and horticultural systems (Pathak et al., 2020; Dutta et al., 2024).

Studies have demonstrated the effectiveness of UAV-based spraying systems against major agricultural pests. Significant reductions in whitefly populations in cotton and brown planthopper infestations in rice have been achieved under optimized flight heights and forward speeds (Parmar et al., 2021).

Field studies have shown that UAV spraying systems can cover 4-10 hectares per hour, making them substantially faster than manual spraying operations (Parmar et al., 2021). Moreover, drone-based applications can significantly reduce pesticide and water consumption compared to conventional high-volume sprayers (García-Munguía et al., 2024).



Figure 2. AI-assisted drone systems for real-time pest detection, crop monitoring, and precision pest management in agriculture.

Table 2. Comparison Between Conventional and Drone-Based Spraying

Parameter	Conventional Spraying	Drone Spraying
Labour requirement	High	Low
Water use	High	Low
Spray precision	Moderate	High
Field accessibility	Limited	Excellent
Operator exposure	High	Minimal
Spray uniformity	Variable	Better
Crop damage	Possible	Negligible
Operational speed	Slow	Fast

In flooded rice ecosystems, drones provide an additional advantage because they can spray standing crops without disturbing the field or damaging plants.



Figure 3. UAV-assisted precision pesticide spraying in rice ecosystems using agricultural drones.

Spray Physics, Adjuvants, and Application Efficiency

Although drone spraying appears technologically advanced, its effectiveness depends heavily on several scientific and operational parameters. Flight height, flight speed, nozzle type, droplet size, spray pressure, rotor airflow, weather conditions, and canopy structure all influence spray deposition and pest control efficiency (Qin et al., 2016).

One of the major challenges in UAV spraying is spray drift. Fine droplets generated during spraying may drift away from the target area due to wind or rotor-generated turbulence, reducing application efficiency and increasing environmental contamination. Recent research has highlighted the importance of adjuvants in improving drone spray performance. Tank-mix adjuvants can alter the physicochemical properties of spray solutions by reducing surface tension, improving droplet adhesion, and enhancing canopy penetration (Wang et al., 2024).

Studies conducted under rice ecosystems demonstrated that suitable adjuvant formulations significantly reduced spray drift, improved droplet deposition uniformity, enhanced canopy penetration, and increased insecticidal efficacy against rice planthopper (Qin et al., 2016; Parmar et al., 2021). Optimized adjuvant concentrations improved pest control efficacy by more than 35% compared with applications without adjuvants (Wang et al., 2024). Such findings emphasize that successful drone spraying is not merely about flying a machine over crops; it involves a sophisticated understanding of spray physics, aerodynamics, formulation chemistry, and canopy interactions.

Drones and Sustainable Agriculture

The excessive and indiscriminate use of pesticides has become a major environmental and public health concern worldwide. Conventional spraying practices often contaminate soil and water resources, harm non target organisms, and accelerate pesticide resistance in insect populations.

Drone-assisted precision pest management aligns closely with the principles of sustainable agriculture and Integrated Pest Management (IPM). By identifying pest hotspots and applying pesticides only where necessary, drones reduce unnecessary chemical applications and preserve beneficial insects and pollinators (Carvalho et al., 2020).

Precision pest management systems focus on subfield-level decision-making rather than field-wide pesticide application (Saini et al., 2024). This targeted approach reduces environmental pollution, lowers pesticide residues, and improves input-use efficiency.

Drones are also increasingly being explored for:

- Release of biological control agents
- Precision application of biopesticides
- Weed mapping and targeted herbicide spraying
- Monitoring of natural enemy populations
- Eco-friendly pest management programs

Such applications support climate-smart agriculture and help balance productivity with environmental sustainability.

The Indian Scenario: Rise of Kisan Drones

India is rapidly emerging as one of the leading countries promoting agricultural drone technology. Government initiatives supporting “Kisan Drones” are accelerating the adoption of UAVs in precision agriculture and crop protection (Singh & Singh, 2025).

The Government of India has introduced several measures, including:

- Drone subsidies
- Pilot training programs
- Standard Operating Procedures (SOPs) for drone use
- Approval of pesticides for UAV spraying
- Financial support for agri-drone startups and entrepreneurs

The use of drones during locust management operations in India demonstrated their efficiency in rapid surveillance and targeted pesticide application over large areas.

Agricultural drone adoption in India is driven by several factors:

- Labour shortages
- Rising input costs
- Need for timely spraying operations
- Increasing awareness about precision farming
- Growing focus on sustainable agriculture

Research institutions, agricultural universities, startups, and private companies are actively developing indigenous drone technologies tailored to Indian farming conditions. Drone-based applications are already expanding across rice, cotton, maize, sugarcane, fruits, vegetables, and plantation crops (Qin et al., 2016; García-Munguía et al., 2024). The agricultural drone market is expected to grow rapidly in the coming years as precision farming technologies become more accessible and affordable (Avhale et al., 2025).

Challenges and Future Prospects

Despite their enormous potential, several challenges continue to limit the widespread adoption of drones in agriculture. Further research is still needed regarding nozzle design, droplet behaviour, canopy penetration, and pesticide formulations specifically suited for UAV applications (Cunha et al., 2021).

Table 3. Challenges in Agricultural Drone Adoption

Challenge	Impact
High initial cost	Limited adoption among smallholders
Limited battery life	Reduced operational duration
Spray drift	Reduced application efficiency
Skilled operator requirement	Need for technical training
Regulatory issues	Operational limitations
Weather dependency	Affects spray accuracy
Limited payload	Frequent refilling required

Nevertheless, the future of drone-based pest management remains extremely promising. Rapid advancements in AI, robotics, sensor technology, IoT integration, and autonomous systems are continuously improving drone efficiency and affordability.

Future agricultural drones may:

- Predict pest outbreaks before visible symptoms appear
- Generate real-time pest advisory systems
- Apply ultra-low pesticide doses with extreme precision
- Operate autonomously using AI-driven decisions
- Integrate with weather forecasting and smart farming systems
- Release biological control agents automatically

Such innovations could fundamentally transform the future of crop protection and sustainable agriculture.

Conclusion

Drones are redefining the future of pest management by transforming the way crops are monitored, analysed, and protected. From early pest scouting and intelligent crop surveillance to precision pesticide spraying and AI-assisted decision-making, drones are bringing remarkable efficiency, accuracy, and sustainability to modern agriculture.

Their ability to reduce pesticide use, conserve water, minimize labour dependency, improve spray precision, and support Integrated Pest Management makes them one of the most promising technologies for next-generation farming systems.

Although challenges related to cost, regulations, and operational standardization still remain, continuous technological advancements and supportive government initiatives are steadily overcoming these barriers. As precision agriculture continues to evolve, drones are expected to become an integral part of sustainable and climate-smart crop protection strategies.

The transition from conventional blanket spraying to intelligent, data-driven precision pest management has already begun and drones are leading this agricultural revolution from the skies.

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HARNESSING NUCLEAR SCIENCE FOR NEXT- GENERATION AGRICULTURE



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ABSTRACT

Nuclear-based technologies offer a safer, effective alternative. This article reviews key applications of nuclear techniques in agriculture and food science, promoted by IAEA, FAO, and BARC. In soil science, isotopic tracers like nitrogen-15 and fallout radionuclides optimize fertilizer and water use efficiency, monitor erosion, and assess salinity, while neutron probes enable precise irrigation. Food irradiation using gamma rays controls pathogens, delays ripening, and extends shelf life without residues, with dosages tailored for sprout inhibition, pathogen reduction, or industrial sterilization. The Sterile Insect Technique employs radiation to produce sexually competitive but sterile insects, achieving eco-friendly pest control as demonstrated in screwworm eradication in Libya and fruit fly management in Mexico. Radiation-induced mutation breeding accelerates crop improvement, with over 3,200 new varieties developed globally, including 72 BARC-mutated crops in India such as the wind-resistant Kaaveri Vaaman banana. While nuclear technologies enhance yield, sustainability, and food safety, further research is needed on irradiation effects on food components, packaging interactions, and consumer acceptance to ensure long-term adoption.

KEY WORDS: Agriculture, Food security, Nuclear and radiation technology, Sustainability.

INTRODUCTION

Presently, we all are aware about the rise of population globally, which is expected to reach ten billion by 2050. To avoid food shortages and to meet the increasing food demands, our agriculture and food production must increase globally with special focus on developing and more populated countries. Diseases, climate change, seasonal conditions, natural calamities, pests/insect attacks, all are creating more obstacles for our food and agriculture sector. To tackle or manage these problems, we are adopting different remedies involving dangerous chemicals, and we are losing a lot of money, which is further leading towards other problems which are spoiling our finance, soil, water, air, and ecosystem. There is a need for safe agriculture and food practices, which will be beneficial for human beings as well as for our ecosystem. Nuclear-based technology (e.g., radiation mutagenesis) is a frequently applied technology and the safest way as compared to the many other chemical methods. Presently, with the great efforts of the International Atomic Energy Agency (IAEA), Food and Agriculture Organization (FAO), and Bhabha Atomic Research Centre (BARC) the nuclear technology is being widely used in the field of agriculture and food science. In this article, we are presenting an overview of applications of different nuclear technologies in agriculture and food sectors.

NUCLEAR TECHNOLOGY APPLICATIONS

SOIL SCIENCE

More than 90% of the food is grown directly or indirectly from our soil, but now our fertile land is threatened by many forms of degradation. According to an IAEA statement in December 2021, over the past two decades, approximately 2000 hectares of irrigated land per day in arid and semi-arid areas across 75 countries have been degraded by salinisation. Using nuclear techniques, we can maximize the yield using tracing isotopes in water, fertilizers, and soil. Isotopic techniques can increase the nutrient and water use efficiencies and increase the biological nitrogen (N) fixation through the capture of atmospheric nitrogen (N₂) and carbon (C) stored in salt-affected soils. According to the IAEA, excess fertilisers which are not taken up by plants/crops are increasing the soil salinity, and use of nitrogen-15 (a stable isotope of N) helps to determine the exact amount of nitrogen that plants/crops need using various nuclear techniques. Isotopic tracers (oxygen, hydrogen) can provide information regarding water movement, while Fallout Radionuclides (e.g., Cs-137, Pb-210, Be-7) help to monitor

the soil erosion. Using neutron probes (neutron moisture meter) and cosmic ray neutron probe, we can measure the soil moisture, leading to efficient irrigation.

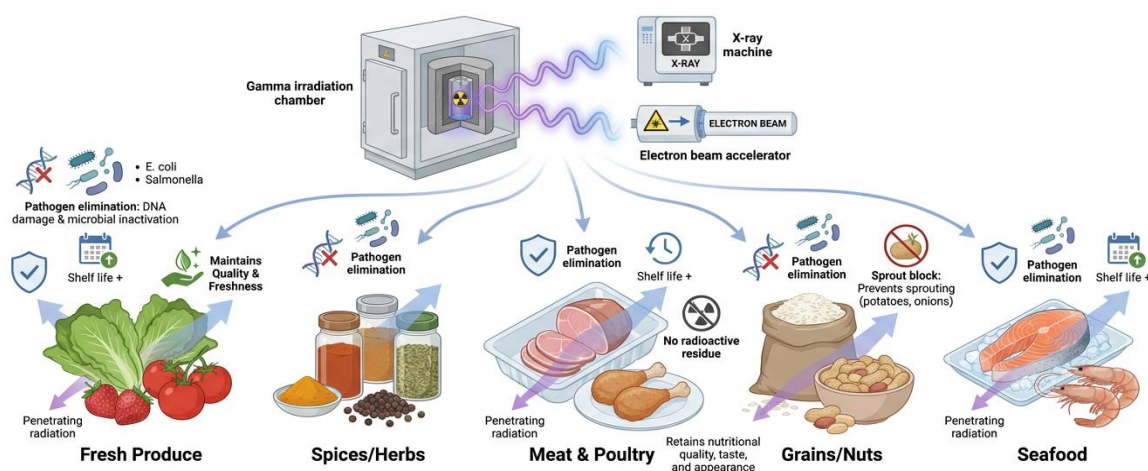
FOOD IRRADIATION

Some 25-30% of food harvested is lost as a result of spoilage before it can be consumed. This problem is particularly prevalent in hot, humid countries. Food irradiation is the process of exposing foodstuffs to gamma rays to kill bacteria that can cause food-borne disease, and to increase shelf-life. It has the same benefits as when food is heated, refrigerated, frozen, or treated with chemicals, but does not change the temperature or leave residues. In all parts of the world there is growing use of irradiation technology to preserve food. It can replace potentially harmful chemical fumigants that are used to eliminate insects from dried fruit and grain, legumes, and spices.

In addition to inhibiting spoilage, irradiation can delay ripening of fruits and vegetables to give them greater shelf-life. Its ability to control pests and reduce required quarantine periods has been the principal factor behind many countries adopting food irradiation practices.

DOSAGE	EFFECTS	APPLICATIONS
Low dosage (upto 1 kGy)	Inhibition of sprouting, Insect and parasite disinfestation, Delay ripening.	Potatoes, onions, garlic, ginger, yam, fresh fruit, dried foods.
Medium dosage (1-10 kGy)	Extend shelf life, Kill pathogens.	Fish, strawberries, mushroom, seafood, poultry.
High dose (10-50 kGy)	Industrial sterilization	Meat, poultry, seafood, spices, processed foods etc..

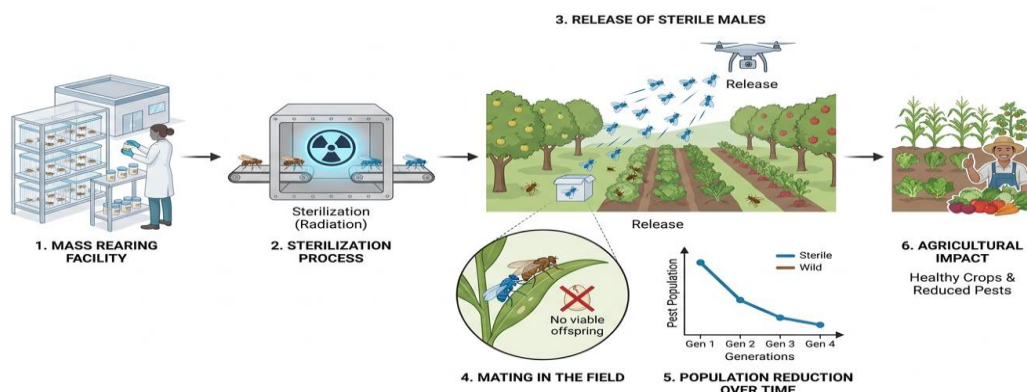
Uses of Radiation in Food Sterilization and Preservation



Summary: Radiation ensures food safety, extends shelf life, and preserves quality—without significantly affecting taste, appearance, or nutritional value.

INSECT CONTROL

Despite widespread use of insecticides, losses are likely to be of the order of 10% globally and often notably higher in developing countries. One approach to reducing insect depredation in agriculture is to use genetically-modified crops, so that much less insecticide is needed. Another approach is to disable the insects. Radiation is used to control insect populations via the Sterile Insect Technique (SIT). This involves rearing large populations of insects that are sterilized through irradiation (gamma or X-rays), and introducing them into natural populations (Kabore *et al.*, 2023). The sterile insects remain sexually competitive, but cannot produce offspring. The SIT technique is environmentally-friendly, and has proved an effective means of pest management even where mass application of pesticides had failed. The IPPC recognizes the benefits of SIT, and categorizes the insects as beneficial organisms.



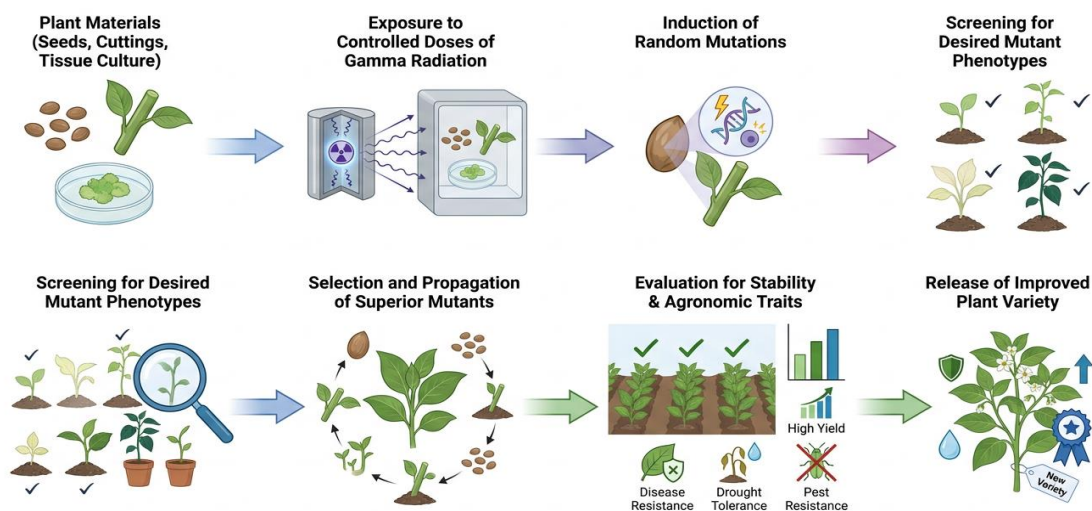
Case studies

In 1998 screwworm was discovered in Libya. A major national and international response utilising SIT prevented its spread to the rest of Africa and the Mediterranean Basin (Singh M, 2025) The campaign successfully eradicated the infestation. According to Chen in Mexico, the Moscafrut Fruit Fly Facility produces hundreds of millions of sterile fruit flies each week and then releasing the sterile flies into local citrus and mango crops to reduce the number of future offspring (Chen J, 2021)

PLANT MUTATION BREEDING

Plant mutation breeding is the process of exposing the seeds or cuttings of a given plant to radiation, such as gamma rays, to cause mutations. The irradiated material is then cultivated to generate a plantlet, which is selected and multiplied if it shows desired traits. A process of marker-assisted selection (or molecular-marker assisted breeding) is used to identify desirable traits more quickly based on genes. The use of radiation essentially enhances the natural process of spontaneous genetic mutation, significantly shortening the time it takes. The IAEA, jointly with the FAO, assists its member states in the development and implementation of plant mutation breeding.

Ionizing radiation to induce mutations in plant breeding has been used for several decades, and some 3200 new crop varieties have been developed in this way. Gamma or neutron irradiation is often used in conjunction with other techniques to produce new genetic lines of root and tuber crops, cereals, and oil seed crops. New kinds of sorghum, garlic, wheat, bananas, beans, and peppers have been developed that are more resistant to pests and more adaptable to harsh climatic conditions.



BioRender-style flowchart illustrating the use of gamma radiation for mutation breeding in plants.

In India, some 72 improved crop varieties had been created by the Bhabha Atomic Research Centre using mutation as of 2026. Its Kaaveri Vaaman banana matures more quickly than its parent and has a shorter stem, which avoids the need for support structures and makes it suitable for windy coastal areas, dense planting on terraces and home cultivation.

CONCLUSION

IAEA, FAO, and WHO regularly provide the protocols, guidance, training, and specialized services in a variety of areas of the agriculture and food sector globally. Although nuclear and radiation techniques have already extensively been used in every field of science and technology, there is still a direct need to study further expansion, especially in agriculture and the food sector. A deeper study is needed to understand the basic irradiation processes and irradiation effects on food components to assure customers about the food safety after irradiation. Irradiation can produce secondary products from packaging that could migrate into food, can affect odor, taste, and safety of the food. Therefore, the effects of radiation on food-packaging materials (mostly polymers) and other possible negative results must also be considered for the safety of irradiated foods. However, some unsolved questions and some gaps remain, and need to be resolved for sustainable agricultural production.

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Role of Pre-breeding in Broadening the Genetic Base of Linseed (*Linum usitatissimum* L.)



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Abstract

Linseed (*Linum usitatissimum* L.), also known as flax, is an important oilseed and fiber crop valued for its high content of omega-3 fatty acids, particularly alpha-linolenic acid, as well as its industrial and nutritional applications. Despite its significance, the crop suffers from a narrow genetic base due to intensive selection and domestication, limiting progress in breeding for yield, stress tolerance, and disease resistance. Pre-breeding serves as a crucial bridge between genetic resources and cultivar development by facilitating the identification and introgression of novel alleles from diverse germplasm, including landraces and wild relatives. This article highlights the importance, methodologies, achievements, and future prospects of pre-breeding in linseed improvement.

Keywords: Linseed, Pre-breeding, Genetic resources, Germplasm, Wild relatives, landraces.

1. Introduction

Linseed is one of the oldest cultivated crops, grown for both oil and fiber. The seed oil contains approximately 40–45% oil, with more than 50% comprising alpha-linolenic acid, making it highly valuable for nutritional and industrial purposes (Green & Marshall, 1984). However, modern linseed cultivars have been developed from a limited genetic pool, resulting in reduced variability and increased vulnerability to environmental stresses and diseases (Diederichsen & Ulrich, 2009; Fu, 2011). Broadening the genetic base is therefore essential for sustainable crop improvement, and pre-breeding provides an effective strategy to achieve this goal. It provides a method to bypass cross-incompatibility and reduce linkage drag, making exotic germplasm accessible for breeding (Shivakumar *et al.*, 2022). Pre-breeding facilitates the identification and transfer of desirable traits, such as biotic and abiotic stress tolerance (drought, salinity, disease resistance) or nutritional quality from unadapted germplasm (wild relatives, landraces) into elite cultivated backgrounds. This process aims to increase genetic variability, reduce genetic vulnerability, and develop improved, usable parental lines for breeders, ultimately aiming to achieve higher-yielding cultivars with broader genetic diversity.

2. Concept and Importance of Pre-breeding

Pre-breeding serves as a critical bridge between gene bank conservation and cultivar development in linseed, enabling the effective utilization of diverse genetic resources for sustainable crop improvement. Modern linseed cultivars often suffer from a narrow genetic base, which restricts further genetic gains and increases vulnerability to biotic and abiotic stresses. Pre-breeding addresses this limitation by incorporating variability from landraces, wild relatives (*Linum spp.*), and exotic germplasm, thereby broadening the genetic base and enhancing long-term breeding progress. It also facilitates the transfer of valuable traits such as disease resistance and stress tolerance from unadapted germplasm into agronomically acceptable backgrounds, making them usable in breeding programs (Upadhyaya *et al.*, 2018). Through this process, trait-specific donor or bridge lines are developed, carrying resistance to major diseases like *Fusarium* wilt, *Alternaria* blight, and powdery mildew, along with tolerance to drought, heat, and salinity, which accelerates targeted varietal development.

Furthermore, pre-breeding plays a key role in identifying and mobilizing novel alleles governing important traits such as oil content and quality (particularly omega-3 fatty acids like alpha-linolenic acid), fiber quality, early maturity, and plant architecture, thereby expanding the scope for genetic improvement beyond existing cultivars. The continuous evolution of pathogens necessitates a constant supply of new resistance sources, and pre-breeding ensures a steady pipeline of resistance genes, contributing to the durability of resistant varieties. In addition, as linseed is predominantly cultivated under rainfed and marginal environments, pre-breeding helps

incorporate abiotic stress tolerance traits, enhancing resilience to climate variability and ensuring yield stability (Varshney et al., 2021).

Pre-bred materials also serve as valuable genomic resources for advanced breeding approaches, including QTL mapping, marker-assisted selection (MAS), and genomic selection, thereby facilitating precision breeding for complex traits (Varshney et al., 2021). By providing ready-to-use breeding lines, pre-breeding reduces the time lag between gene discovery and cultivar release, significantly improving breeding efficiency. Importantly, it strengthens the linkage between gene banks, such as the National Bureau of Plant Genetic Resources, and crop improvement programs, promoting the effective utilization of conserved linseed germplasm. Overall, pre-breeding ensures continuous genetic enhancement, prevents yield stagnation, and supports the development of high-yielding, nutritionally superior, and stress-resilient linseed varieties suited to future agricultural challenges.

3. Genetic Resources for Linseed Pre-breeding

- Landrace: - Landraces are valuable reservoirs of genetic variability and local adaptation. They often possess tolerance to environmental stresses and unique quality traits (Casa *et al.*, 2012).
- Exotic Germplasm: - Introductions from different geographical regions provide novel alleles that can be exploited for yield and adaptation (Diederichsen & Ulrich, 2009).
- Wild Relatives: - Wild species such as *Linum bienne*, *L. angustif*, and *L. grandiflo* serve as important sources of resistance to diseases and environmental stresses (Fu, 2011).
- Germplasm Collections: - Gene banks such as the National Bureau of Plant Genetic Resources (NBPGR), India, and international repositories maintain extensive linseed collections that are crucial for pre-breeding programs (Upadhyaya *et al.*, 2011).

4. Pre-breeding Approaches in Linseed

- Germplasm Characterization and Evaluation: - Comprehensive phenotypic and genotypic characterization facilitates the identification of desirable traits for introgression (Casa *et al.*, 2012).
- Hybridization and Introgression: - Crossing cultivated varieties with diverse germplasm followed by backcrossing enables the transfer of beneficial genes while maintaining agronomic performance (Hausmann *et al.*, 2004).
- Interspecific hybridization: - Interspecific hybridization with wild relatives expands the genetic base, although it may require techniques such as embryo rescue to overcome crossability barriers (Fu, 2011).
- Induced mutations: - Induced mutations using physical or chemical mutagens generate novel variability that can be incorporated into breeding programs (Shivakumar *et al.*, 2022).
- Marker-Assisted Selection (MAS): - Molecular markers linked to desirable traits enhance the efficiency of selection and reduce linkage drag (Varshney *et al.*, 2021).

6. Achievements of Pre-breeding in Linseed

Pre-breeding efforts in linseed have resulted in several significant achievements that support sustainable crop improvement and varietal development. These efforts have led to the identification of valuable genetic sources resistant to major diseases such as wilt, rust, and *Alternaria* blight, thereby enhancing the scope for developing durable resistant cultivars. In addition, pre-breeding has facilitated the development of lines tolerant to important abiotic stresses including drought and salinity, which is essential for maintaining productivity under changing climatic conditions. Considerable progress has also been made in improving seed quality traits, particularly increasing alpha-linolenic acid and lignan content, which enhance the nutritional and industrial value of linseed. Furthermore, pre-breeding programmes have contributed to the development of high-yielding and widely adaptable breeding lines with improved agronomic performance. These initiatives have also enabled the creation of dual-purpose genotypes suitable for both oil and fiber production, broadening the utility and commercial potential of linseed cultivars.

7. Challenges in Linseed Pre-breeding

Linseed pre-breeding faces several important challenges that limit the efficient utilization of genetic resources in crop improvement programme. Crossability barriers between cultivated linseed and its wild relatives restrict the transfer of useful genes for stress resistance and quality traits. In many cases, introgression of desirable genes is accompanied by linkage drag, leading to the transfer of undesirable traits along with target characteristics. The

comparatively limited availability of genomic resources and molecular tools in linseed, as compared to major cereal and oilseed crops, further constrains precision breeding efforts. In addition, long breeding cycles required for stabilization and selection delay the development of improved cultivars. Despite the availability of extensive germplasm collections, a large proportion remains underutilized due to inadequate characterization and evaluation, thereby limiting their effective use in pre-breeding programme.

8. Conclusion

Pre-breeding plays a pivotal role in broadening the genetic base of linseed and ensuring sustainable crop improvement. By harnessing the untapped potential of landraces, exotic germplasm, and wild relatives, pre-breeding facilitates the development of superior cultivars with enhanced yield, quality, and resilience to biotic and abiotic stresses. The integration of conventional breeding with modern genomic tools will further strengthen linseed improvement programs and contribute to global food and nutritional security.

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Dairy Cooperative Societies: Strengthening Rural Economy and Empowering Farmers



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Abstract

Dairy cooperative societies have emerged as an important instrument for improving the socio-economic condition of rural households in India. These societies help milk producers collectively organise milk collection, processing, and marketing activities while ensuring fair prices and reducing the role of middlemen. Dairy cooperatives contribute significantly to employment generation, women's empowerment, nutritional security, and rural development. The success of the cooperative movement, particularly through the White Revolution, has transformed India into the world's largest milk producer. This article discusses the importance, structure, functions, services, challenges, and prospects of dairy cooperative societies in India.

Keywords: Dairy cooperatives, milk production, rural development, women empowerment, White Revolution, dairy farming

Introduction

Dairy cooperative societies have played an important role in transforming the rural economy and strengthening the livelihood security of dairy farmers in India. These societies are formed when milk producers collectively organise activities related to milk collection, processing, transportation, and marketing. The cooperative approach helps farmers receive fair prices for their milk while reducing the exploitation caused by middlemen and private traders (NDDB, 2023). In addition, dairy cooperatives contribute to employment generation, poverty reduction, nutritional security, and rural development.

The success of the dairy cooperative movement in India is closely associated with the White Revolution led by Dr. Verghese Kurien, who is widely known as the "Father of the White Revolution" (Kurien, 2005). Through cooperative efforts and scientific dairy development programmes, India emerged as the world's largest milk producer. Dairy cooperatives have significantly improved the economic condition of rural households and strengthened the participation of small and marginal farmers in the dairy sector (GOI, 2024).

What is a Dairy Cooperative Society?

A dairy cooperative society is a farmer-owned and farmer-managed organization established for the collective procurement, processing, and marketing of milk and milk products. Farmers become members of the cooperative by contributing a small share of capital and supplying milk regularly. The society ensures milk quality testing, storage, transportation, and market linkage for its members (NDDB, 2023). The profits generated through cooperative activities are distributed among members, thereby promoting collective economic welfare and social development. Studies conducted on dairy cooperative societies in Kerala reported that cooperative participation

improves economic opportunities and strengthens farmers' access to institutional support services (Kujur & Bashir, 2024).

Objectives of Dairy Cooperative Societies

The major objective of dairy cooperative societies is to improve the socio-economic condition of dairy farmers through organised milk marketing and scientific dairy development programmes (GOI, 2024).

To Provide Fair and Stable Prices

Dairy cooperative societies ensure that milk producers receive fair and stable prices for their milk. Unlike private traders who often exploit farmers by offering low prices, cooperatives establish transparent pricing systems and provide timely payments to members (NDDB, 2023).

To Eliminate the Role of Middlemen

Before the establishment of dairy cooperatives, farmers depended heavily on local milk vendors and middlemen for marketing milk. Dairy cooperatives directly procure milk from farmers, reducing unnecessary intermediaries and increasing the farmers' share in consumer prices (Kurien, 2005).

To Improve Milk Production and Quality

Cooperative societies encourage scientific dairy farming practices such as balanced feeding, vaccination, artificial insemination, and breed improvement programmes. These interventions help improve milk productivity and maintain milk quality standards (GOI, 2024).

To Provide Veterinary and Extension Services

Many dairy cooperatives provide veterinary health services, disease control programmes, farmer training, and extension support. These services improve animal health, reduce mortality, and increase dairy productivity (NDDB, 2023).

To Strengthen Rural Employment

The dairy cooperative sector creates employment opportunities in milk collection, transportation, processing, packaging, and marketing. Rural women and youth especially benefit from these employment opportunities (Kujur et al., 2026).

To Ensure Quality Milk for Consumers

Dairy cooperatives maintain hygienic milk handling and quality testing systems to provide safe and nutritious milk products to consumers (GOI, 2024).

Importance of Dairy Cooperative Societies

Dairy cooperative societies are considered an important component of rural development and agricultural progress in India (NDDB, 2023).

1. Economic Support to Farmers

Dairy cooperatives provide a regular and dependable source of income to farming households. Since milk is sold daily, farmers receive continuous cash flow, which helps them manage household expenses, agricultural investments, and educational needs (GOI, 2024).

2. Employment Generation

The dairy sector generates employment opportunities in milk procurement, transportation, processing, packaging, and retail marketing. Both skilled and unskilled workers benefit from dairy-related activities (Kujur et al., 2026).

3. Women Empowerment

Women play a major role in dairy management activities such as feeding, milking, cleaning, and animal care. Participation in dairy cooperatives improves women's financial independence, decision-making ability, and social status within the family and community (Nitu et al., 2024).

4. Improvement in Milk Production

Through scientific feeding practices, breed improvement programmes, and veterinary support, dairy cooperatives help farmers increase milk yield and improve animal productivity (GOI, 2024).

5. Rural Development

Dairy cooperatives contribute to the development of rural infrastructure, including roads, milk collection centres, chilling plants, veterinary clinics, and training centres. Such infrastructure improves the overall standard of living in rural areas (NDDB, 2023).

6. Nutritional Security

Milk and dairy products are rich sources of protein, calcium, vitamins, and minerals. Dairy cooperatives help ensure regular availability of quality milk products, thereby contributing to nutritional security (GOI, 2024).

Structure of Dairy Cooperative System in India

The dairy cooperative system in India generally follows a three-tier organisational structure (NDDB, 2023).

Village Level Cooperative Society

At the village level, milk producers form cooperative societies that collect milk from members and maintain procurement records.

District Milk Union

District milk unions collect milk from village societies, process milk, and provide technical and veterinary support services.

State Federation

State federations are responsible for branding, marketing, distribution, and coordination of dairy cooperative activities at the state level.

This three-tier system ensures efficient milk procurement, processing, and marketing operations throughout the cooperative network (Kurien, 2005).

Success Story of Dairy Cooperatives in India

Anand Milk Union Limited (AMUL) in Gujarat is considered one of the most successful examples of a dairy cooperative in India. AMUL played a major role in the White Revolution and demonstrated how cooperative efforts can improve the livelihood of rural dairy farmers (Kurien, 2005).

The AMUL model helped farmers access better market opportunities, scientific dairy technologies, and stable income sources. It also became an inspiration for cooperative dairy development across the country (NDDB, 2023).

Services Provided by Dairy Cooperative Societies

Dairy cooperative societies provide several services that support dairy farmers and improve milk production, animal health, and profitability (GOI, 2024).

1. Milk Collection and Marketing

Dairy cooperatives collect milk directly from farmers through village collection centres. Milk quality and fat content are tested before procurement. Cooperatives also arrange transportation, processing, packaging, and marketing of milk products, ensuring fair prices and timely payments to farmers (NDDB, 2023).

2. Veterinary Health Care Services

Veterinary services such as vaccination, deworming, disease treatment, and regular health check-ups are provided to improve animal health and reduce mortality (GOI, 2024).

3. Artificial Insemination Facilities

Artificial insemination services are provided to improve the genetic potential of dairy animals. Access to semen from high-yielding breeds improves milk production and reproductive efficiency (NDDB, 2023).

4. Supply of Cattle Feed and Fodder Seeds

Cooperatives supply quality cattle feed, mineral mixtures, fodder seeds, and silage materials at reasonable prices to ensure balanced nutrition for dairy animals (GOI, 2024).

5. Training and Capacity Building Programmes

Training programmes and awareness campaigns educate farmers about scientific dairy management, clean milk production, fodder cultivation, and disease control practices. Such programmes improve farmers' knowledge and technical skills (Kujur & Bashir, 2024).

6. Credit and Financial Assistance

Many dairy cooperative societies facilitate loans and financial assistance for purchasing dairy animals, constructing sheds, and expanding dairy enterprises (GOI, 2024).

7. Insurance Support for Dairy Animals

Livestock insurance schemes protect farmers against economic losses caused by animal diseases, accidents, or natural calamities (NDDB, 2023).

Challenges Faced by Dairy Cooperative Societies

1. Lack of Adequate Infrastructure

Many rural dairy cooperatives lack proper infrastructure such as chilling plants, storage facilities, milk testing laboratories, and veterinary clinics. This affects milk quality and operational efficiency (GOI, 2024).

2. Poor Transportation and Cold Chain Facilities

Inadequate transportation and weak cold chain systems often lead to milk spoilage and economic losses during transportation from villages to processing centres (NDDB, 2023).

3. Rising Feed and Fodder Costs

Rising costs of cattle feed, fodder, and mineral supplements have increased dairy production costs and reduced profit margins for farmers (GOI, 2024).

4. Disease Outbreaks Among Dairy Animals

Diseases such as Foot and Mouth Disease (FMD), mastitis, and lumpy skin disease reduce milk production and increase economic losses for dairy farmers (NDDB, 2023).

5. Low Awareness About Clean Milk Production

Many dairy farmers still lack awareness regarding hygienic milking practices, proper milk storage, and sanitation measures, which affects milk quality (GOI, 2024).

6. Competition from Private Dairy Companies

Private dairy companies often attract farmers by offering competitive prices and faster payment systems, thereby creating strong competition for dairy cooperatives (Kujur et al., 2026).

7. Limited Participation of Small and Marginal Farmers

Small and marginal farmers in some regions face difficulties in accessing cooperative services because of poor infrastructure, lack of awareness, and social barriers (Kujur & Bashir, 2024).

Proper policy support, technological advancement, and farmer participation are essential for strengthening dairy cooperatives and overcoming these challenges (NDDB, 2023).

Government Support for Dairy Cooperatives

The Government of India has implemented several schemes and programmes to strengthen dairy cooperative societies and improve milk production (GOI, 2024).

1. National Dairy Plan (NDP)

The National Dairy Plan focuses on increasing milk productivity through scientific breeding, balanced feeding, and strengthening milk procurement systems.

2. Rashtriya Gokul Mission (RGM)

The Rashtriya Gokul Mission promotes conservation and genetic improvement of indigenous cattle breeds through selective breeding and artificial insemination programmes.

3. National Programme for Dairy Development (NPDD)

The NPDD supports dairy infrastructure development including milk collection centres, chilling plants, and milk testing laboratories (NDDB, 2023).

4. Dairy Processing and Infrastructure Development Fund (DIDF)

The DIDF provides financial assistance for modernization of dairy processing facilities, installation of bulk milk coolers, and value-addition units (GOI, 2024).

Future Prospects of Dairy Cooperatives

The demand for milk and dairy products is continuously increasing because of population growth, urbanisation, and changing food habits (GOI, 2024). Dairy cooperatives have strong potential for promoting value-added dairy products such as cheese, paneer, yoghurt, butter, and ice cream.

Digital technologies, e-marketing systems, mobile-based payment methods, and milk quality testing equipment can further improve the efficiency and profitability of dairy cooperatives (Kujur et al., 2026).

Conclusion

Dairy cooperative societies are important institutions for promoting rural development, employment generation, women empowerment, and livelihood security in India. They provide fair market opportunities, technical support, and financial benefits to dairy farmers while strengthening the rural economy (NDDB, 2023). With scientific

dairy management practices, government support, and active participation of farmers, dairy cooperative societies can continue to contribute significantly to sustainable agricultural development and socio-economic progress (Government of India, 2024; Kujur et al., 2026).

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Empowering Rural India through Sheep and Goat Farming



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Introduction

Small ruminants such as sheep and goats play an important role in the socio-economic and cultural livelihood of rural India. They provide employment and income to small, marginal, and landless farmers because of their low initial investment, easy management, and high feed conversion efficiency. According to the 20th Livestock Census (2019), goats constitute 27.74% and sheep 13.83% of the total livestock population in India. These animals are highly adaptable to harsh climates, poor nutrition, water scarcity, and long migratory conditions, making them suitable for arid and semi-arid regions.

Production Statistics

India possesses around 223.2 million small ruminants, including 148.9 million goats and 74.3 million sheep. Between 2012 and 2019, goat and sheep populations increased by 10.13% and 14.13%, respectively. Small ruminants contribute significantly through the production of milk, meat, wool, skin, and manure. India annually produces about 5.4 million tonnes of goat milk, 226.1 thousand tonnes of sheep milk, 553.3 thousand tonnes of chevon, and 276.3 thousand tonnes of mutton. The sector contributes nearly 12% to the gross value added from animal husbandry.

Small Ruminant Rearing Systems

Small ruminants in India are reared under different systems depending on resources and management practices:

- **Nomadic/Pastoral System:** Animals move continuously in search of feed and water.
- **Semi-nomadic/Transhumant System:** Seasonal migration with partial settlement and crop cultivation.
- **Sedentary Pastoral System:** Animals are reared near permanent settlements.
- **Ranching System:** Large-scale extensive grazing system.
- **Mixed Farming System:** Combination of crop production and livestock rearing, considered more sustainable.
- **Industrial/Intensive System:** Stall-fed commercial farming mainly for meat production and entrepreneurship.

Due to shrinking grazing lands and climate change, mixed and semi-intensive systems are becoming more important.

Breeds and Breeding

India has rich genetic diversity with 34 recognized goat breeds and 44 sheep breeds. Important goat breeds include Black Bengal, Barbari, Jamunapari, Sirohi, Osmanabadi, and Jakhrana, while important sheep breeds include Nellore, Deccani, Mecheri, Marwari, and Malpura. Heavy breeds are preferred for meat production, whereas prolific breeds are useful for rapid flock multiplication through twin and triplet births.

Marketing and Commercialization

Meat Production

Small ruminants are mainly reared for meat, but marketing systems remain largely unorganized and unhygienic. Development of modern slaughterhouses, cold storage, meat processing units, and value addition facilities is necessary for improving profitability and meat quality.

Milk Production

Goat and sheep milk are highly nutritious and possess medicinal and nutraceutical value. Goat milk is rich in minerals, vitamins, and easily digestible fats, while sheep milk contains higher fat and protein levels suitable for cheese and yoghurt production. These qualities create opportunities for commercialization of dairy sheep and goat farming.

Feeding Modules for Commercial Farming

Different feeding systems are practiced depending on resource availability:

1. **Intensive System:** Stall feeding with milk replacers, creep feed, and finisher diets for faster growth and early marketing.
2. **Semi-intensive System:** Limited grazing combined with stall feeding for improved meat quality.
3. **Semi-extensive System:** Grazing with supplementary feeding, suitable for progressive farmers.
4. **Extensive System:** Low-input grazing-based system followed by landless and migratory farmers.

Commercial farming focuses on efficient feeding during pre-weaning, post-weaning, gestation, and lactation stages to improve growth and profitability.

Challenges in Small Ruminant Production

Major constraints affecting productivity include:

- Shortage of feed and fodder
- Shrinking grazing lands
- Poor infrastructure and financial support
- Lack of organized markets
- Limited availability of superior breeding stock
- Disease and parasite problems
- High kid/lamb mortality
- Climate change impacts
- Low adoption of advanced reproductive technologies
- Declining interest among younger generations

Future Development Strategies

Development of the small ruminant sector requires:

- Improvement and conservation of indigenous breeds
- Better healthcare and vaccination programs
- Scientific feeding and intensive rearing systems
- Adoption of reproductive technologies
- Reduction of kid/lamb mortality
- Promotion of organic meat production
- Digital marketing and traceability systems
- Improved slaughterhouse and animal welfare standards
- Encouraging youth and women participation in small ruminant farming

Conclusion

Small ruminants are highly valuable for rural livelihood, nutritional security, and economic sustainability in India. Their adaptability, low investment requirement, and increasing demand for meat and milk make them suitable for commercialization and entrepreneurship. Scientific breeding, feeding, healthcare, and marketing strategies can greatly enhance productivity, profitability, and sustainability of the small ruminant sector in India.

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SMART FARMING WITH PHOSPHORUS: IMPROVING PULSES YIELD AND SOIL FERTILITY



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Introduction

Pulses are indispensable to Indian agriculture, serving as a primary source of dietary protein for millions while contributing significantly to soil health and sustainability. Major pulse crops such as chickpea, pigeonpea, black gram, and green gram are cultivated across diverse agro-climatic zones. In addition to their nutritional importance, pulses improve soil fertility through biological nitrogen fixation in association with symbiotic bacteria. Despite their importance, pulse productivity in India remains below potential levels. One of the major constraints is poor nutrient management, particularly phosphorus deficiency. Phosphorus (P) is a critical macronutrient that plays a vital role in plant growth, root development, nodulation, energy transfer, and reproductive development. Many Indian soils, especially in rainfed regions, are deficient in available phosphorus due to fixation and low organic matter content. Smart farming approaches that integrate inorganic fertilizers, organic manures, biofertilizers, foliar nutrition, liquid fertilizers, and nano technologies can significantly improve phosphorus-use efficiency, enhance pulse yields, and sustain soil fertility.

Area and Production of Pulses in India and Tamil Nadu

India

India is the largest producer and consumer of pulses globally.

- **Area:** ~29–30 million hectares
- **Production:** ~25–27 million tonnes
- **Productivity:** ~850–950 kg/ha

Major pulse-growing states include Madhya Pradesh, Maharashtra, Rajasthan, Uttar Pradesh, Karnataka, and Andhra Pradesh.

Tamil Nadu

In Tamil Nadu, pulses are cultivated under rainfed, irrigated, and rice-fallow systems.

- **Area:** ~8–9 lakh hectares
- **Production:** ~4–5 lakh tonnes
- **Major crops:** Black gram, green gram, red gram, cowpea, horse gram

Soils in Tamil Nadu often show low to medium phosphorus availability, particularly in red and lateritic soils, necessitating efficient phosphorus management.

Functions of Phosphorus in Pulses

Phosphorus is known as the “energy nutrient” due to its role in ATP formation.

Key Functions

- Promotes strong **root development**
- Enhances **nodulation and nitrogen fixation**
- Facilitates **energy transfer** (ATP)
- Improves **flowering and pod formation**
- Supports **seed development and grain filling**
- Accelerates **crop maturity**
- Enhances **yield and quality**

Deficiency Symptoms

- Stunted growth
- Dark green or purplish leaves
- Poor nodulation
- Delayed flowering
- Reduced yield



Phosphorus

Deficiency Symptoms :

No clearly defined symptoms. Plants small and stunted, leaves dark green; no obvious leaf symptoms.

Correction Measure:

Foliar spray of DAP 2% at fortnightly interval.

Recommended Dose of Phosphorus for Pulse Crops

Balanced phosphorus application is essential for achieving optimum yields.

General Recommendation

- **40–60 kg P₂O₅/ha**

Crop-wise Recommendation

Crop	Recommended Dose (kg P ₂ O ₅ /ha)
Chickpea	40–60
Pigeonpea	40–50
Black gram	25–40
Green gram	25–40
Cowpea	30–40
Horse gram	20–30
Lentil	30–40

Tamil Nadu Recommendations (Generalized)

- Black gram / Green gram: **25 kg P₂O₅/ha**
- Red gram: **40 kg P₂O₅/ha**
- Cowpea: **30–40 kg P₂O₅/ha**

Soil test-based application is always recommended for precise nutrient management.

Types of Phosphorus Fertilizers

A. Inorganic Fertilizers

- Single Super Phosphate (SSP)
- Diammonium Phosphate (DAP)
- Monoammonium Phosphate (MAP)
- Rock Phosphate
- NPK Complex fertilizers

B. Organic Sources

- Farmyard manure (FYM)
- Compost
- Vermicompost
- Poultry manure
- Green manure

Advantages:

- Improve soil structure
- Enhance microbial activity

- Increase nutrient availability

Methods of Phosphorus Application

1. Basal Application

Applied at sowing for early growth.

2. Band Placement

Placed near root zone to reduce fixation.

3. Seed Treatment

Using biofertilizers improves nutrient uptake.

4. Fertigation

Application through irrigation systems.

Foliar Application of Phosphorus

Recommended Sprays

- 2% DAP solution
- 1% 19:19:19 NPK

Stages

- Flowering
- Pod formation

Benefits

- Quick correction of deficiency
- Improved pod set and yield

Liquid Phosphorus Fertilizers

- Liquid DAP
- Polyphosphate solutions
- Phosphoric acid

Advantages:

- Rapid absorption
- Uniform distribution
- Suitable for precision agriculture

Liquid phosphorus fertilizers are widely used in pulse crops such as chickpea, pigeonpea, blackgram, greengram, lentil, and soybean to promote strong root development, better nodulation, early flowering, and higher pod formation. Common liquid phosphorus fertilizers include phosphoric acid (H_3PO_4), polyphosphate solutions, and liquid formulations containing phosphorus-solubilizing microorganisms. These fertilizers are quickly available to plants and are especially useful in soils where phosphorus fixation is high. Foliar application helps correct phosphorus deficiency symptoms like stunted growth, dark green or purplish leaves, delayed flowering, and poor yield. In pulses, a recommended dose for foliar spray is generally 1–2% liquid phosphorus solution (10–20 ml per litre of water) sprayed during vegetative and pre-flowering stages. For soil application through fertigation, about 5–10 litres per acre may be used depending on soil fertility and crop requirement. Proper application improves nutrient uptake, enhances root growth and nodulation, and ultimately increases grain yield and quality in pulse crops.

Nano Phosphorus Fertilizers

Nano fertilizers are advanced nutrient carriers.

Benefits

- High nutrient-use efficiency
- Reduced application rates
- Controlled nutrient release
- Enhanced crop productivity

Nano phosphorus fertilizers are advanced nutrient formulations containing phosphorus particles in nano size, which improve nutrient use efficiency and increase phosphorus availability to pulse crops such as greengram,

blackgram, chickpea, pigeonpea, lentil, and soybean. Due to their extremely small particle size and large surface area, nano phosphorus fertilizers are absorbed quickly by plants and help in better root growth, vigorous nodulation, early flowering, improved pod setting, and higher seed yield. They also reduce phosphorus fixation in soil and minimize nutrient losses compared to conventional phosphorus fertilizers. Nano phosphorus is mainly applied as a foliar spray and is especially useful in phosphorus-deficient soils. In pulse crops, the recommended dose is generally 2–4 ml per litre of water for foliar application, sprayed twice during active vegetative growth and pre-flowering stages. Some formulations may also be applied at 250–500 ml per acre depending on the manufacturer's recommendation. Regular use of nano phosphorus fertilizers enhances nutrient uptake, improves crop growth and productivity, and supports sustainable and efficient fertilizer management in pulses.

Biofertilizers and Their Functions in Pulse Production

Biofertilizers are eco-friendly inputs containing beneficial microorganisms that enhance nutrient availability and soil fertility.

Major Biofertilizers Used in Pulses

1. *Rhizobium*

- Forms symbiotic association with pulse roots
- Fixes atmospheric nitrogen into usable form
- Improves plant growth and yield

2. *Phosphobacteria (Phosphate Solubilizing Bacteria – PSB)*

- Convert insoluble phosphorus into available forms
- Increase phosphorus uptake efficiency
- Reduce chemical fertilizer requirement

3. *Arbuscular Mycorrhizal Fungi (AMF)*

- Extend root surface area through hyphae
- Improve phosphorus and micronutrient absorption
- Enhance drought tolerance

4. *Plant Growth-Promoting Rhizobacteria (PGPR)*

- Produce growth hormones
- Improve nutrient uptake
- Protect plants from pathogens

Biofertilizers are living microorganisms that improve soil fertility and enhance nutrient availability to pulse crops such as chickpea, pigeonpea, greengram, blackgram, lentil, and soybean. Important biofertilizers used in pulse production include *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria (PSB), and plant growth-promoting rhizobacteria (PGPR). *Rhizobium* forms nodules on pulse roots and fixes atmospheric nitrogen, supplying a major portion of the crop's nitrogen requirement. PSB helps convert insoluble soil phosphorus into available forms, while PGPR improves root growth, nutrient uptake, and disease resistance. The use of biofertilizers increases nodulation, enhances root development, improves flowering and pod formation, and ultimately increases yield while reducing the need for chemical fertilizers. In pulse crops, seed treatment with *Rhizobium* and PSB is commonly recommended at 25–30 g or 25–30 ml per kg of seed before sowing. For soil application, about 2–5 kg biofertilizer culture per acre mixed with farmyard manure or compost can be applied. Biofertilizers are eco-friendly, cost-effective, and play an important role in sustainable pulse production and soil health management.

Functions of Biofertilizers

- Enhance **nutrient availability** (N, P, micronutrients)
- Improve **root growth and development**
- Increase **nodulation and nitrogen fixation**
- Promote **soil microbial activity**
- Improve **soil structure and fertility**
- Reduce dependency on chemical fertilizers

- Support **sustainable agriculture**

Role of Phosphorus in Soil Fertility Improvement

- Enhances root biomass and soil organic matter
- Improves microbial activity and nutrient cycling
- Supports biological nitrogen fixation
- Improves soil structure and water retention
- Increases long-term soil productivity

Integrated Phosphorus Management (IPM)

Smart farming involves integrating multiple nutrient sources:

Components

- Soil testing
- Balanced fertilizer use
- Organic manures
- Biofertilizers
- Nano fertilizers
- Foliar nutrition

Benefits

- Higher nutrient-use efficiency
- Reduced cost of cultivation
- Improved soil health
- Increased crop productivity
- Environmental sustainability

Conclusion

Phosphorus plays a pivotal role in pulse production and soil fertility improvement. Its involvement in root development, nodulation, energy transfer, and reproductive growth makes it indispensable for achieving higher yields. In India and Tamil Nadu, phosphorus deficiency is a major constraint limiting pulse productivity. Adopting smart farming practices that integrate inorganic fertilizers, organic sources, biofertilizers, foliar nutrition, and modern technologies such as nano fertilizers can significantly improve phosphorus-use efficiency and crop performance. Biofertilizers, in particular, offer sustainable and eco-friendly solutions by enhancing nutrient availability and soil health. Future strategies should focus on soil test-based nutrient management, precision agriculture, and farmer awareness programs to ensure sustainable pulse production and long-term soil fertility.

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Supercharging Fish Farms: How "Biotics" Are Turbocharging Growth and Wellness



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Introduction

Imagine fish farms where salmon plump up 30% faster, disease outbreaks plummet, and antibiotics become relics of the past. This isn't sci-fi—it's the biotech revolution sweeping aquaculture, powered by "biotics": probiotics, prebiotics, and synbiotics tailored for underwater life. These microbial marvels are flipping the script on fish production, delivering healthier stocks, bigger yields, and a greener footprint.

The Gut Check That Changed Everything

At the heart of this boom is the fish microbiome—the trillions of bacteria living in their guts, much like ours. Stress from crowded pens or poor water quality throws this ecosystem off-kilter, stunting growth and inviting pathogens. Enter biotics: live beneficial microbes (probiotics) that crowd out the bad guys, fibers that feed the good ones (prebiotics), or combos of both (synbiotics).

Take *Lactobacillus plantarum*, a probiotic star now common in trout feed. Studies from Norway's aquaculture hubs show it boosts weight gain by enhancing nutrient absorption—fish convert feed into muscle more efficiently, slashing waste and costs. In shrimp ponds across Southeast Asia, *Bacillus subtilis* preps have cut vibriosis infections by up to 70%, proving biotics aren't just supplements; they're game-changers.

Real-World Wins: From Lab to Lagoon

Chile's salmon giant, AquaChile, rolled out synbiotic feeds in 2024, reporting 25% faster growth cycles and zero antibiotic use in trial pens. Vietnamese catfish farmers, facing rice-paddy-turned-pond challenges, swear by prebiotic-enriched algae: their yields jumped 15% while water quality improved, thanks to microbes mopping up ammonia.

Why does it work so well? Biotics fortify fish immunity by ramping up antibodies and enzymes. A 2025 trial in the *Journal of Aquatic Animal Health* found tilapia fed synbiotics had gut walls 40% thicker—natural barriers against invaders. Plus, they're sustainable: sourced from fish-safe strains, they reduce reliance on chemical feeds that pollute waterways.

Challenges and the Road Ahead

Not all smooth sailing yet. Dosage matters—overdo it, and you risk microbial imbalances. Cost remains a hurdle for smallholders, though prices are dropping as biotech firms like BioMar scale production. Regulators are catching up, with EU approvals for 20+ biotic strains last year.

Looking forward, gene-edited microbes promise even smarter biotics, targeting specific fish species or stressors like warming oceans. Pair them with AI-monitored ponds, and we're eyeing a \$50 billion aquaculture surge by 2030, per FAO projections.

The Ripple Effect

This biotic wave isn't just about fatter fish; it's reshaping global food security. With wild stocks dwindling, farmed fish supplies half our seafood. By harnessing microbial power, we're not just growing better fish—we're building resilient, eco-friendly systems for tomorrow's tables.

Beyond Sightseeing: Why Food is the Heart of Every Journey



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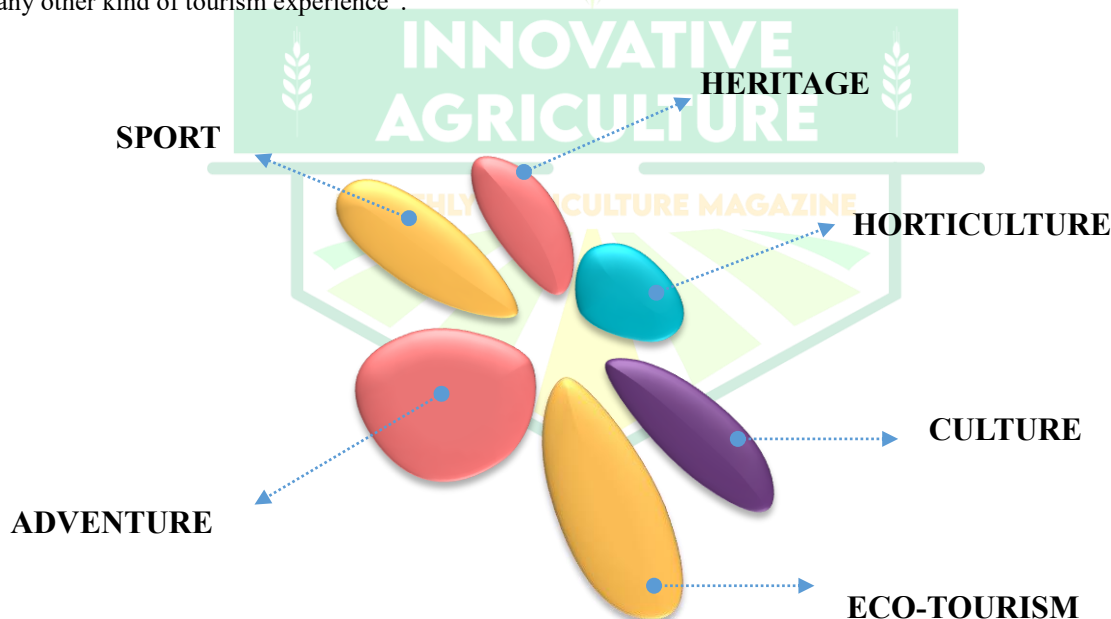
Email Author: Gangashree Ganganalli

Travel is no longer just about visiting famous landmarks or taking photographs, it is about experiencing a destination with all the senses. Among these, food plays a central role in shaping unforgettable journeys. Every dish tells a story of a place, its people, traditions, and history. From street-side delicacies to traditional feasts, food connects travellers to the cultural roots of a destination in a way that sightseeing alone cannot. As culinary tourism gains popularity, it transforms ordinary trips into rich, immersive experiences, making food the true heart of every journey.

Role of Food in Enriching every Travel Experience

Food is a big part of travel. It makes sports events more fun, connects people to history and culture, supports nature-friendly travel, and adds adventure to trips. Culinary tourism makes every journey more memorable and enjoyable!

“All travelers eat and drink. Therefore, food and drink have a greater ability to make long- lasting memories than any other kind of tourism experience”.



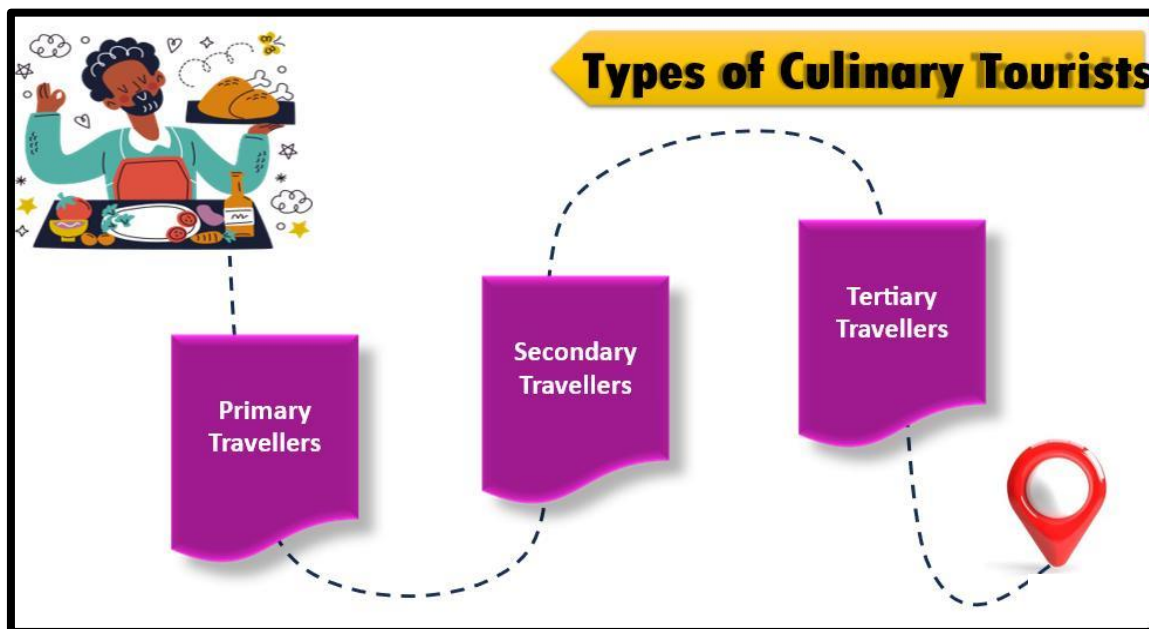
Importance of Food Tourism for Rural Farming Communities

- ✓ Boosts farmers' income: Tourists buy local food, helping farmers earn more money
- ✓ Encourages local food production: High demand for local dishes motivates farmers to grow more
- ✓ Creates jobs: It provides work in farming, food processing, and tourism services
- ✓ Promotes sustainability: It encourages organic farming and reduces food transport costs
- ✓ Preserves traditional food & culture: It keeps local recipes and food traditions alive
- ✓ Strengthens farmer-tourist links: Farm visits and food experiences create direct connections

FOOD TOURISM AS A VALUABLE DEVELOPMENTAL TOOL

When done properly, culinary tourism tells the story of the heritage, the people and the landscape of a geographic area. It reflects 'place', enriches experiences, and can be a valuable tool to boost economic, social and community development.

Types of Culinary Tourists



Primary Travelers: These people travel mainly for food. They visit places just to try special dishes, attend food festivals, or join cooking classes.

Example: Someone going to Hyderabad just to taste Hyderabad Biryani

Secondary Travelers: They enjoy food but travel for other reasons like sightseeing or culture. Food is an important part of their trip but not the main reason

Example: A tourist exploring Hyderabad who also enjoys the Hyderabad Biryani

Tertiary Travelers: Food is not their main focus while traveling. They eat what is available but don't seek out special food experience

Example: A business traveler who eats mostly at hotels and occasionally tries local food.

In today's world of travel, food has emerged as more than just a necessity, it is an experience, a cultural bridge, and a powerful tool for development. Culinary tourism not only enriches the traveler's journey but also supports rural communities, preserves traditions, and promotes sustainable practices. Whether one travels specifically for food or simply enjoys it along the way, the flavors encountered often become the most lasting memories of the trip. Ultimately, food reminds us that to truly understand a place, we must taste it.

From Farm to Feast: How Food Tourism Creates Sustainable Travel Experiences



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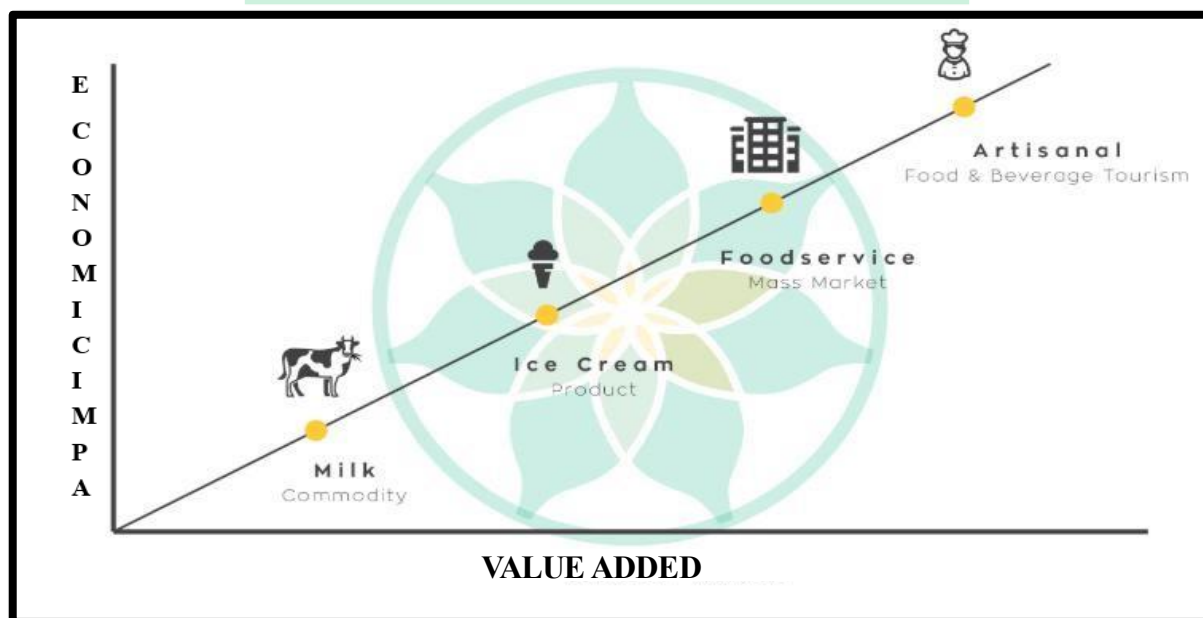
Email Author: Gangashree Ganganalli

Food tourism is transforming the way people travel by connecting agriculture, culture, and sustainability into a single experience. It goes beyond tasting dishes, offering travellers a journey from farm to table while supporting local communities and preserving traditions. By linking farmers, food producers, and tourists, food tourism creates meaningful and sustainable travel experiences that benefit both visitors and rural economies.

Sustainable Practices in Agro Food Tourism

- ✓ Establishment of community kitchens, distribution of food packets, Engaging student and private volunteers
- ✓ Establishment of de-centralised cold storage units operating of renewable energy
- ✓ The user can demonstrate on a projector or computer, or print the presentation and make it film
- ✓ Promotion of agronomically suitable crop diversification with price assurance
- ✓ Dietary supplementation with vitamins, herbs, probiotics and other therapeutic foods
- ✓ Enhancing role of digital technology within agri-food systems and digital literacy among agriculture workers

Value Chain in Food Tourism



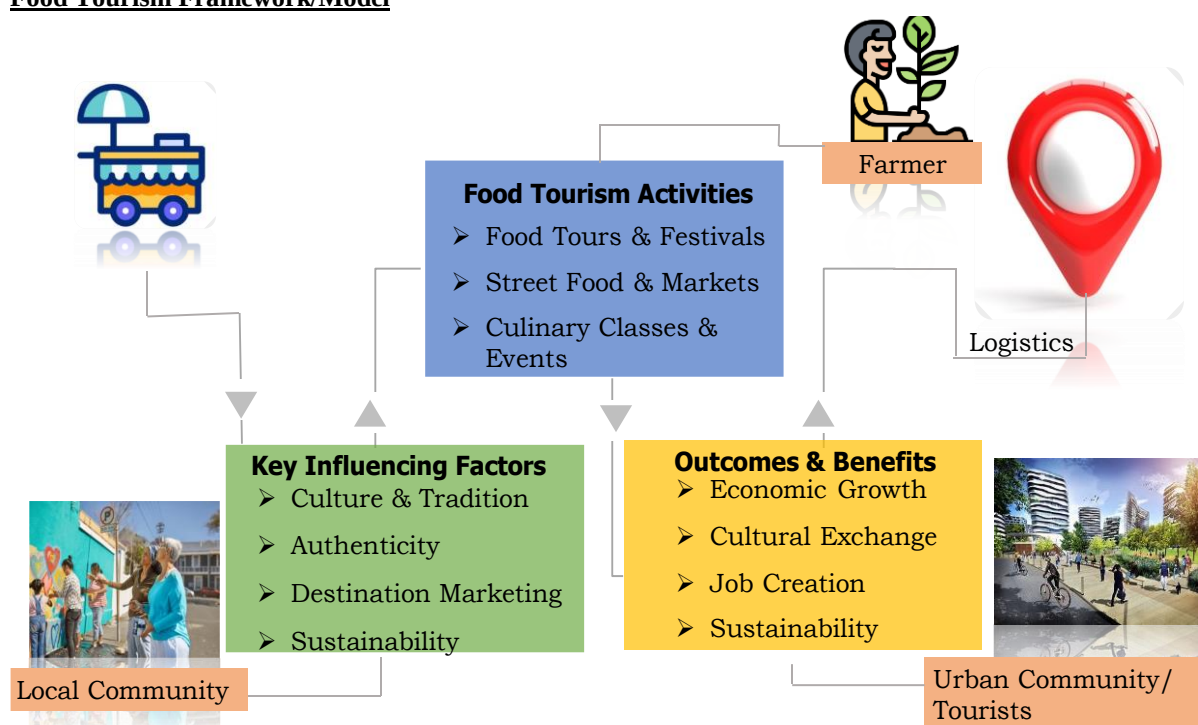
The image presents a Value Chain in Food Tourism diagram, illustrating how food products gain economic impact and value addition as they move through different stages.

1. **Milk (Commodity Stage):** At the base level, milk is a raw commodity with minimal value addition and lower economic impact.

2. **Ice Cream (Product Stage):** When milk is processed into ice cream, it gains additional value as a product, increasing its market worth.
3. **Foodservice (Mass Market Stage):** When ice cream is served in restaurants, cafes, or dessert parlors, it moves into the foodservice sector, further increasing its value and economic impact.
4. **Artisanal (Food & Beverage Tourism):** At the highest level, artisanal or specialty food experiences, such as gourmet ice cream parlors, food festivals, or unique culinary tourism activities, create the most value and economic impact.

This value chain demonstrates how basic agricultural products can evolve into high- value experiences in food tourism, benefiting local economies and attracting tourists.

Food Tourism Framework/Model



Establishing food tourism models requires a multi-faceted approach that integrates agriculture, cultural heritage, and sustainable tourism practices. By involving local communities, adopting eco-friendly methods, and leveraging digital marketing, food tourism can become a powerful tool for rural development and cultural preservation.

Logistics: connects farmer to urban communities.

This model highlights the role of food tourism in boosting local economies, preserving cultural heritage, and promoting sustainability.

Food tourism is more than a travel trend; it is a pathway to sustainable development. By adding value to local products, strengthening rural livelihoods, and promoting eco-friendly practices, it creates a win-win situation for both communities and travellers. As this approach continues to grow, it has the potential to reshape tourism into a more inclusive, culturally rich, and sustainable experience for the future.

Carbonomics: Unlocking the Power of Aquatic Ecosystems in the Fight Against Climate Change



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Abstract

This article explores the burgeoning field of Aquatic Carbonomics, which comprehensively studies the cycling, transformation, and storage of carbon in aquatic environments including oceans, rivers, lakes, and wetlands and links these biogeochemical processes to economic and policy solutions for climate change. These ecosystems function as critical carbon sinks, notably through the Biological Carbon Pump (BCP), which exports primary production to the deep ocean, and the Microbial Carbon Pump (MCP), which converts readily available dissolved organic carbon (DOC) into a durable, recalcitrant form (RDOC) that can be sequestered for millennia. The modern ocean alone accounts for approximately 50% of global photosynthesis and has absorbed an estimated 25% of anthropogenic CO₂ since the Industrial Revolution. However, the stability of the BCP is increasingly compromised by global warming and ocean acidification. The concept of Carbonomics formalizes carbon as an economic variable, tracing its roots to ecological economics and market mechanisms like carbon pricing. This integration is crucial for mitigating climate change, informing sustainable management practices for blue carbon habitats, and guiding fisheries policy to minimize disruption to oceanic carbon storage capacity. Ultimately, Carbonomics provides the necessary framework to align financial incentives with environmental protection, promoting climate resilience and sustainable global economic models.

Keywords: Carbonomics, Biological Carbon Pump (BCP), Microbial Carbon Pump (MCP), Blue Carbon, Recalcitrant Dissolved Organic Carbon (RDOC), Carbon Pricing.

Introduction

Imagine a world where our oceans, rivers, and wetlands work as silent warriors in the battle against climate change. These aquatic ecosystems are far more than just homes to vibrant marine life or scenic backdrops for coastal communities; they function as powerhouse carbon sinks, quietly capturing vast amounts of atmospheric carbon and playing an indispensable role in regulating the planet's climate feedback loops. Historically, mainstream economic models treated environmental degradation and carbon emissions as external factors, largely detached from capital markets and developmental metrics. Today, a transformative paradigm shift is underway. Falkowski et al. (2000) and Jiao et al. (2010) noted that Earth as an integrated biological and economic system requires tracking both the natural pathways of carbon and its financial implications. This intersection has given rise to Carbonomics a fascinating field that sheds light on how carbon moves through aquatic environments and how society can harness these natural systems to engineer a healthier planet, balance economic growth, and drive sustainable development.

Aquatic Carbonomics refers to the comprehensive study of carbon cycling, metabolism, transformations, and interactions within marine and freshwater environments. It investigates how carbon is biologically and biogeochemically processed encompassing carbon fixation, microbial respiration, long-term storage, and deep-ocean export. This article explores how these complex biogeochemical engines function, how human activities threaten their stability, and how Carbonomics bridges the gap between ecological preservation and global financial systems to forge a sustainable, net-zero future.

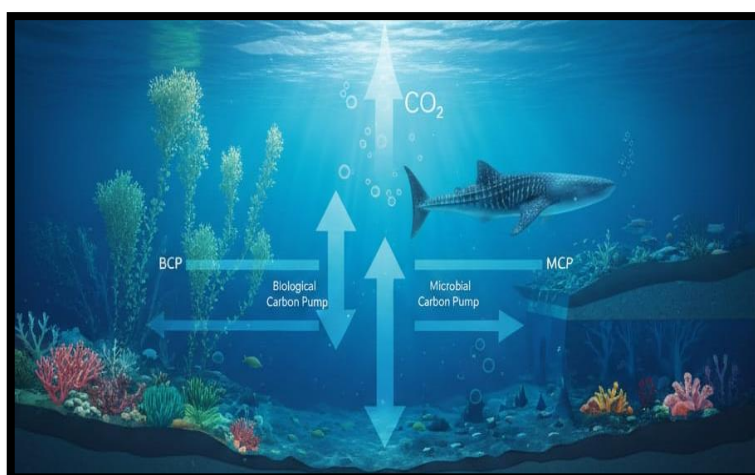


Figure 1: Integrating Biogeochemical Carbon

Biogeochemical Engines: BCP and MCP

To understand the economic valuation of aquatic carbon, one must first explore the dual engines that power oceanic carbon sequestration: the Biological Carbon Pump (BCP) and the Microbial Carbon Pump (MCP). Together, these biological mechanisms determine the efficiency with which the ocean mitigates atmospheric greenhouse gases.

Biological Carbon Pump (BCP)

The modern ocean plays a foundational role in the global carbon cycle, facilitating roughly 50% of the world's total photosynthetic activity. This primary production of organic matter fundamentally alters the atmosphere's chemistry and redox state by absorbing carbon dioxide CO_2 and releasing oxygen. The transport of this captured carbon from the sunlit surface waters (the euphotic zone) into the dark, deep ocean layers is managed by the BCP. While early oceanographic assessments generalized that the BCP moved a flat 25% of surface primary production to the depths, subsequent detailed analyses by Siegel et al, 2016 refined this estimation by classifying the transport into specific, distinct physical and biological mechanisms. Contemporary data indicates that:

- **Gravitational sinking** of organic particles (such as dead phytoplankton and fecal pellets) accounts for 10% to 15% of the carbon transfer.
- **Passive transport**, driven by large-scale ocean currents and water movement, accounts for roughly 5% of the transfer.
- **Active transport**, carried out by vertically migrating marine organisms that feed at the surface at night and descend into the deep ocean during the day, accounts for another 5%.

When carbon is successfully transported below depths of 1,000 meters, it enters a zone where deep-water residence times span between 100 and 1,000 years, effectively locking the carbon away from the atmosphere for centuries. Ultimately, a very small proportion approximately 0.3% of oceanic primary production gets buried permanently within marine sediments, eventually incorporating into rock formations where it remains for millions of years.

Microbial Carbon Pump (MCP)

According to Hansell et al. (2009) and Jiao et al. (2010) the Microbial Carbon pump focuses on the immense, unseen dissolved organic carbon (DOC) reservoir in the water column. The global ocean inventory of DOC is estimated at a staggering 662 gigatons of carbon (Gt C) a pool almost equal in magnitude to the entire atmospheric carbon dioxide reservoir, which sits at roughly 750 Gt C. Therefore, the biogeochemical behavior of DOC has profound implications for global climate regulation.

The MCP describes how marine microbes transform easily degradable, labile dissolved organic carbon into a highly complex, stable form known as Recalcitrant Dissolved Organic Carbon (RDOC). Hansell et al. (2009) formally defines RDOC as dissolved organic carbon that is fundamentally resistant to rapid microbial degradation, causing it to accumulate and persist throughout the global ocean.

- **Sequestration Timeline:** Unlike sinking particles that may be consumed or re-mineralized, RDOC remains dissolved in the water column, staying securely sequestered for 4,000 to 6,000 years.
- **Microbial Loops and Viral Shunts:** This process operates alongside other complex microbial phenomena, including the classic microbial loop and the viral shunt. The viral shunt ruptures host cells, producing dissolved organic matter (DOM) that alters local nitrogen and phosphorus balances.
- **Nutrient Recycling vs. Carbon Storage:** Microbes continuously recycle vital nutrients, boosting local primary productivity while leaving behind carbon-rich, structurally intricate DOM that cannot be easily broken down. Because the chemical structures of DOM and the metabolic diversity of marine microbes are highly complex, scientists are combining advanced microbiological genomics with geochemical techniques to map these precise pathways.

Anthropogenic Stressors and System Vulnerability

The natural efficiency of these aquatic carbon pumps is under severe threat from human-driven environmental changes. Since the dawn of the Industrial Revolution, the world's oceans have absorbed an estimated 25% of all anthropogenic CO₂ emissions. While this buffer has spared the atmosphere from even more severe warming, it has come at a steep ecological cost, resulting in widespread ocean warming and ocean acidification. The stability of the biological carbon pump is increasingly compromised by these dual stressors. Ocean acidification reduces the capacity of calcifying organisms (such as coccolithophores and shelled pteropods) to form their structural shells, altering the weight and sinking velocity of organic aggregates. Simultaneously, rising water temperatures increase stratification, limiting the upward mixing of deep-sea nutrients required by primary producers.

Nutrient availability and shifting carbon-to-nutrient ratios heavily influence coastal and freshwater systems. When agricultural run-off supplies excessive amounts of nitrogen and phosphorus, phytoplankton can grow uncontrollably, resulting in harmful algal blooms dominated by toxic cyanobacteria and dinoflagellates. As documented by Brandenburg et al. (2019) the elevated CO₂ and warmer conditions synergistically enhance the growth rates and toxicity of these harmful algae. When these massive blooms die, their subsequent microbial decomposition consumes dissolved oxygen, creating hypoxic "dead zones" that disrupt local biodiversity and cause severe ecosystem instability.

The Economic Integration: Mapping the Roots of Carbonomics

To counteract the degradation of these natural sinks, environmental managers must speak the language of modern global policy and capital markets. This is where the core doctrine of Carbonomics becomes indispensable: it formalizes carbon as a quantifiable, tradable economic variable, effectively aligning financial incentives with ecological protection.

Historical Development of Carbon Valuation

The theoretical foundations of carbonomics did not emerge overnight; its evolution can be traced across several decades of shifting economic paradigms:

Era	Key Milestones & Theoretical Shifts	Focus & Core Frameworks
1970s–1980s	Emergence of Ecological Economics. Inspired by seminal works like <i>The Limits to Growth</i> (1972).	Challenged neoclassical economic paradigms; emphasized that human economies are sub-systems embedded within a finite biosphere with strict ecological limits.
1990s	Institutionalization of Climate Markets. Facilitated by the 1992 UNFCCC and the 1997 Kyoto Protocol.	Introduced economic accountability for greenhouse gases; established early emissions trading structures.
2010s	Global Proliferation of Carbon Pricing.	Broad-scale adoption of cap-and-trade systems and carbon pricing strategies, notably within the European Union and China.
2020s–Present	Rise of "Green Growth" and Macroeconomics.	Advanced by contemporary financial theorists like Liu et al. (2022), who proposed a formalized "theory of carbon currency" to stabilize the global economy via carbon valuation.

Carbonomics applies directly to pioneering circular energy-economy models. For example, industrial frameworks are shifting from traditional carbon capture and storage (CCS) toward reactive carbon capture. As demonstrated by Bamraan et al. (2024), this process leverages integrated adsorbent-catalyst materials to convert captured CO₂ directly into valuable fuels and green chemical commodities, transforming an environmental pollutant into a functional economic resource.

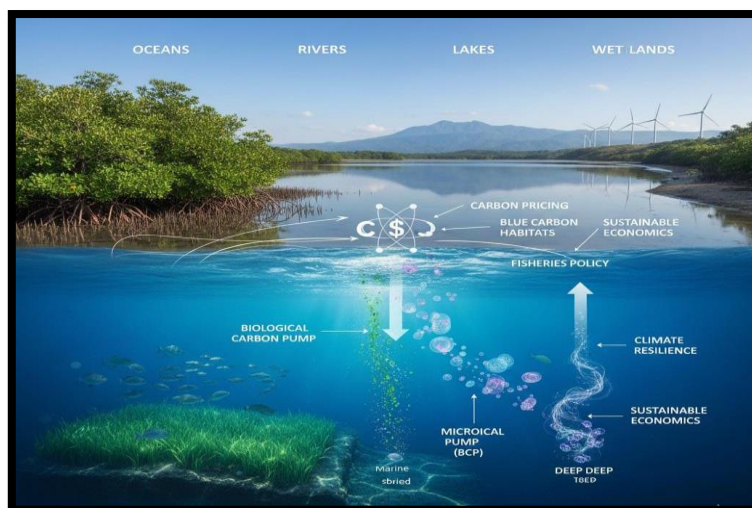


Figure 2: Conceptual Framework for Integrating Blue Carbon Processes, Aquatic Ecosystem Services, and Economic Policy for Climate Resilience

Market Based Tools and Carbon Pricing Mechanisms

At the operational level, carbonomics relies on market-based policy tools designed to internalize the external costs of climate change. By putting an explicit price on carbon, these systems alter corporate financial calculations, incentivizing industries to curb emissions and invest heavily in cleaner technologies.

Carbon Taxes

A carbon tax is a direct, government-imposed fee levied on the carbon content of fossil fuels and industrial greenhouse gas emissions. Muhammad (2022) noted that carbon taxes represent one of the most straightforward and transparent carbon pricing tools, particularly well-suited for developing nations seeking clear administrative structures. The tax increases the operational cost of carbon-intensive practices, creating an immediate commercial incentive for businesses and consumers to switch to low-carbon energy sources. Furthermore, the tax rate can be dynamically adjusted over time by policymakers to hit specific national emission targets, and the generated revenues can be re-routed to fund public renewable energy infrastructure or citizen rebates.

Cap-and-Trade Systems

Emissions trading systems (ETS) or cap-and-trade mechanisms, approach reduction from a structural volume perspective. Under this framework, a central governing authority establishes a rigid cap on the total volume of permissible emissions across targeted sectors over a given timeframe. This cap is systematically lowered year-over-year to align with long-term climate targets. The authority issues a finite number of emission allowances or permits matching the established cap, where one permit grants the right to emit a specific quantity of pollution. Companies must hold a permit for every unit of carbon they discharge into the atmosphere. This structure sparks an active market driven by supply and demand:

- **Surplus Trading:** Companies that reduce their emissions below their allocated threshold can sell their excess permits for a profit on the open market.
- **Deficit Purchasing:** Polluters that exceed their cap must purchase additional permits from cleaner firms, incurring a steep financial penalty.

According to Zou et al. (2024) the supply-demand dynamic naturally establishes an organic market price for carbon, forcing companies to find the most cost-effective internal mitigation strategies while guaranteeing that aggregate emissions stay strictly within legal bounds.

Blue Carbon Ecosystems and Sustainable Marine Policy

One of the most valuable real-world applications of Carbonomics lies in the preservation of coastal "blue carbon" habitats. Blue carbon refers specifically to the organic carbon captured and stored within vegetated coastal ecosystems, primarily mangroves, tidal marshes, and seagrass meadows. Despite their relatively small geographic footprint compared to open oceans, these coastal habitats sequester carbon at rates significantly faster than terrestrial tropical forests. The focus on blue carbon has transitioned from early conceptual mapping to active conservation, ecological restoration, and mitigating human-climate interactions. To maximize their contribution to global net-zero targets, modern Carbonomics insists on preserving ecosystem integrity and mapping the complex interactions between marine industries and natural carbon sinks (Lai et al., 2022).

Reforming Fisheries Management via Carbonomics

Commercial fishing practices directly influence the ocean's capacity to act as an active carbon sink. The commercial harvesting alters both pelagic ecosystems and benthic seabed habitats. For example, the severe overexploitation of small pelagic fish species reduces the volume of fast-sinking fecal pellets, which compromises the BCP and impairs long-term deep-ocean carbon storage (Cavan and Hill, 2021). Furthermore, industrial bottom trawling physically disturbs marine sediments, re-mineralizing ancient buried carbon back into the water column. To address this challenge, Morris et al. (2023) adapted the Marine Stewardship Council's risk-based framework to systematically evaluate the impacts of towed bottom-fishing gear on blue carbon habitats. By embedding specific carbon storage metrics directly into fisheries management, maritime authorities can design low-impact fishing zones that preserve critical seafloor reservoirs while sustaining global seafood security. Globally, innovative policy frameworks are beginning to operationalize these carbonomics principles:

- **The FishClim Model:** This climate-responsive modeling tool quantifies how commercial fishing interacts with changing climate variables. Integrating FishClim with carbonomics helps marine managers balance commercial exploitation rates with the ocean's natural carbon sequestration capacity.
- **European Green Deal Initiatives:** Under broader European Blue Economy strategies, conservation-based fishing regulations and technological innovations are being explicitly leveraged to fulfill Sustainable Development Goal 14 (Life Below Water) while safeguarding marine carbon sinks.
- **Indonesia's INTQ Strategy:** Indonesia has pioneered the implementation of Individual Non-Transferable Quotas (INTQs). This strategy fosters equitable resource distribution among traditional fishing communities while incentivizing fuel efficiency and minimizing gear-driven habitat disturbance, promoting carbon-efficient fisheries management.

Conclusion

Aquatic Carbonomics establishes an irreplaceable bridge between the complex biogeochemical pathways of our waters and the financial mechanisms of global markets. The immense capacity of the ocean's biological and microbial carbon pumps to lock away carbon for centuries underscores the fact that our waters are our greatest natural defense against runaway climate change. Yet, these systems are fragile, vulnerable to the very warming and acidification we continue to generate. By treating carbon as a core economic variable, carbonomics provides nations with the blueprint required to make pollution expensive, turn ecological conservation into a highly profitable enterprise, and transform CO₂ from a hazardous waste product into a circular resource. Whether through the enforcement of rigorous cap-and-trade systems, the restoration of blue carbon mangrove forests, or the implementation of carbon-indexed fisheries quotas, the integration of ecological metrics into economic policy represents the next great frontier in sustainability. The road to a true net-zero future requires refining our understanding of these natural aquatic processes and boldly applying Carbonomics principles to maintain long-term global economic and ecological stability.

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Zero Budget Natural Farming: Scientific Principles and Field Applications of Beejamrit and Jeevamrit



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Abstract

Natural farming is an eco-friendly and sustainable agricultural system that emphasizes working in harmony with nature while avoiding the use of synthetic fertilizers and pesticides. The concept, introduced globally by Masanobu Fukuoka and later popularized in India by Subhash Palekar as Zero Budget Natural Farming (ZBNF), has gained importance due to increasing concerns about the negative impacts of chemical-based agriculture on soil health, human health, and the environment. This review discusses the principles, major formulations, and scientific basis of natural farming practices, which have often been underexplored in earlier studies. Key components such as Beejamrit and Jeevamrit act as microbial inoculants that enhance soil fertility, microbial diversity, and plant growth. Other natural formulations, including Neemastra, Brahmastra, Agniastastra, and Dashaparni ark, provide effective pest and disease management using plant-based and animal-derived inputs. Overall, natural farming improves soil organic carbon, water-holding capacity, nutrient availability, and crop resilience while reducing input costs and promoting long-term sustainability. This review highlights natural farming as a scientifically sound, environmentally safe, and economically viable alternative to conventional agriculture.

Keywords: Natural farming, Zero Budget Natural Farming, Jeevamrit, Beejamrit, soil health, microbial activity, sustainable agriculture.

INTRODUCTION

Natural farming rests on simple ecological principles and a deep respect for the way nature works. Instead of forcing the land with synthetic fertilizers and chemical pesticides, it encourages farmers to partner with natural processes to build healthy soil, nurture beneficial organisms, and let crops grow in a balanced ecosystem. The modern movement has several well known roots: in Japan Masanobu Fukuoka set out a gentle, philosophy rich approach in his book One Straw Revolution; earlier, Mokichi Okada proposed “Nature Farming” in the 1930s; and in India Subhash Palekar popularized a similar approach under the name Zero Budget Natural Farming (ZBNF). Public awareness of the dangers of indiscriminate pesticide use grew sharply after Rachel Carson’s Silent Spring (1962), which exposed how chemical sprays can harm wildlife, water, and human health. Since then, organizations such as the United Nations and the Food and Agriculture Organization have promoted nature friendly farming to make agriculture more sustainable, protect ecosystems, and support rural livelihoods. At the farm level, natural farming relies on simple, locally available inputs like, cow dung, cow urine, plant residues and fermented preparations to feed soil life and control pests. Because these materials are produced on farm, farmers can avoid costly external inputs and reduce debt, which is why the approach is often called Zero Budget Natural Farming. Beyond economics, the method aims to produce nutritious food, restore soil health, and lower environmental risks by minimizing synthetic inputs a practical, low cost path toward resilient and regenerative agriculture.

Science and effects of natural farming:

Natural Farming stands on four practical pillars that together create a resilient, eco-friendly way to grow crops. It uses simple, farm available inputs: cow dung, cow urine, jaggery, pulse flour and uncontaminated soil each

serving a role: feeding soil microbes, supplying nutrients, protecting seeds, and improving plant stress tolerance. Healthy, microbe-rich soil supports nutrient cycling, root health and natural disease resistance.

Jeevamrit (applied to soil) and Beejamrit (for seed treatment) act as microbial inoculants and nutrient sources, boosting beneficial bacteria and fungi, protecting seeds and seedlings, and improving early crop establishment. Botanical preparations such as Neemastra, Brahmastra and Agniastra offer low-cost, locally made pest control that is gentle on beneficial insects and soil life.

By relying on these natural inputs and avoiding synthetic fertilizers and pesticides, natural farming lowers input costs, raises soil organic carbon and water-holding capacity, and builds long-term productivity and resilience for farms and farmers.

Table 1: Natural Farming pillars, their description and components

Pillar of Natural Farming	Descriptions	Components
Beejamrit	Seeds are treated, applied by coating them with the solution before sowing or as root dip before transplanting to protect against seed- and soil-borne diseases and pests.	Cow dung, Cow urine, water, lime, uncontaminated soil
Jeevamrit	Prepared as a liquid and applied to the soil through irrigation water or as foliar application to increase beneficial microorganisms and improve soil fertility.	Cow dung, cow urine, jiggery, gram flour, uncontaminated soil, water
Achhadana (Mulching)	Crop residues or plant materials are spread on the soil surface to reduce evaporation, control weeds, and protect soil moisture.	Crop residues, dry straw leaves, cover crops (legumes)
Waaphasa (Soil Aeration)	Practiced by reducing excess irrigation and maintaining proper soil moisture so that air and water are both available in 50-50 percent.	

Natural farming components:

Natural farming comprises various components including Beejamrit, Jivamrit, Achhadana and Whapasa. These components serve multiple purposes such as seed treatment, growth promotion and plant protection. Jivamrit and Ghanajivamrit are utilized as growth promoters, Beejamrit is employed for seed treatment, while Neemastra, Brahmastra, Agniastra, Dashaparni Ark, etc., are utilized for plant protection (NITI Ayog, 2021).

BEEJAMRIT

Beejamrit is a natural seed treatment solution used before sowing or transplanting to protect seeds from soil- and seed-borne diseases. It is prepared by mixing 5 kg fresh cow dung in 20 L water, adding 5 L cow urine and a lime solution (50 g), then incorporating 50 g of soil containing native microbes; the mixture is



Fig. 1: Beejamrit

stirred clockwise and anti clockwise and kept in shade for 12–24 hours. For application, 20 L of Beejamrit is used to treat 100 kg of seed—seeds are dipped or coated with the solution and shade dried before sowing, and seedlings can be root dipped before transplanting. Beejamrit functions as an anti fungal agent protecting against damping off and root rot, introduces beneficial microbes to the rhizosphere, and increases germination percentage and speed. Its benefits include low cost and eco friendliness, improved seed vigour, reduced dependency on chemical fungicides, and enhanced early crop establishment.

JEEVAMRIT

Jeevamrit is a liquid bio fertilizer that activates soil and phyllosphere microorganisms, boosts earthworm populations, and improves nutrient availability by catalyzing microbial activity; it is prepared by mixing 10 kg fresh cow dung, 10 L cow urine and 200 L water in a large container, adding 2 kg jaggery and 2 kg pulse flour as microbial food, then incorporating 1 kg uncontaminated soil for native microbes, stirring twice daily for aeration, covering and fermenting in shade for 3–5 days, filtering the fermented solution through cloth, and diluting the filtrate for use; 200 L of Jeevamrit treats one acre and may be applied through irrigation or as a foliar spray (about 10% concentration) at 7-15 day intervals. Its functions include triggering a microbial explosion (a single drop can contain millions of beneficial bacteria that mobilize nutrients), stimulating earthworm activity to aerate soil, and improving soil texture and porosity. Benefits include increased soil organic carbon, improved nutrient uptake efficiency, enhanced crop growth and yield, and restoration of soil biological activity.



Fig. 2: Jeevamrit

ACCHADANA (MULCHING)

Acchadana is the practice of covering the soil surface with organic residues, live plants, or soil mulch to protect soil and enhance its physical, chemical, and biological properties; types include soil mulch (shallow cultivation of topsoil to reduce evaporation, improve aeration and moisture retention, minimize deep ploughing, lower cultivation costs, and reduce weed emergence), straw mulch (covering soil with dried biomass, crop residues, fallen leaves or stubble to shield soil from sunlight, cold, rain and evaporation, protect seeds from birds and pests, and gradually add organic matter as it decomposes), and live mulch (growing cover crops or intercrops such as legumes and cereals between main crop rows dicots fix nitrogen while monocots supply nutrients like potash, phosphorus and sulphur thereby improving soil health and nutrient availability). Its functions include moisture retention (reducing evaporation by up to 70% and lowering irrigation needs), humus formation as mulch decomposes into the most fertile soil fraction, weed suppression by blocking sunlight, and temperature regulation that protects soil microbes and roots from extreme heat or cold.

NEEMAISTRA

Neemastra is a neem based natural pesticide used mainly to control sucking pests such as aphids, jassids, and whiteflies; neem's bitter compounds disturb insect feeding and reproduction while sparing beneficial insects. It is prepared by crushing fresh neem leaves or neem seed kernel (10 kg)

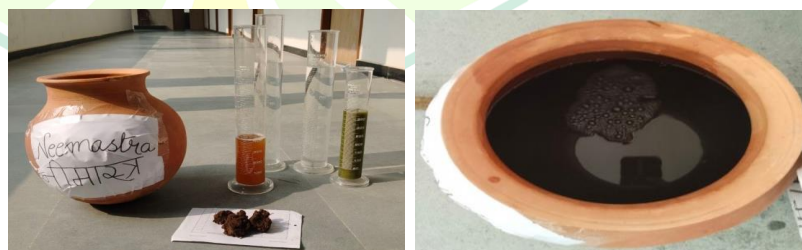


Fig. 3: Neemastra

and mixing the crushed material with 10 L cow urine, 2 kg cow dung and about 200 L water in a covered container, stirring occasionally and fermenting in shade for ~24 hours, then filtering the fermented mix through cloth and diluting the filtrate for foliar use. For application, prepare a 3–5% solution by mixing Neemastra with water, spray uniformly on crop leaves using a knapsack or hand sprayer, and repeat after 7–10 days if pests persist. Functions include controlling sucking pests and disrupting their feeding and reproduction. Benefits are eco friendly, low cost pest management using locally available materials, safety for farmers and consumers, protection of beneficial insects, improved crop health and sustainability, and maintenance of soil and environmental quality.

BRAHMASTRA

Brahmastra is a natural plant protection formulation used in natural farming, prepared from the leaves of various medicinal plants and cow urine; it acts as a broad-spectrum botanical pesticide mainly to control chewing insects and caterpillars. Ingredients include 20 L cow urine and about 2 kg each of neem, custard apple, papaya, datura (and optionally guava and pomegranate) leaves. Preparation involves crushing the collected leaves, adding them to cow urine in a container, boiling the mixture for 30–60 minutes, allowing it to cool, filtering the solution, and storing the filtrate in shade for use. For application, dilute roughly 3-4 L of Brahmastra in 100 L water and apply as a foliar spray with a hand or knapsack sprayer at the first appearance of chewing pests or caterpillars, repeating after 10-15 days if needed. Its functions include acting as a broad-spectrum botanical pesticide, controlling caterpillars, beetles and larvae, repelling insects and reducing feeding, and disturbing pest growth and development; benefits are eco friendly, locally sourced, effective against a wide range of chewing pests, safe for beneficial insects and the environment, and supportive of crop health and sustainability.

AGNIASTRA

Agniastra is a traditional natural bio pesticide used in natural and zero budget farming to control sucking pests and chewing insects such as aphids, jassids, thrips, whiteflies, caterpillars, borers, and beetles; it is prepared from locally available ingredients: 10 L cow urine, 10 L water, 1 kg cow dung, 500 g green chili paste, 500 g garlic paste, 500 g crushed tobacco leaves, and 2 kg crushed neem leaves by boiling the mixture in an iron or earthen pot on low flame for 30–45 minutes, cooling, filtering through cloth, and storing the filtrate in a plastic or earthen container, then diluting 2-3 L of Agniastra in 100 L water for foliar spraying (apply evenly with a knapsack or hand sprayer in early morning or evening to avoid leaf burn and repeat every 7–10 days if needed); Agniastra functions as a strong repellent and contact poison because of its pungent and hot constituents, kills or repels a wide range of pests, prevents egg laying on leaves, and when prepared and applied properly protects crops while being safe for beneficial insects, earthworms, soil microbes and the environment, offering a low cost, locally made alternative that improves crop health, reduces dependence on chemical pesticides, and is suitable for cereals, pulses, vegetables, fruits and cash crops.

Conclusion

Natural farming is a sustainable and eco-friendly agricultural system based on simple ecological principles and the use of nature-based inputs. This review highlights that practices such as Beejamrit, Jeevamrit, Acchadana, and Waaphasa form the strong foundation of natural farming by improving soil health, enhancing microbial activity, conserving moisture, and ensuring balanced soil aeration. These inputs not only reduce dependency on chemical fertilizers and pesticides but also restore soil fertility, increase organic carbon, and improve nutrient availability to crops.

Natural formulations like Neemastra, Brahmastra, Agniastra, and Dashparni Ark provide effective pest and disease management without harming beneficial organisms or the soil ecosystem. The scientific basis of these practices lies in their ability to promote beneficial microorganisms, enhance plant metabolism, and strengthen crop resistance. By maintaining ecological balance and reducing production costs, natural farming supports farmer livelihoods and long-term agricultural sustainability.

Thus, natural farming emerges as a viable alternative to chemical-based agriculture, ensuring healthy food production, environmental protection, and sustainable crop productivity while aligning with the principles of Zero Budget Natural Farming.

ROLE OF SOFTWARE IN FISHERIES BIOLOGY AND RESOURCE MANAGEMENT



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ABSTRACT

Fisheries biology and resource management are essential for ensuring sustainable utilization of aquatic resources. The growing challenges of overfishing, biodiversity loss, habitat degradation, pollution, and climate change demand accurate data analysis and scientific decision-making. In this context, software applications play a major role in fisheries research, stock assessment, biodiversity documentation, spatial mapping, ecosystem modeling, aquaculture monitoring, and fisheries governance. Software tools such as MS Excel, R, SPSS, GIS platforms, remote sensing applications, and stock assessment packages have improved efficiency, reduced manual errors, and enhanced resource planning. This article highlights the key applications of software in fisheries biology and resource management, including data management, statistical analysis, GIS-based mapping, remote sensing, modeling, disease surveillance, and decision support systems, with emphasis on their importance for sustainable fisheries and conservation.

Keywords: Fisheries software, GIS, Stock assessment, Remote sensing, Aquaculture monitoring, Decision support systems

INTRODUCTION

Fisheries resources contribute significantly to food security, nutritional needs, and livelihood generation across the world. In India, fisheries support millions of fishermen and provide valuable animal protein at affordable cost. However, fisheries resources are increasingly threatened by overexploitation, habitat destruction, pollution, invasion of exotic species, and climate variability.

Fisheries biology and resource management aim to understand fish population structure, biodiversity status, stock health, and ecosystem functioning. Traditionally, these studies depended heavily on manual observations, paper-based data entry, and basic calculations. Although these methods were useful, they were time-consuming and limited in accuracy and analytical capability.

In recent decades, the rapid growth of information technology has transformed fisheries science. Software tools have become essential in fisheries research and management by improving the speed and precision of data analysis. Digital tools assist in monitoring fish stocks, mapping fish habitats, analyzing growth and reproductive patterns, predicting fishing zones, monitoring aquaculture farms, and supporting conservation planning.

Today, fisheries management is no longer based solely on field observations; it is supported by advanced software-driven approaches such as Geographic Information Systems (GIS), Remote Sensing, Stock Assessment Models, Decision Support Systems, and Artificial Intelligence (AI). The integration of software in fisheries has improved sustainable management strategies and strengthened scientific governance.

SOFTWARE APPLICATIONS IN FISHERIES BIOLOGY

Fisheries biology deals with fish diversity, population dynamics, growth, reproduction, feeding habits, and ecological interactions. Software tools help researchers analyze biological data efficiently and accurately.

Data Collection and Digital Data Management

Fisheries studies generate large datasets such as length, weight, maturity stage, gut content, water quality parameters, plankton density, and catch composition. Managing such data manually is difficult and may lead to calculation errors and loss of information. Software such as MS Excel, Google Sheets, MS Access, and database platforms such as MySQL and PostgreSQL are used for efficient storage, organization, and retrieval of fisheries

data. These tools allow researchers to store large amounts of biological data, filter and sort records quickly, reduce manual calculation errors, and maintain systematic documentation for long term monitoring.

Statistical Analysis of Fish Biological Parameters

Statistical analysis is essential to interpret fisheries biological data. Software helps in computing descriptive statistics and advanced analyses. Commonly used software includes MS Excel (basic statistics and graphs), SPSS (regression, ANOVA, multivariate analysis), Minitab (experimental analysis and modeling), and R software (advanced statistical and ecological analysis). For example, MS Excel can be used for length–weight relationship analysis, condition factor estimation, growth rate calculations, and correlation and regression analysis. Similarly, SPSS and R are used for advanced analysis such as Principal Component Analysis (PCA), cluster analysis, diversity indices, and seasonal and spatial comparisons. Thus, statistical software strengthens fisheries biology research by providing accurate results and improving scientific interpretation.

Fish Growth and Population Dynamics Analysis

Fish growth studies are essential for understanding stock condition and exploitation level. Growth parameters help estimate age, size structure, mortality, and recruitment patterns. Important software used for growth analysis includes FiSAT II (FAO-ICLARM Stock Assessment Tools), ELEFAN (Electronic Length Frequency Analysis), and TropFishR (R-based stock analysis package).

These tools help estimate von Bertalanffy growth parameters (L_{∞} and K), total mortality (Z), natural mortality (M), fishing mortality (F), exploitation ratio (E), and recruitment patterns. Such parameters are highly useful for stock assessment and management decisions like fishing regulation and mesh size control.

Reproductive Biology and Breeding Studies

Fish reproductive studies focus on maturity stages, fecundity, spawning season, and breeding potential. Software tools assist in analyzing reproductive parameters efficiently. Using Excel and statistical software, researchers can calculate gonadosomatic index (GSI), hepatosomatic index (HSI), size at first maturity (L_{m50}), fecundity estimation, and seasonal breeding cycle analysis. Graph plotting features in software help present results in an easy and attractive manner for journals and reports.

Biodiversity Assessment and Species Documentation

Biodiversity studies require species identification, checklist preparation, habitat mapping, and conservation assessment. Software tools support biodiversity documentation and analysis. Important tools include FishBase (global fish database), GBIF (species distribution records), PAST software (ecological and diversity analysis), and Biodiversity Pro (diversity indices). These platforms help researchers compare species richness, abundance, and diversity indices across different habitats. They also assist in identifying rare, endemic, and threatened species.

Bioinformatics and Molecular Biology Applications

Modern fisheries biology includes molecular identification of species through DNA barcoding. Bioinformatics software supports genetic analysis, phylogenetic studies, and evolutionary research. Software used includes MEGA (Molecular Evolutionary Genetics Analysis), BLAST (NCBI online tool), BioEdit, and ClustalW. These tools help in DNA sequence alignment, species confirmation, phylogenetic tree construction, and genetic diversity assessment. Thus, software has improved accuracy in species identification and conservation genetics.

SOFTWARE IN FISHERIES RESOURCE MANAGEMENT

Fisheries resource management involves planning strategies to ensure sustainable utilization of fish stocks while protecting ecosystems. Software applications play a major role in scientific decision-making.

Stock Assessment and Fishery Modeling Software

Stock assessment is the backbone of fisheries management. It helps determine whether fish stocks are overexploited, underexploited, or sustainable. Major stock assessment software includes FiSAT II, Stock Synthesis (SS3), ASPIC (production model), and FLR (Fisheries Library in R). These tools analyze catch and effort data, age/length structure, and mortality parameters to estimate maximum sustainable yield (MSY), total allowable catch (TAC), stock biomass, and recruitment trends. Such outputs help managers implement scientific regulations such as catch quotas, seasonal bans, and fishing effort reduction.

GIS Applications in Fisheries Management

Geographic Information System (GIS) is one of the most powerful tools for fisheries resource management. GIS software supports spatial mapping and habitat analysis. Common GIS software includes ArcGIS (commercial), QGIS (free open-source), and Google Earth Pro. GIS is used for mapping fish distribution patterns, identifying breeding and nursery grounds, mapping fishing zones and fish landing centers, identifying biodiversity hotspots, and mapping pollution sources and habitat degradation zones. For example, GIS mapping of Western Ghats rivers can help identify endemic fish hotspots and prioritize conservation areas.

Remote Sensing and Satellite-Based Fisheries Monitoring

Remote sensing uses satellite imagery to study ocean and waterbody characteristics. It plays an important role in marine fisheries management. Remote sensing tools include ERDAS Imagine, ENVI, and SeaDAS. Remote sensing helps monitor sea surface temperature (SST), chlorophyll concentration (primary productivity), ocean currents and upwelling zones, and turbidity and sedimentation. In India, PFZ (Potential Fishing Zone) advisories use satellite-based data to guide fishermen to productive fishing areas, reducing fuel consumption and increasing catch efficiency.

Fishery Monitoring and Surveillance Systems

Illegal, unreported, and unregulated (IUU) fishing is a major threat to fisheries sustainability. Software tools help in monitoring fishing activities through digital surveillance systems. Examples include Vessel Monitoring Systems (VMS), GPS tracking and navigation software, digital fish landing data portals, and e-logbooks and online reporting systems. These systems help fisheries departments monitor fishing effort and enforce regulations effectively.

Ecosystem-Based Fisheries Management (EBFM) Software

Traditional management focuses on single species, but modern management considers ecosystem interactions. Ecosystem-based fisheries management requires modeling of food webs and ecological balance. Important ecosystem modeling tools include Ecopath with Ecosim (EwE) and Atlantis ecosystem model. These tools help predict the impact of fishing on predator-prey relationships, trophic level balance, biodiversity stability, and ecosystem resilience. Such models support sustainable harvesting strategies and habitat conservation.

BENEFITS OF SOFTWARE IN FISHERIES SECTOR

The use of software provides several advantages such as saving time and reducing manual workload, improving accuracy in calculations and analysis, supporting large-scale data storage and retrieval, enhancing graphical representation and reporting, improving decision-making through predictive modeling, helping in mapping and visualization of fish habitats, supporting sustainable and ecosystem-based management, and promoting transparency in fishery governance. Software tools have become essential for modern fisheries research and management.

CHALLENGES IN SOFTWARE ADOPTION

Despite its importance, software adoption in fisheries faces certain limitations such as lack of digital training among field staff, poor internet connectivity in remote fishing villages, high cost of licensed software (ArcGIS, ENVI), limited awareness about open-source alternatives, lack of standard fisheries databases, and difficulty in integrating multi-source data. These challenges can be addressed through capacity building, training programs, and promotion of open-source software such as QGIS and R.

FUTURE PROSPECTS AND EMERGING DIGITAL TECHNOLOGIES

The future of fisheries science is strongly connected with advanced digital tools. Emerging innovations include Artificial Intelligence (AI) for fish species identification and stock prediction, mobile applications for fishermen to provide weather alerts and PFZ advisories, big data and cloud computing for large fisheries datasets, and Internet of Things (IoT) in aquaculture for automated feeding and real-time water quality monitoring. These technologies will enhance sustainable fishery development and resource conservation.

CONCLUSION

Software applications have become a key component of fisheries biology and resource management. From simple tools like MS Excel to advanced GIS and remote sensing platforms, software supports fisheries research, stock assessment, biodiversity conservation, ecosystem modeling, aquaculture management, and fishery governance.

Digital tools improve accuracy, reduce time consumption, enhance visualization, and strengthen decision-making. To achieve sustainable fisheries development, training and awareness on fisheries software should be promoted among students, researchers, and fishery managers. The future of fisheries management lies in digital innovation, smart monitoring systems, and technology-based conservation planning.

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Analyzing Fish Length–Weight Relationship Using MS Excel



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Abstract

Length–weight relationship (LWR) is one of the most widely used tools in fisheries biology to study fish growth patterns and stock condition. It provides valuable information for biomass estimation, fish stock assessment, and management strategies. The relationship is expressed as $W = aL^b$, where W is weight, L is length, and a and b are constants. Although statistical software is available, MS Excel is a simple and accessible platform for analyzing LWR. This article provides a step-by-step method to analyze fish length–weight relationship using MS Excel, interpret the regression results, and understand its applications in fisheries research and aquatic ecosystem monitoring.

Keywords: Fish growth, Length–weight relationship, MS Excel, Allometric growth, Stock assessment

Introduction

Fish growth studies are essential in fisheries science because they help in understanding fish population dynamics, exploitation status, and ecosystem health. Among various growth analysis methods, the length–weight relationship (LWR) is one of the simplest and most effective techniques used worldwide.

In many fishery surveys, length data are collected easily from landing centers, rivers, reservoirs, and coastal areas. However, weight measurements may not always be possible due to lack of equipment or time constraints. In such cases, LWR is useful to estimate fish weight from length data and to calculate fish biomass.

The length–weight relationship also provides insight into the fish's body condition. Fish living in healthy and productive environments generally show better weight gain compared to fish living in stressed habitats. Factors like food availability, maturity stage, spawning period, seasonal changes, and water quality strongly influence fish growth patterns. Hence, LWR is an important biological indicator for assessing fish condition and habitat quality.

Traditionally, LWR is calculated using statistical packages such as SPSS, R, and Minitab. But MS Excel is widely available and user-friendly, making it suitable for students and researchers to analyze fish length–weight data easily. This article explains the complete procedure of LWR analysis using MS Excel in a simple manner.

Principle of length–weight relationship

The length–weight relationship is expressed by the following equation:

$$W = aL^b$$

Where:

W = Fish weight (g)

L = Fish length (cm or mm)

a = Intercept (constant related to body form)

b = Slope (growth coefficient)

This relationship indicates that fish weight increases with increase in length. The parameter b is important because it explains the nature of fish growth.

Since the above equation is non-linear, it is converted into linear form using logarithmic transformation:

$$\text{Log } W = \log a + b \log L$$

This is a straight-line equation in the form:

$$y = c + mx$$

Where:

$$\begin{aligned} y &= \log W \\ x &= \log L \\ c &= \log a \\ m &= b \end{aligned}$$

Thus, regression analysis provides the values of a and b .

Types of growth based on 'b' value

The value of b indicates fish growth pattern: Isometric Growth ($b = 3$) Fish grows proportionally in length and weight. Body shape remains constant. Positive Allometric Growth ($b > 3$) Fish gains weight faster than length. Fish becomes heavier and plumper. Negative Allometric Growth ($b < 3$) Fish gains length faster than weight. Fish becomes slender as it grows.

In general, b values for most fish species range between 2.5 and 3.5 depending on environmental conditions and species characteristics.

Importance of LWR studies

Length–weight relationship is widely applied in fisheries science for the following purposes:

Estimation of fish biomass from length frequency data, Fish stock assessment and exploitation status evaluation, Growth comparison among populations in different habitats, Assessment of fish health and condition, Evaluation of environmental stress caused by pollution or habitat degradation, Support for sustainable fishery management strategies, Hence, LWR acts as a fundamental biological tool in fishery research.

Data collection requirements

Accurate data collection is necessary for reliable results. Sample size: minimum 30–50 fish samples are recommended. Larger sample size gives better accuracy. Length measurement measure fish length using measuring board. Record either total length (TL) or standard length (SL). Use the same length type for all samples. Weight measurement measure fish weight using digital balance. Record weight in grams (g). Precautions avoid damaged or partially cut fish samples. Remove excess water before weighing. record measurements carefully to avoid errors.

Step-wise procedure for LWR analysis using MS Excel

Step 1: Data Entry

Prepare an Excel sheet with the following format:

Fish No	Length (L) cm	Weight (W) g
1	12.5	25.4
2	14.2	35.7
3	15.8	45.2

Step 2: Log Transformation

Create two additional columns:

$\log L$

$\log W$

Use the following formulas:

For $\log$ length:

=LOG10(B2)

For $\log$ weight:

=LOG10(C2)

Drag down the formula for all fish samples.

Step 3: Scatter Plot

Select $\log L$ and $\log W$ columns.

Click Insert → Scatter Plot.

Scatter graph will appear.

Step 4: Add Trendline

Click on scatter points.

Right click → Add Trendline.

Select Linear trendline.

Tick the options:

Display equation on chart

Display R^2 value on chart

Excel will show regression equation like:

$$y=2.98x-1.25$$

Step 5: Identify b and a Values

From the regression equation:

$$b = \text{slope} = 2.98$$

$$\log a = \text{intercept} = -1.25$$

$$\text{Now calculate a: } a=10^{-1.25}=0.056$$

$$\text{Excel formula: } =10^{(-1.25)}$$

Step 6: Final LWR Equation

Now write the final equation:

$$W=0.056L$$

$$2.98$$

Role of r^2 value

The R^2 value indicates the strength of correlation between length and weight.

R^2 near 1.0 = strong relationship

R^2 near 0.0 = weak relationship

For most fish species, R^2 values are generally above 0.80, showing good regression fit.

Presentation of results (report format)

The results should be presented in scientific form:

Example:

“The length–weight relationship was estimated as $W = 0.056L^{2.98}$ ($R^2 = 0.91$). The b value (2.98) indicates negative allometric growth.”

This statement is suitable for research papers, project reports, and thesis writing.

Common errors and precautions

While performing LWR analysis, the following mistakes should be avoided:

Mixing Total Length and Standard Length data

Using very small sample size

Incorrect unit conversion (mm vs cm)

Not removing water before weighing fish

Inclusion of outlier values without verification

Seasonal bias (sampling only during one season)

Careful sampling and accurate measurement improve reliability.

Applications of LWR in fisheries

Length–weight relationship is useful in many fisheries research areas: Fish Stock Assessment: Helps estimate biomass and yield potential of fish populations. River and Reservoir Monitoring: LWR indicates growth variations across different habitats. Aquaculture Growth Studies: Used to monitor growth performance in culture systems. Environmental Impact Assessment: Pollution and habitat degradation affect fish growth, reflected in b values. Conservation and Management: Helps develop sustainable exploitation strategies.

Conclusion

Length–weight relationship is a simple and effective tool to analyze fish growth patterns and condition. It plays a major role in biomass estimation, fish stock assessment, and environmental monitoring. MS Excel is an easy platform for performing LWR analysis by log transformation and regression method. With proper sample size and accurate measurements, reliable LWR parameters can be obtained. This method is highly useful for fisheries students, researchers, and fishery managers for scientific and management purposes.

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Pet Parasite Control: A Proactive One Health Approach



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1. Introduction

Companion animals occupy an increasingly important position in human society, functioning not only as pets but also as integral members of households. The close association between humans and companion animals provides psychological, emotional, and social benefits; however, it simultaneously increases the risk of transmission of infectious and parasitic diseases. Among these, parasitic infections remain a major concern because of their effects on animal health, welfare, productivity, and public health. Traditionally, parasite management in dogs and cats relied on reactive treatment after the appearance of clinical signs such as poor body condition, diarrhea, anemia, pruritus, or visible ectoparasites. Contemporary veterinary medicine has shifted toward preventive parasite management, emphasizing routine surveillance, risk assessment, and prophylactic interventions. This proactive strategy is particularly important because many parasitic infections remain subclinical while infected animals continue shedding infective stages into the environment (Bowman, 2020).

Parasites affecting companion animals are broadly categorized into endoparasites and ectoparasites. Endoparasites inhabit internal tissues and organs and include nematodes, cestodes, trematodes, and protozoa, whereas ectoparasites live on the skin surface and include fleas, ticks, mites, and lice. Both groups significantly influence animal welfare and several possess zoonotic importance (Taylor et al., 2016).

2. Companion Animal Parasites and Health Significance

2.1 Endoparasites

Internal parasites commonly encountered in companion animals include *Toxocara canis*, *Toxocara cati*, *Ancylostoma* spp., *Trichuris vulpis*, *Dipylidium caninum*, and *Dirofilaria immitis*. These parasites cause intestinal, systemic, and cardiovascular disorders depending on the species involved. Roundworms (*Toxocara* spp.) are among the most prevalent parasites in puppies and kittens because of transplacental and transmammary transmission. Heavy infections may result in poor growth, gastrointestinal disturbances, abdominal distension, and nutritional deficiencies. Hookworms (*Ancylostoma* spp.) produce blood loss leading to anemia, especially in young animals. Heartworm disease caused by *Dirofilaria immitis* affects pulmonary arteries and cardiac tissues, often resulting in severe cardiopulmonary complications and mortality if untreated (ESCCAP, 2023).

2.2 Ectoparasites

Ectoparasites constitute another major challenge in companion animal practice. Fleas, particularly *Ctenocephalides felis*, and ticks such as *Rhipicephalus sanguineus*, are widely distributed and contribute substantially to disease transmission. Flea infestations cause irritation, dermatitis, alopecia, and flea allergy dermatitis (FAD). In addition, fleas act as intermediate hosts for *Dipylidium caninum*. Tick infestations are associated with transmission of pathogens causing ehrlichiosis, babesiosis, and other vector-borne diseases. Since many tick species readily shift hosts, they also represent an important zoonotic concern (CAPC, 2022).

3. Zoonotic Importance and Public Health Concerns

The close interaction between pets and humans creates opportunities for parasite transmission. Numerous companion animal parasites exhibit zoonotic potential and constitute an important component of the One Health framework. *Toxocara* spp. are recognized globally as important zoonotic nematodes. Humans acquire infection through accidental ingestion of embryonated eggs present in contaminated soil, food, or hands. Migrating larvae may invade internal organs causing visceral larva migrans (VLM) or localize in ocular tissues resulting in ocular larva migrans (OLM), which may lead to visual impairment or blindness (Overgaauw and van Knapen, 2013).

Hookworm larvae can penetrate human skin and cause cutaneous larva migrans, while vector-borne pathogens transmitted by ticks may infect humans directly. Consequently, parasite control programs should aim not only at animal health but also at minimizing environmental contamination and human exposure (Robertson et al., 2000).

4. Environmental Contamination and Transmission Dynamics

Environmental persistence plays a crucial role in maintaining parasitic infections among companion animals. Many parasite eggs and larvae possess considerable resistance and remain viable for prolonged periods. *Toxocara* eggs are highly resistant and may survive in soil for several months to years under suitable environmental conditions. Public areas such as parks, playgrounds, gardens, and sandboxes become important reservoirs of infection when contaminated with infected feces. Similarly, ectoparasites utilize the household environment for completion of their life cycle. Only adult fleas remain on animals, whereas eggs, larvae, and pupae persist in bedding, carpets, furniture, and surrounding premises. Failure to eliminate environmental stages often results in reinfection despite treatment of the host animal (Taylor et al., 2016).

5. Proactive Parasite Control Strategies

Effective parasite management requires an integrated and individualized preventive approach rather than generalized treatment schedules.

5.1 Risk-Based Preventive Programs

Parasite control should consider:

- Age and physiological status of animals
- Indoor versus outdoor lifestyle
- Hunting behavior and diet type
- Boarding exposure
- Geographic distribution of vectors
- Presence of children, elderly, or immunocompromised individuals within households

Young animals generally require more frequent deworming because of increased susceptibility and vertical transmission.

5.2 Routine Antiparasitic Administration

Regular administration of veterinary-prescribed anthelmintics and ectoparasiticides forms the cornerstone of prevention. Drug selection depends on parasite species, life stage, and exposure risk.

Common classes include:

Benzimidazoles: Nematocidal Agents

Benzimidazoles are broad-spectrum anthelmintics commonly employed against gastrointestinal nematodes including *Toxocara canis*, *Toxocara cati*, *Ancylostoma* spp., and *Trichuris vulpis*. Common representatives include fenbendazole, febantel, oxfendazole, and albendazole.

Mechanism of Action

Benzimidazoles exert their activity by binding selectively to parasite β -tubulin, thereby inhibiting microtubule formation and polymerization. Disruption of microtubule assembly impairs cellular transport processes, glucose uptake, and energy metabolism, resulting in progressive depletion of glycogen reserves and parasite death (Bowman, 2020).

Clinical Applications

These compounds are primarily used for treatment of:

- Roundworms
- Hookworms
- Whipworms
- Selected protozoal infections
- Certain larval stages and tissue parasites

Because their action depends on gradual metabolic disruption, treatment often requires repeated administration for 3–5 consecutive days, particularly in persistent infections and encysted larval stages.

Macrocytic Lactones: Heartworm Preventives and Endectocides

Macrocytic lactones include ivermectin, moxidectin, selamectin, and milbemycin oxime. These drugs possess endectocidal properties, acting against both internal nematodes and selected ectoparasites.

Mechanism of Action

Macrocytic lactones bind to glutamate-gated chloride channels located in nerve and muscle cells of invertebrates. Activation of these channels causes increased chloride influx and membrane hyperpolarization, leading to neuromuscular paralysis, inhibition of feeding, and eventual parasite death (Taylor et al., 2016).

Clinical Applications

Major indications include:

- Prevention of *Dirofilaria immitis* infection
- Control of gastrointestinal nematodes
- Management of mites and selected ectoparasites
- Reduction of larval migration stages

Monthly administration is widely recommended for heartworm prevention because these agents eliminate susceptible tissue stages (L₃ and L₄ larvae) before adult establishment within pulmonary arteries and cardiac tissues.

Praziquantel: Cestocidal Agent

Praziquantel is the principal cestocidal drug used in companion animal medicine and is highly effective against tapeworm infections caused by *Dipylidium caninum*, *Taenia* spp., and *Echinococcus* spp.

Mechanism of Action

Praziquantel increases membrane permeability to calcium ions in cestodes. The resulting influx of calcium causes sustained muscular contraction, paralysis, vacuolization, and disruption of the parasite tegument. Damage to the tegument exposes parasite tissues to host digestive enzymes and immune responses, facilitating elimination (Zajac and Conboy, 2012).

Clinical Applications

Praziquantel is commonly incorporated into broad-spectrum deworming formulations because:

- Tapeworm infections frequently occur with flea infestations
- Elimination of the scolex is essential to prevent recurrence
- *Echinococcus* species possess important zoonotic significance

Treatment frequency is generally determined according to exposure risk, flea burden, and hunting behavior.

Isoxazolines: Advanced Ectoparasitocides

Isoxazolines represent a newer class of ectoparasitocides used extensively for flea and tick control. Important compounds include afoxolaner, fluralaner, sarolaner, and lotilaner.

Mechanism of Action

Isoxazolines inhibit GABA-gated and glutamate-gated chloride channels in arthropod nervous systems. Blocking these inhibitory pathways causes uncontrolled neuronal excitation, muscular hyperactivity, paralysis, and death of ectoparasites (CAPC, 2022).

Clinical Applications

These drugs provide:

- Rapid flea elimination
- Tick control
- Prevention of environmental contamination
- Reduction of vector-borne pathogen transmission

Most formulations show prolonged activity ranging from one to three months depending on the active compound and dosage regimen.

6.Strategic Deployment and Importance of the Prepatent Period

Successful parasite control depends not only on drug efficacy but also on timing of administration relative to parasite development.

Prepatent Period (PPP)

The prepatent period refers to the interval between initial infection and the appearance of reproductive stages such as eggs, larvae, or microfilariae.

Examples include:

Parasite	Approximate Prepatent Period

<i>Toxocara canis</i>	21–30 days

<i>Ancylostoma caninum</i>	14–21 days

<i>Dirofilaria immitis</i>	6–7 months

When treatment intervals exceed the prepatent period, adult parasites may establish and begin environmental shedding, increasing reinfection and zoonotic risk.

Strategic Drug Deployment in Companion Animal Parasite Control

Drug Class	Primary Target	Example Compounds	Typical Frequency	Strategic Objective
Benzimidazoles	Gastrointestinal nematodes	Fenbendazole, Febantel, Oxfendazole	Targeted or pulse treatment	Elimination of active infections and larval stages
Macrocyclic lactones	Heartworm and systemic nematodes	Ivermectin, Moxidectin, Milbemycin oxime	Monthly	Prevention of larval development and heartworm establishment
Praziquantel	Cestodes	Praziquantel	Risk-based; monthly to quarterly	Interruption of tapeworm transmission
Isoxazolines	Fleas and ticks	Fluralaner, Sarolaner, Afoxolaner	Monthly to tri-monthly	Rapid ectoparasite elimination and vector control

Conclusion

Pharmacological management forms the foundation of proactive parasite control programs in companion animals. Understanding mechanisms of action, parasite biology, and prepatent periods enables clinicians to design individualized treatment protocols that reduce environmental contamination, interrupt transmission cycles, and minimize zoonotic risks. Integration of targeted chemotherapy with preventive diagnostics and environmental management supports effective long-term parasite control under a One Health framework.

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INTERNATIONAL WORKERS' DAY: MAY 01



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First day of fifth month celebrated as International Workers Day, International Labour Day or May Day honors workers' rights, addressing different challenges they face at their workplace and the need for fair working conditions. Celebrated on May 1st, the day commemorates the 1886 Haymarket affair in Chicago which observed a general strike for the eight-hour workday. On this day in 1886, more than 300,000 workers in 13,000 businesses across the United States walked off their jobs in the first ever May Day celebration in history. A glimpse back to the history reveals that in the late nineteenth century, the working class was in constant struggle to have an eight hour working day. As early as the 1860's, working people agitated to shorten the workday without a cut in pay, but it wasn't until the late 1880's that organized labour was able to garner enough strength to declare the 8-hour workday. This proclamation was without consent of employers, yet demanded by many of the working class. At this time, socialism was a new and attractive idea to working people, many of whom were drawn to its ideology of working class control over the production and distribution of all goods and services. Workers had seen first-hand that Capitalism benefited only their bosses, trading workers' lives for profit. Thousands of men, women and children were dying needlessly every year in the workplace, with life expectancy as low as their early twenties in some industries, and little hope but death of rising out of their destitution.

Beginning in the late 19th century, as the trade union and labour movements grew, a variety of days were chosen by trade unionists as a day to celebrate labour. May 1 was chosen to be International Workers' Day to commemorate the 1886 Haymarket affair in Chicago. In that year beginning on May 1, there was a general strike for the eight-hour workday. The 1904 Sixth Conference of the Second International, called on all Social Democratic Party organizations and trade unions of all countries to demonstrate energetically on the First of May for the legal establishment of the 8-hour day, for the class demands of the proletariat, and for universal peace.

In Chicago, the epicenter for the 8-hour day agitators, 40,000 went out on strike with the anarchists in the forefront of the public's eye. With their fiery speeches and revolutionary ideology of direct action, anarchists and anarchism became respected and embraced by the working people and despised by the capitalists. More and more workers continued to walk off their jobs until the numbers swelled to nearly 100,000, yet peace prevailed. It was not until two days later, May 3, 1886, that violence broke out at the McCormick Reaper Works between police and strikers. In 1887, Oregon was the first state of the United States to make it an official public holiday. By the time it became an official federal holiday in 1894, thirty US states officially celebrated Labour Day. Thus by 1887 in North America, Labour Day was an established, official holiday but in September, not on 1 May. In 1889, a meeting in Paris was held by the first congress of the Second International, following a proposal by Raymond Lavigne that called for international demonstrations on the 1890 anniversary of the Chicago protests. May Day was formally recognized as an annual event at the International's second congress in 1891. May Day is an official holiday in 66 countries and unofficially celebrated in many more, but rarely is it recognized in this country where it began.

The day in the year 2026 focuses on Ensuring a Healthy Psychosocial Working Environment for workers at their workplace. It highlights mental health & well-being by tackling workplace stress, burnout, and 'always-on' fatigue in the digital age. It also ensures Safety & Climate action by ensuring safe working conditions and climate transitions and green job shifts. The May Day also brings into focus on social justice by promotion of fair wages, gender equality, and rights for informal workers and also recognizing the resilience and struggles of the global workforce.

The farming community is a class of agriculture workers that work in farms and is are not confined to a particular gender. If we analyze the data, we see that in 2001, of the 100 cultivators in India 67.1 were male and 32.9 were female and within a decade in 2011 the male went up to 69.7 and female came down to 30.3. Similarly

of 100 agricultural labourers in India in 2001, 53.7 were male and 46.3 were female and a decade later in 2011 the number was 57.3 for males and 42.7 for females. The agriculture workers have been in the forefront in ensuring food and nutritional security to all of use. Despite all this, there are frequent reports of the agriculture workers being harassed by landlords and owing to the apathy from respective governments, some of them are leaving agriculture and some others are committing suicides. All this comes as a shock to all of us. Agriculture is a dangerous occupation also. Let us take the case of United States where agriculture is also called the backbone of the country. A few years ago, agriculture ranked eighth as one of the most dangerous occupations. Today agriculture ranks as fourth dangerous occupation. According to the U.S Bureau of Labour Statistic, fatalities and injuries among agricultural workers are on the rise. Farm workers are 800 per cent more likely to dies on the job than in other industries. The National Safety Council of the U.S reports that of the about 3.1 million peoples who work on America's 2.3 million farms and ranches, 1300 die each year and 120,000 are injured. This means for every 100,000 farmers. About 25 die each year and equipments injure another 243 and five per cent of these injuries result in permanent disabilities. In agrarian economies, such things should usually not happen.

Farmers' who produce everything on this planet should be ensured with appropriate protection and safety. They should enjoy certain exclusive rights related to agriculture that must be upheld to give due recognition to them in their efforts to produce food for all of us. This is also necessary to save them from the unnecessary harassment from different sources. Farming must be made more sustainable and remunerative by adopting practices which do not promote usage of external inputs, but use of local resources.

The country had 29 separate labour laws with outdated and overlapping provisions, making compliance complex and time-consuming for workers and employers. Many laws were created during the pre-Independence and early post-Independence era, and no longer suited modern industry practices, technology, or new forms of employment. The Multiple licences, registrations and returns increased paperwork and made it difficult for businesses especially for Micro, Small, and Medium Enterprises (MSME) to operate smoothly. Most of the protections applied only to specific categories or sectors, leaving large numbers of informal and unorganized workers uncovered. The rise of gig work, platform jobs, fixed-term employment and flexible service-based roles required updated regulatory frameworks.

For the welfare of workers, Indian government has also come up with four Labour Codes (the Code on Wages, 2019, Industrial Relations Code, 2020, Code on Social Security, 2020, Occupational Safety, Health and Working Conditions (OSH) Code, 2020) replacing 29 earlier labour laws. The reform aims to modernize labour regulation, strengthen worker protections and create a simpler, future-ready framework supporting a resilient workforce and *Atmanirbhar* Bharat. The Code of Wages, 2019 merges four key laws (The Payment of Wages Act, 1936; The Minimum Wages Act, 1948; The Payment of Bonus Act, 1965; and The Equal Remuneration Act, 1976) into a single framework. It brings uniformity in wage rules, ensures fair and timely payment, promotes gender equality and simplifies compliance for employers while strengthening workers' rights. The Industrial Relations Code, 2020 combines and simplifies provisions from earlier laws like the Trade Unions Act, 1926, the Industrial Employment (Standing Orders) Act, 1946 and the Industrial Disputes Act, 1947. It seeks to balance worker rights with industrial stability by streamlining rules on union recognition, employment terms and dispute resolution. The Code on Social Security, 2020: It merges nine existing laws like The Employee's Compensation Act, 1923, The Employees' State Insurance Act, 1948, The Employees' Provident Funds and Miscellaneous Provisions Act, 1952 into one unified framework and extends benefits to all workers, including those in the unorganized, gig and platform sectors. It covers maternity, health, life insurance and provident fund benefits while promoting digital processes and easier compliance. The Occupational Safety, Health and Working Conditions Code 2020: It consolidates 13 labour laws such as Factories Act, 1948, Plantations Labour Act, 1951, and Mines Act, 1952. All the four new labour laws aims to ensure safer working conditions, guarantee for their genuine rights while simplifying compliance for businesses, creating a more efficient, fair and future-ready labour workforce and a robust framework.

Rising Demand for Cut Fillers in the Floral Industry



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Abstract

Floriculture is a fast-growing and profitable sector of horticulture with increasing demand in both domestic and international markets. Along with cut flowers, filler flowers play an important role in enhancing the beauty, volume, texture, and value of floral arrangements such as bouquets, garlands, weddings, and event decorations. In India, filler flowers are mainly produced in states like Karnataka, Tamil Nadu, Andhra Pradesh, and Uttarakhand, and they contribute significantly to exports to markets such as Europe, the USA, and Japan. This study highlights the importance and market potential of major filler flowers such as Limonium, Gypsophila, Mum Chrysanthemum, Solidago, and Stock. These fillers are widely preferred due to their long vase life, wide colour range, durability during transport, cost-effectiveness, and suitability for both fresh and dry flower arrangements. Many of these fillers also support sustainable and eco-friendly floriculture practices by requiring lower maintenance and fewer inputs. Overall, the rising global demand for filler flowers reflects changing consumer preferences toward mixed and textured floral designs. The increasing use of fillers not only improves the visual appeal of floral products but also enhances economic returns for growers and exporters, making filler flowers an essential component of the modern floriculture industry.

Keywords: Filler, Global Export market, Gypsophilla, Limonium, Vase life.

Introduction

Floriculture is rising, profitable, rapidly escalating industries of the world. Different types of cut flowers, cut filler, dry flowers and post-harvest products are demand in local and an international market. Cut flower arrangements are supported primarily by foliage filler crops. The cut fillers support the cut flower in various decorative things such as bouquets, garland etc. Cut filler are mostly grown in the region of Karnataka, Tamil Nadu, Andhra Pradesh and Uttarakhand. The production of cut filler in India is about 877,00 tons of produce in 2023-2024. The demand is very both domestic market and an international market of Europe, USA and Japan. The global market cap of floriculture in India is about the INR 292 million. The market growth rate is increasing 10%.

What are cut Fillers:



White Aster



Bells of Ireland



Limonium

- The backbone of an arrangement, foliage is used to set the shape and size of the arrangement, and to add texture whereas, Fillers are smaller flowers or plants that complement the focal flowers.
- Fillers can add structure, bulk, and interest to bouquets.
- They can also add a textural contrast or colorful counterpoint.
- Some filler flowers can double as foliage, and can play different roles in a bouquet depending on the design.
- They provide essential structure, volume, and texture to floral arrangements, serving as a high-growth, profitable segment for farmers, especially during "lean" periods when flower production is low

Importance of cut fillers in Floriculture Industry:

i. Aesthetic Importance:

- ✚ **Volume and Structural Support:** Filler materials help to add bulk to floral arrangements, enabling florists to create fuller, more luxurious designs while minimizing the use of costly focal flowers.
- ✚ **Texture and Visual Contrast:** They enhance aesthetic appeal by introducing diverse shapes and colors ranging from spiky forms like thistle to delicate textures such as Limonium thereby creating contrast with primary blooms.
- ✚ **Background and Framing Effect:** Cut foliage acts as a natural green backdrop that highlights the vibrancy of flowers while also concealing structural elements like floral foam and wiring.
- ✚ **Softening and overall harmony:** Light-colored fillers, such as Baby's Breath and Waxflower, help tone down strong hues and contribute to a balanced, cohesive, and natural "garden-style" appearance.

ii. Economic Importance:

- ✚ **Enhanced Profitability for Growers:** The commercial cultivation of filler flowers is emerging as a highly profitable sector due to its low initial investment, lower production risks, and consistently high market demand, making it suitable for both small and large-scale farmers.
- ✚ **Continuous Market Supply:** Unlike seasonal flowers, many filler plants such as *Gypsophila*, *Mum*, *Chrysanthemum*, *Limonium* etc., are available throughout the year, ensuring a stable and regular source of income.
- ✚ **Strong Export Opportunities:** Premium-quality, well-graded cut fillers have significant demand in international markets, especially in regions like Europe, the United States, and Japan.
- ✚ **Scope for Value Addition:** These filler flowers also play an important role in value-added products such as dried, bleached, and dyed arrangements, which enhance shelf life and increase overall market value.

iii. Post Harvest Importance:

- ✚ **Prolonged Vase Life:** Several cut filler species exhibit significantly longer vase life compared to fresh flowers, making them highly preferred by consumers seeking long-lasting decorative options.
- ✚ **Greater Transport Durability:** Filler materials are generally sturdier than delicate blooms, enabling them to endure long-distance transportation and handling with minimal damage.
- ✚ **Eco-Friendly Production:** The cultivation of cut fillers typically requires fewer chemical inputs, less controlled heating, and lower energy consumption than greenhouse-grown flowers, making it a more sustainable and environmentally friendly option in the floriculture industry.

Brief about few Important Filler crops:

1. Limonium

Limonium commonly known as Statice or Sea Lavender belongs to the family *Plumbaginaceae* and includes important species such as *Limonium sinuatum* (Annual Statice), *Limonium latifolium* (Perennial Statice) and *Limonium perezii*. Common varieties are Blue River, Yellow Sunbird, Iceberg, Gold Coast, Midnight Blue, American Beauty. It is high value for adding the volume, color good texture for bouquets. It has long life as a vase life since it remains bright fresh even dry for longer time is known as "Everlasting flower". It can maintain for 12- 24 months as wreath and arrangements. It is a popular, hardy filler flower that is used in both fresh and dried bouquets. Due to varietal, it is different in color such as the deep color white, pink, and yellow, along with fragrance free variety. It is eco- conscious and low maintenance flower for import purpose. The market value for the global export is Mexico with 3800 shipments with high significant holding after the Netherlands.

It prefers a light, well-drained sandy loam soils and is tolerant to salinity and drought conditions. It grows well in full sun and mild climate. The propagation of Limonium is commercially done through seeds. The seeds are first sown in plugtrays or pottrays or nursery beds using cocopeat and the seedlings are ready for transplanting in the field after one month. Planting is done at a spacing of 30 × 30 cm or 45 × 45 cm depending on variety. Planting season varies with region but generally grown as a winter crop. Proper nutrition management plays a crucial role in achieving higher yield and quality in flower crops. Intercultural operations such as regular weeding are essential to minimize competition for nutrients and moisture, and mulching helps conserve soil moisture, regulate temperature, and suppress weed growth. Additionally, pinching of plants may be practiced to promote better branching and increased flower production. Harvesting should be done when the flowers are fully open but before pollen shedding to ensure maximum quality, making them suitable for both fresh and dried flower purposes; however, the yield largely depends on the variety and management practices adopted. In terms of post-harvest handling, these flowers exhibit excellent drying qualities, retaining their color even after drying, and can be processed using air drying or silica gel methods. Furthermore, they possess a relatively long shelf life compared to many other cut flowers, making them highly suitable for commercial use.



2. Gypsophilla

Gypsophilla, commonly known as Baby's Breath, belongs to the family Caryophyllaceae and includes important species such as *G. elegans*, *G. paniculata*, *G. repens*, *G. muralis*, *G. pacifica*, and *G. acutifolia*, while popular varieties are Fun Time Ultra, Over Time, Cassiopeia, Dynamic Love, Orion, New Love, Million Stars, and Pink Fairy. Native to Europe and West Asia, it is widely used in borders, rock gardens, and as a filler in floral bouquets. Propagation is mainly done through seeds by direct or staggered sowing, as well as vegetatively through stem cuttings treated with growth regulators like IBA or NAA to enhance rooting. The crop prefers well-drained soil rich in organic matter and thrives under cool-season conditions, requiring protection from frost along with sunny weather and light rainfall. Planting is generally done with a spacing of 90 cm between rows and 35- 40 cm within rows, maintaining a plant density of about 3-4 plants per square meter. Growth regulators such as gibberellic acid (GA) promote flowering under long-day conditions, while CCC and MH help suppress excessive vegetative growth, and BA enhances flowering. Intercultural operations like mulching improve flowering and yield, staking supports tall stems, and pinching encourages uniform shoot growth. Harvesting is carried out when about 50% of the flowers are open, and stems are usually bunched in groups of five; however, the flowers are sensitive to ethylene. Post-harvest management includes treatment with silver thiosulfate (STS) to improve longevity and storage at 0–1°C under high humidity, although the vase life is relatively short but can be extended with preservatives. Tinting is used in gypsophilla for adding the different color such purple, pink, gold. The crop is susceptible to diseases such as root rot, powdery mildew, stem rot, and crown rot, while common insect pests include mites, leaf miners, and aphids.

3. Blue Aster

Blue Aster (*Aster* spp.), belonging to the family Asteraceae, is a popular filler flower widely used in bouquets and floral arrangements, and is commonly known as Blue Aster or Michaelmas Daisy. It produces attractive daisy-

like flowers in shades of blue, purple, pink, and white, adding texture and color to floral designs. Important species include *Aster amellus*, *Aster novi-belgii*, and *Aster novae-angliae*, while notable varieties are Blue Moon, Lady in Blue, Purple Dome, White Ladies, and Sapphire. The crop can be propagated through seeds, stem cuttings, and division, with division of clumps being the most commonly practiced method. It prefers well-drained, fertile loamy soil and thrives in cool to mild climatic conditions, requiring full sun to partial shade for optimal growth. Planting is usually carried out during spring or early winter, with recommended spacing of 30 × 30 cm or 45 × 45 cm. Proper nutrition is essential, and the application of farmyard manure improves plant growth, while balanced fertilization with nitrogen, phosphorus, and potassium enhances flowering. Intercultural operations such as regular weeding and irrigation are necessary for healthy plant development, and practices like pinching promote bushy growth and increased flower production, while staking may be required for taller varieties. Harvesting is done when the flowers are partially open to ensure better quality and longer usability as cut flower fillers, with yield depending on the variety and cultural practices followed. Post-harvest, Blue Aster exhibits a moderate vase life, which can be improved with the use of floral preservatives, and storage under cool conditions helps extend shelf life. The crop is commonly affected by pests such as aphids, spider mites, and thrips, and diseases like powdery mildew and leaf spot, which need to be managed for successful cultivation.

4. Golden Rod

Golden Rod (*Solidago canadensis*), belonging to the family Asteraceae (Compositae), is a perennial herb widely used as a border, bedding, potted plant, and act as a cut flower or filler, characterized by its erect growth habit reaching 90–120 cm in height and producing numerous small yellow flower heads arranged in terminal panicles over an extended period. Popular varieties include Minuta, Golden Wing, Golden Mosa, Leraft, Lesden, Peter Pan, and Little Lemon. The crop is propagated through seeds, rhizomes, suckers, and cuttings, although commercial cultivation mainly relies on suckers and clump division. It can grow in a wide range of soils but performs best in well-drained, porous soil under mild climatic conditions, with flowering influenced by photoperiod. Land preparation involves ploughing to a depth of 25–30 cm, and planting is generally done during May–June with spacing of 60 × 60 cm or 30 × 30 cm in the first year. Nutrient management includes the application of FYM and organic manure along with recommended doses of 100–150 kg nitrogen, 100–150 kg phosphorus, and 50–100 kg potassium per hectare. Immediate irrigation after planting and regular weeding are essential for proper growth. Harvesting is carried out when about 25% of the flowers are open, yielding around 20–25 stems per square meter per season.



5. Mum Chrysanthemum

Mum chrysanthemum is preferred as a filler flower in the floral industry due to its spray type inflorescence, long vase life, year-round availability, wide colour range, durability during transport, and cost-effectiveness. These qualities make it one of the most reliable and commercially important filler flowers worldwide. While traditionally used as a focal flower, Mum chrysanthemums have seen a massive surge in demand as "fillers" because they offer volume, a wide color palette, and exceptional durability. Multiple small blooms on a single stem make them

perfect for "bulking up" bouquet. Mum chrysanthemums typically last 10-20 days, outlasting most other filler flowers. This makes them the top choice for supermarket bouquets and subscription flower boxes. With rising shipping and production costs, Mum chrysanthemums offer a high "visual-impact-to-cost" ratio. They allow florists to create lush, full-bodied arrangements while staying within consumer budgets. The global market for fresh Mum chrysanthemum bouquets was valued at approximately USD 42.53 Billion in 2025 with a projected growth rate (CAGR) of around 4-7% through 2025-2035. Poland recently saw a 38.9% increase in Mum chrysanthemum imports, signalling a shift in Eastern European consumer preferences. In Japan, Mum chrysanthemums are already a dominant flower type culturally and commercially, contributing significantly to sales and exports. India exported fresh Mum chrysanthemums to multiple countries (e.g., Singapore, Georgia, Australia) with ~324 recorded shipments from Indian exporters. The year of 2024 witnessed the highest amount of fresh cut flower Mum chrysanthemum imports. Total 23 shipments weighing 179 Tons were imported during the year 2024. All the fresh cut flower Mum chrysanthemum importers accounted for 47 import shipments weighing 341 Tons.



Use of fillers in hand bouquet

Conclusion

The rising demand for cut fillers such as Limonium, Gypsophila, Blue Aster, Solidago, and Mum chrysanthemum clearly reflects their growing importance in the modern floral industry. These fillers not only enhance the aesthetic appeal, volume, and texture of floral arrangements but also provide cost-effective solutions for both florists and consumers. Their versatility, wide range of colors, and longer vase life compared to many primary flowers make them indispensable in bouquets, event decorations, and export markets. Additionally, the increasing popularity of dried flowers and sustainable floristry has further boosted their demand, as many fillers retain color and structure even after drying. With expanding market opportunities, ease of cultivation, and adaptability to diverse climatic conditions, cut fillers are emerging as a promising segment in floriculture, offering significant potential for growers, entrepreneurs, and the global floral trade.

From Soil to Screen: The Digital Twin Revolution in Agriculture



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Introduction

Agriculture consumes about 70% of the world's freshwater, making it the leading user of water resources worldwide. This heavy reliance on water for farming presents major challenges, including water shortages, inefficient use and damage to local ecosystems. As population grow and climate patterns shift, implementing sustainable water management practices in agriculture becomes increasingly crucial.

Precision irrigation is vital in modern agriculture, delivering water exactly when and where plants need it. It reduces water waste, environmental impact and enhances crop yield by managing soil moisture and nutrients in better way. Digital twin technology, creating virtual models of physical systems, gains importance by enabling real-time monitoring, simulation and analysis of farming activities, thus supporting data-driven decisions and predictive management.

The integration of digital twin technology with precision irrigation offers substantial benefits, including more accurate water application and improved resource management. It also allows farmers to simulate irrigation scenarios before implementation. This combined approach supports sustainable farming practices by reducing water consumption, preventing over-irrigation and enabling dynamic adaptation of irrigation strategies to environmental conditions and crop needs.

Digital Twin Technology in Agriculture

Digital twin technology in agriculture develops a live virtual model of farming systems that reflects real conditions and activities. It allows for ongoing, real-time tracking, simulation and analysis of elements like soil, crops, weather and irrigation. By combining sensor data with environmental factors, digital twins offer a thorough and current overview of farm operations.

In agriculture, digital twins enable predictive management and support data-driven decisions, helping farmers optimize resources, forecast crop needs and respond proactively to changing conditions. In precision irrigation, digital twin technology enhances water delivery accuracy and efficiency by simulating irrigation scenarios and adjusting strategies based on real-time feedback. This approach encourages sustainable farming by reducing water waste, preventing over-irrigation and improving crop health and yields.

Layers of Digital Twin

Digital Twin technology is revolutionizing agriculture by enabling farmers to manage resources more effectively, boost productivity and base decisions on data. It relies on a layered architecture that models and enhances real-world farming activities within a virtual environment. The five layers - Physical, Data, Integration, Modelling & Simulation and Applications, demonstrate how Digital Twins are shaping the future of farming.

1. Physical Layer: The Farm and its Sensing Network

The foundation of an agricultural Digital Twin is the Physical Layer, comprising all real-world assets and processes on the farm. This includes fields, crops, livestock, irrigation infrastructure, tractors, greenhouses, storage facilities, sensors and devices that monitor them. Soil moisture probes, weather stations, IoT-enabled equipment, drones and cameras capture environmental and operational data. These devices are strategically placed for comprehensive monitoring and their quality determines the data's richness and accuracy. A well-instrumented farm provides the raw data for smart management.

2. Data Layer: Collecting and Storing Agricultural Information

The Data Layer is the digital repository for sensor readings, equipment logs, weather, and operational data. In agriculture, it includes soil pH, nutrient levels, crop health from drone images, irrigation, machinery fuel and yield data. It must handle real-time data from many devices and support structured and unstructured data like photos and satellite images. Secure cloud platforms ensure data integrity, traceability and access. Data preprocessing filters errors, calibrates and timestamps to ensure high-quality data for the next layer.

3. Integration Layer: Harmonizing Data Sources

Agricultural operations generate data from various sources: sensors, weather APIs, farm management software, drone imagery and equipment telemetries. The Integration Layer functions as a bridge, unifying and connecting this data for analysis. It employs middleware, APIs and data connectors to standardize formats, align timestamps and combine streams from multiple devices. Soil moisture data is integrated with weather information and irrigation logs, while drone images are mapped to specific locations and crop stages. Additionally, it provides actionable insights or control signals to the field, such as directing smart irrigation systems based on a Digital Twin's recommendations.

4. Modeling and Simulation Layer: The Virtual Farm

The core component of the agricultural Digital Twin is the Modeling and Simulation Layer. It leverages harmonized data to craft a virtual replica of the farm, including its fields, equipment and processes. Using advanced models, crop simulators and machine learning, it animates this virtual farm to support scenario analysis and predictive simulations. Farmers can explore various "what-if" scenarios such as altering irrigation, trying different fertilizer applications or responding to drought forecasts without risking crops or resources. The system can forecast yields, simulate pest or disease outbreaks and optimize planting or harvesting schedules based on real-time and historical data. The reliability of this layer hinges on the quality of the models and data used.

5. Application Layer: Insights, Decisions and Control

The Application Layer provides farmers and stakeholders with the value of the Digital Twin through user-friendly dashboards, alerts, mobile apps and reports. It enables visualization of farm conditions, delivers recommendations and supports decision-making. By leveraging advanced analytics, AI insights and simulations, it helps optimize operations and planning, potentially allowing automated control of farm systems based on model suggestions. This layer supports multiple use cases- precision irrigation, pest detection, labor planning, supply chain and compliance-transforming complex data into practical insights and smarter promoting towards more resilient farming.

Comparison between Traditional Agriculture and Digital Twin Agriculture

Parameters	Traditional Agriculture	Digital Twin Agriculture
Data Basis	Intuition and on-site manual inspections and traditional standards.	Real-time IoT sensors, satellite imagery and weather APIs.
Model Nature	Static relies on fixed empirical constants.	A dynamic, "living" model that updates through real-time feedback loops.
Decision Making	Reactive (responding to visible crop stress/wilting)	Proactive (predicting stress before it manifests).
Irrigation Strategy	Uniform (field-level application).	Precision-based (variable-rate and zone-specific application).
Scenario Testing	Impossible without physical field risk.	"What-if" simulations in a virtual environment.
Feedback Loop	Open-loop: No automated adjustment.	Closed-loop: Real-time correction of irrigation actuators.

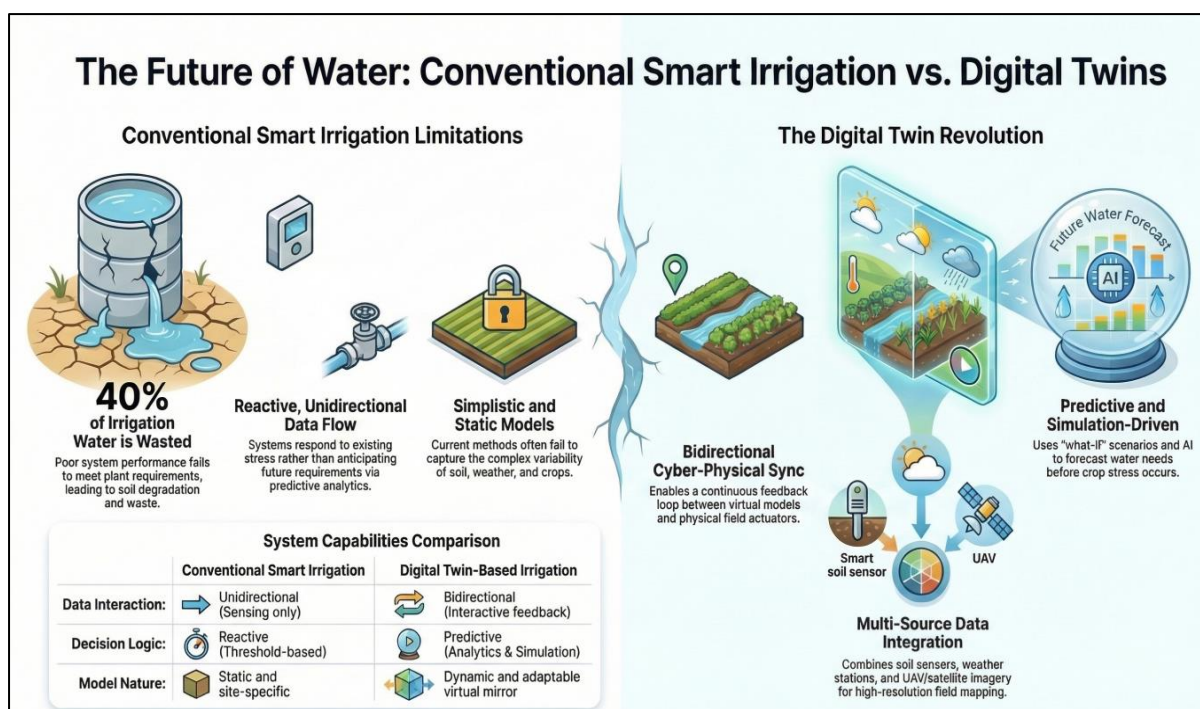


Fig. 1: The future of water – The Digital Twin technology

Conclusion

Digital twin technology transforms smart farming from reactive to proactive, predictive approaches. By combining real-time data with virtual simulations, it improves efficiency, reduces resource waste and promotes long-term food security. Overall, integrating Digital twin technology with smart farming turns agriculture into a data-driven, efficient and sustainable system, enabling real-time monitoring, accurate decision-making and optimal use of resources to boost productivity and ensure food security.

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Net-Zero Farming Through Carbon Sequestration and Sustainable Land Management



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Abstract

Agriculture is among the most vulnerable industries adversely impacted by climate change effects. Increases in greenhouse gases, soil erosion, depletion of water resources, and changing weather conditions threaten food security and the sustainability of agriculture around the world. In this regard, net-zero farming can be referred to as a climate-smart method of farming that concentrates on cutting down carbon emissions and increasing carbon sequestration in the soil and vegetation. Carbon sequestration and sustainable farming play key roles in net-zero farming, and they play critical roles in improving soil quality, managing resources sustainably, and promoting agricultural productivity. Agroforestry, crop rotation, conservation tillage, organic farming, crop residues management, and precision farming are some of the sustainable farming practices that have a great contribution to atmospheric carbon capture and minimizing negative environmental effects. This paper highlights net-zero farming importance, methods of carbon sequestration, sustainable land management practices, advantages for farmers and the environment, challenges in adopting them, and prospects for sustainable agriculture.

Keywords: Net-zero farming, Carbon sequestration, Sustainable agriculture, Climate-smart farming, Soil carbon, Carbon farming.

Introduction

Agriculture plays an essential role in the provision of food security, income, and economic development globally. The current farming practices have been found to cause significant emissions of greenhouse gases through extensive use of synthetic fertilizers, crop burning, deforestation, and land degradation (IPCC, 2021). On the other hand, climate change poses a great threat to agriculture through increased warming, altered precipitation patterns, droughts, floods, and loss of soil fertility. As a solution to environmental problems in agriculture, the idea of net-zero farming has received much attention worldwide as a sustainable means of agriculture. Net-zero farming is a practice of balancing the emission of greenhouse gases in agriculture by reducing carbon emissions and improving carbon uptake using sustainable farming practices. Carbon sequestration, which is the process of taking atmospheric carbon dioxide and storing it in soils, plants, and biomass, has been identified as one of the most reliable ways of achieving climate-smart agriculture and addressing climate change (Lal, 2015). Soil carbon sequestration, increased soil fertility, resource conservation, and improved farm productivity can be achieved through the adoption of sustainable land use practices like conservation tillage, agroforestry, organic farming, crop rotation, and integrated nutrient management. As such, net zero farming represents a viable strategy towards climate-smart agriculture and food security.

Understanding Net-Zero Farming

Net-zero farming refers to an agricultural practice whereby the level of emissions of greenhouses produced by agriculture is equal to the amount of carbon that is sequestered through various agricultural practices. The key aim of net-zero farming is achieving low environmental impact without jeopardizing agricultural productivity. Net-zero farming involves practices that ensure reduction in carbon emissions, increase in soil carbon sequestration, conserve resources, increase biodiversity, and promote sustainable agricultural practices. Practices such as conservation tillage, agroforestry, organic farming, diversified cropping, and management of resources contribute towards making net-zero farming successful as far as improving soil health, mitigating risks related to climate change, and environmental conservation are concerned. Economic sustainability of farming communities is also achieved through net-zero farming practices.

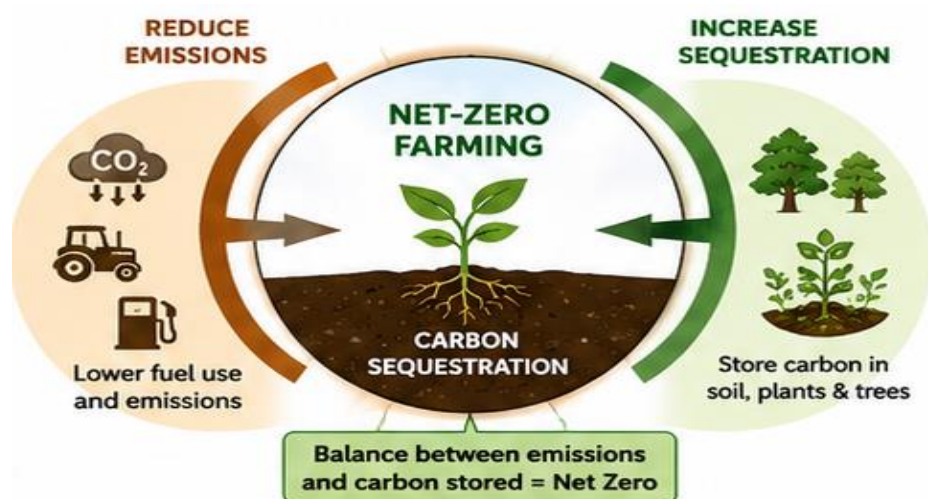


Figure 1: Understanding Net-zero farming

Role of Carbon Sequestration in Agriculture

Carbon sequestration refers to the process of capturing atmospheric carbon dioxide and storing it in soil, plants, trees, and organic matter. Agricultural soils have significant potential to function as carbon sinks when managed using sustainable agricultural practices (Paustian et al., 2016). Farmers can enhance soil carbon storage through practices such as reduced tillage, cover cropping, crop residue incorporation, agroforestry, organic manure application, and crop rotation. These sustainable farming practices improve soil organic matter content, enhance microbial activity, and increase the soil's ability to retain water and nutrients. In addition to reducing greenhouse gas concentrations in the atmosphere, carbon sequestration also improves soil fertility, strengthens ecosystem sustainability, and enhances overall agricultural productivity.

Sustainable Land Management Practices for Net-Zero Farming

Agroforestry

Agroforestry is a form of sustainable agriculture where trees are used together with crops and livestock in farming. Trees have a very important role in the uptake of carbon dioxide from the atmosphere and its storage in the form of carbon within plant biomass and soil, thus facilitating carbon sequestration and climate change adaptation (Nair, 2012). Carbon storage aside, agroforestry helps increase biodiversity, prevent soil erosion, increase soil fertility, conserve water, and create a microclimate conducive for growing crops. It also helps farmers earn extra income through selling timber, fruits, fodder, firewood, and medicinal plants among other products. Agroforestry is therefore an important agricultural system that benefits the environment as well as farmers financially. For example, farmers practicing coconut-based farming systems along with fodder grasses and fruit trees would help increase carbon storage while at the same time earn income from their farms.

Cover Crops

Cover crops refer to planting crops mainly to benefit soil quality instead of harvesting them. The benefits include minimizing soil erosion, adding organic matter to soil, retaining soil moisture, suppressing weed growth, and increasing soil carbon levels. The planting of cover crops ensures microbial activities and recycling of nutrients in soil, hence promoting soil fertility and sustainability. Leguminous cover crops facilitate biological nitrogen fixation and minimize the use of synthetic fertilizers in farming. For example, planting legume cover crops such as sunhemp or cowpea during fallow periods helps fix more nitrogen and improves soil fertility and carbon storage.

Conservation Tillage

Conservation tillage involves minimal disruption of the soil through tillage and is useful for maintaining soil organic carbon. The practice involves less frequent ploughing to reduce carbon dioxide emissions from the soil, conserve soil water, improve soil structure, and prevent soil erosion (Lal, 2004). It also uses less energy in terms of fuel and reduces labor by decreasing the number of field operations. Conservation tillage is useful in practicing

sustainable agriculture and smart climate practices. For example, zero tillage wheat farming uses less fuel, improves soil structure, conserves soil water, and increases soil carbon sequestration.

Management of Crop Residues

The management of crop residues refers to making efficient use of the residues of the crops, rather than setting them on fire within the field. The farmers can use crop residues either by mixing them into the soil, composting, or using them as fodder or mulches. The technique ensures the increase in the soil carbon level and prevents soil pollution in the environment. It helps save soil moisture, recycle nutrients, stimulate microbial activities, and retain carbon in the soil. For example, mulching through the use of paddy straw in the crop field ensures soil moisture retention and carbon enrichment in the soil.

Organic Farming

Organic farming favors the use of natural and biological materials like farmyard manure, compost, green manure, bio-fertilizer, and bio-pesticides in lieu of chemical products. Organic farming benefits the soil microbial life, increases the soil organic matter, improves nutrient availability in the soil, and leads to improved soil health in the long term. Organic farming facilitates carbon sequestration through increased carbon stock in the soil. Use of vermicompost in farming results in higher soil fertility, greater soil microbial activity, and an increased organic carbon stock in the soil.

Precision Agriculture

Precision agriculture is the practice that makes use of technologies like drone, sensor, GPS, remote sensing, and artificial intelligence for making the use of agricultural inputs as efficient as possible (Gebbers & Adamchuk, 2010). Precision agriculture makes sure that proper quantities of water, fertilizers, and pesticides are used based on the requirement of crops. It helps in making sustainable agriculture by minimizing wastage and minimizing greenhouse gas emissions. The irrigation system with the help of sensors helps farmers avoid wastage of water and energy.

Benefits of Net-zero farming

Environmental Benefits

Net-zero farming provides significant environmental benefits by reducing greenhouse gas emissions and enhancing carbon sequestration in agricultural soils and vegetation. Sustainable farming practices such as agroforestry, conservation tillage, crop residue management, and organic farming help increase soil carbon storage and reduce the release of carbon dioxide into the atmosphere. These practices also contribute to the conservation of biodiversity, protection of natural resources, reduction of soil erosion, and prevention of land degradation. By improving soil health and ecosystem stability, net-zero farming plays an important role in mitigating climate change and promoting environmental sustainability.

Economic Benefits

Net-zero farming help to promote efficient use of resources and reduce costs in the production process. The adoption of sustainable agriculture practices promotes the efficient use of water, fertilizer, and energy, hence reducing cost. Soil fertility and soil organic matter improve the ability to ensure productivity and sustainable crop yields. Additionally, carbon farming practices provide an opportunity for farmers to engage in carbon trading to earn more money. Moreover, diversified farming practices like agroforestry ensure that there are various income streams from crops, timber, fruits, and livestock products.

Social Benefits

A net zero approach in farming practices promotes social sustainability by enhancing the lives of people in rural areas and providing adequate food security. Sustainable farming practices facilitate the maintenance of productive farmlands with sufficient production of nutritious foods for increasing numbers of people. Moreover, sustainable farming promotes collective action in agriculture and conserving the environment among the farming community. The practice increases the level of awareness about sustainable resource management and climate-friendly agricultural practices in rural settings.

Carbon Credits and Farmer Opportunities

The adoption of carbon farming and net-zero agriculture is gaining ground as a new way not only to achieve sustainability but also to increase farmers' income due to carbon credits. A carbon credit is basically a certificate

issued for lowering greenhouse gas emissions or for enhancing carbon storage, whereby a carbon credit usually represents one metric ton of carbon dioxide (CO₂) emission reduction or removal from the atmosphere (World Bank, 2023). The agriculture sector provides many ways for farmers to make profits by earning carbon credits. These ways include the application of sustainable farming techniques like agroforestry, conservation tillage, cover crops, crop residues management, organic farming, precision agriculture, and integrated nutrient management. These innovative approaches to agriculture contribute to capturing atmospheric CO₂ and storing it in the soil, trees, and biomass. In this regard, farmers producing carbon credits can then go on to sell them in carbon markets to businesses trying to reduce their carbon footprint, thus earning some money and promoting sustainable farming at the same time.

Apart from earning money through carbon credit schemes, carbon farming not only makes the soil fertile but also increases its water retention ability, promotes biodiversity, cuts down input expenses, and leads to increased productivity over the long term. To illustrate, agroforestry practices involving crop planting alongside tree plantation allow for more carbon storage in plants and the soil, as well as additional revenue from selling timber, fruits, and fodder. Likewise, zero tillage and cover cropping enable the accumulation of soil organic carbon while cutting fuel usage and emissions of greenhouse gases. Nonetheless, the involvement of farmers in carbon farming is hampered by such issues as poor knowledge of carbon markets, expensive certification, technical ignorance, inability to measure soil carbon content, and weak policies. As a result, training, technical expertise, digital platforms, and funding should be provided by the government, agricultural universities, extension services, and agritech businesses to ensure successful implementation. Given current attention paid to climate change and net zero goals worldwide, carbon credits appear to hold great promise for agricultural transformation.

Challenges in Achieving Net-Zero Farming

- Limited awareness among farmers regarding carbon farming practices.
- High initial costs involved in adopting sustainable technologies.
- Lack of technical knowledge and training programs.
- Poor policy support and limited access to carbon markets.
- Difficulty in measuring and monitoring soil carbon levels.
- Small landholdings and resource limitations among farmers.
- Limited access to advanced technologies and precision farming tools.
- Climate uncertainties affecting farming systems and carbon management practices.

Future Prospects of Net-Zero Farming

The future of net zero farming looks very promising because of the growing attention to climate change mitigation, environmental sustainability, and climate-smart agriculture across the world. Many governments, agricultural research organizations, agricultural universities, and agritech firms are working on carbon farming technologies, sustainable land management techniques, and low-carbon agricultural systems to enhance the sustainability of farming practices and promote environmental conservation. The technologies that can be helpful for achieving the above objectives include Artificial Intelligence (AI), Internet of Things (IoT), drones, remote sensing, satellite monitoring, and precision agriculture. Moreover, carbon credits, green finance initiatives, and supportive government policies can motivate farmers to adopt sustainable and climate-resilient farming practices in the future.

Conclusion

Net zero farming through carbon capture and sustainable land use is fast proving to be a successful strategy for combating climate change, improving soil condition, and sustaining agriculture. Some of the sustainable strategies such as agroforestry, crop cover, conservation tillage, organic farming, and precision farming aid in cutting down on the amount of greenhouse gases emitted by farms and at the same time enhance soil fertility and conserve natural resources. Besides the environmental benefits that net zero farming can afford, there is also the possibility of creating new economic activities from it since it involves lower input costs, efficient use of resources, and involvement in carbon credits among other things. Despite the obstacles that exist in promoting this approach,

especially in terms of lack of knowledge and inadequate technology and policy support, increasing funding in climate-smart agriculture shows great promise for the future.

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White Muscle Disease in Shrimp: Emerging Threats in Aquaculture



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Introduction

Shrimp aquaculture has become one of the fastest-growing sectors in global food production. Commercially cultured shrimp species occupies an important position due to its high market value, excellent taste, adaptability, and export demand.

However, disease outbreaks continue to pose serious challenges to sustainable shrimp farming worldwide. Bacterial, viral, fungal, and parasitic infections can rapidly spread in intensive aquaculture systems and cause heavy economic losses. The most commonly encountered diseases such as White spot syndrome Virus (WSSV) and *Enterocytozoon hepatopenaei* (EHP) accounts for severe production loss ($2.58 \pm 0.32 \text{ t ha}^{-1} \text{ crop}^{-1}$) and economic loss (US\$ 567.62 M). Recently, White Muscle Disease (WMD) has emerged as an important condition affecting shrimp health and farm productivity.

With this background this article describes the pathogenicity and causative agents for the WMD and the possible biosecurity measures to be carried out

White Muscle Disease in Shrimp

White Muscle Disease (WMD) in shrimps is characterized by the appearance of opaque or whitish muscles. The WMD is also described as “cotton shrimp,” “chalky shrimp,” or “cooked meat shrimp” because of the pale white coloration of the musculature.

The disease onset starts with small whitish patches in the abdominal muscle segments. As the infection progresses, the white patches spread throughout the body musculature, leading to muscle necrosis and tissue degeneration. In severe cases, the entire body appears milky white.

Etiology of WMD in shrimps:

Coming to the pathogen associated with White Muscle Disease is not caused by a single etiologically agent. Different microorganisms including viruses, bacteria, and microsporidians have been associated with this condition. Among bacterial agents, *Photobacterium damsela* subsp. *damsela* has recently attracted scientific attention due to its association with severe outbreaks in cultured shrimp.

Different Etiological Agents Associated with White Muscle Disease (WMD) in shrimps:

1. Microsporidian causes

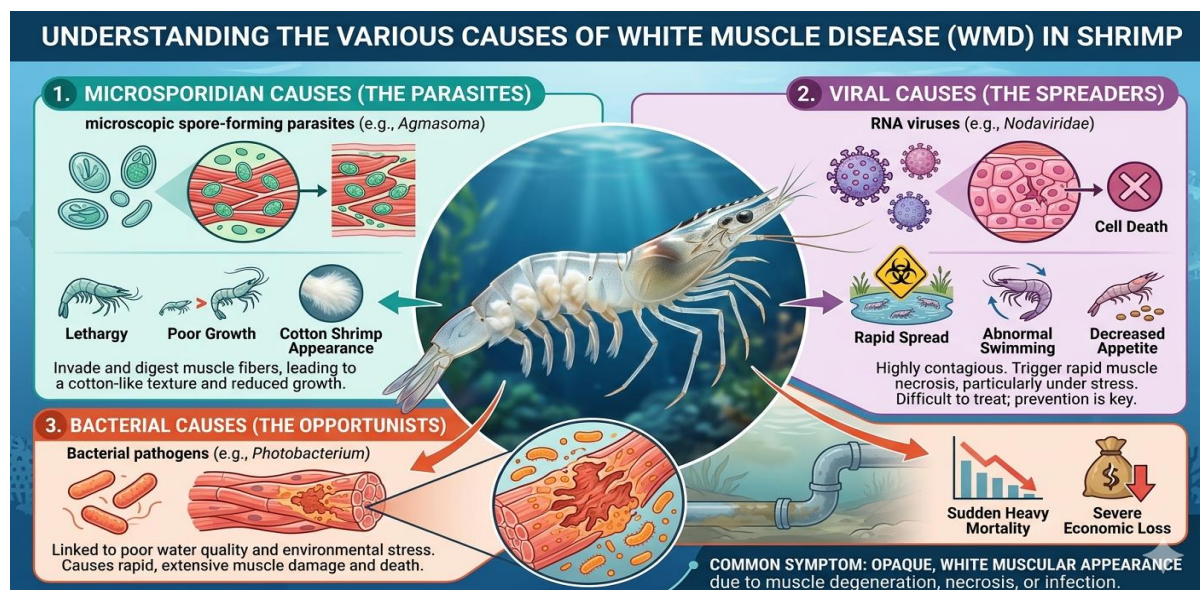
Microsporidians are tiny, spore-forming parasites. These microscopic organisms move into the shrimp's muscle cells and start multiplying. **The main causative agents includes** parasite groups such as *Agmasoma* or *Ameson* which invades the shrimp tissue. This results in the muscle wasting and destruction of muscle fibres from inside out. The gross signs includes fluffy and solid white muscle and hence the name "**cotton shrimp disease**."

2. Viral Causes

These are caused by RNA viruses specifically from the *Nodaviridae* and *Totiviridae* families. These viruses hijack the shrimp's cells to replicate. This happens when shrimps are in extreme stressed environment. The WMD by viruses causes muscle necrosis leading to the loss of normal transparency of the muscle and formation of the opaque muscle. Behavioural signs usually notice includes abnormal swimming with white patches on the muscle

3. Bacterial Causes (The Opportunists)

Bacterial WMD is usually caused by opportunistic bacterium like *Lactococcus* and *Photobacterium*. These are normal inhabitants of the shrimp ecosystem often present in the water and causes infection when the shrimp is weak or immune compromised. The bacteria infest flesh causing severe tissue damage and rot. There is rapid whitening in tails with sudden onset of mortality.



Representative illustration created using AI tools.

Behavioural symptoms:

- Infected shrimp become weak, lethargic, and less active.
- Feeding behavior decreases, swimming becomes abnormal, and affected shrimp often remain near pond edges or the bottom.
- Mortality may occur within a few days after the onset of symptoms, with losses ranging from 30% to 100% depending on the severity of infection and farm conditions.

Disease Outbreak in Okinawa, Japan

Recent WMD outbreak has been reported at Okinawa, Japan, in Kuruma shrimp associated with *Photobacterium damsela* subsp. *damsela* (Pdd). This bacterium is known to infect various marine organisms and is now gaining attention as an emerging pathogen in shrimp aquaculture. The outbreak highlighted the need for better disease monitoring, biosecurity practices, and scientific understanding of bacterial infections in cultured shrimp.

This investigation represented the first report linking Pdd with White Muscle Disease in Kuruma shrimp. The study emphasized the importance of integrating molecular diagnostics, microbiology, and epidemiological investigations in aquatic disease surveillance.

The Emerging Pathogen: *Photobacterium damsela* subsp. *damsela*

Photobacterium damsela subsp. *damsela* is a Gram-negative, rod-shaped opportunistic marine bacterium commonly found in marine and brackishwater environments. It is considered a mesophilic organism, meaning it grows well under moderate temperature conditions.

Historically, the bacterium was first isolated from diseased fish and was initially classified under the genus *Vibrio*. Later, detailed genetic and biochemical studies resulted in its reclassification as *Photobacterium damsela* subsp. *damsela*.

Zoonotic Importance of the Bacterium

An important concern associated with *Photobacterium damsela* subsp. *damsela* is its zoonotic potential. Human infections have been reported in coastal regions of Japan, China, Korea, Australia, and the United States.

Most human infections occur through exposure of wounds to contaminated seawater or during handling of infected fish and marine organisms. The bacterium can cause severe soft tissue infections and necrotizing fasciitis, which may become life-threatening if not treated promptly.

In addition, the bacterium has been associated with histamine food poisoning in seafood products due to its ability to produce histidine decarboxylase. Therefore, maintaining good hygiene and proper seafood handling practices is essential.

Factors Favoring Disease Outbreaks

Several environmental and management-related factors contribute to the occurrence of bacterial diseases in shrimp farms.

1. Poor Water Quality

Deterioration of water quality is one of the primary reasons for disease outbreaks. Elevated ammonia, nitrite accumulation, low dissolved oxygen, and organic matter buildup stress shrimp and reduce their immune resistance.

2. High Stocking Density

Overcrowding increases stress and facilitate rapid transmission of pathogens among shrimp populations.

3. Temperature Fluctuations

Sudden changes in water temperature may weaken shrimp immunity and favor bacterial growth.

4. Improper Feed Management

Overfeeding and poor-quality feed contribute to organic waste accumulation and microbial imbalance in ponds.

5. Inadequate Biosecurity

Movement of infected seed, contaminated equipment, untreated water, and farm workers between ponds can spread bacterial pathogens.

Diagnosis of White Muscle Disease

Early diagnosis is critical for preventing heavy mortality losses.

Clinical Examination

The presence of white or opaque muscles is the first visible indicator. Reduced feeding, lethargy, and abnormal swimming behavior may also be observed.

Microscopic Examination

Muscle tissue examination helps identify tissue degeneration and necrosis.

Bacterial Isolation

Samples collected from diseased shrimp are cultured on selective bacteriological media for isolation and identification.

Molecular Diagnosis

Polymerase Chain Reaction (PCR), sequencing, and molecular characterization techniques help confirm the pathogen accurately.

Histopathology

Histopathological examination reveals muscle damage, inflammatory responses, and tissue abnormalities associated with infection.

Prevention and Management Strategies

Prevention remains the most effective approach in shrimp disease management. Farmers should adopt integrated health management practices to minimize disease risks.

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Trichoderma's biodegradation of polyethylene: A sustainable way to combat plastic pollution



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Abstract

The widespread usage of plastic and the enormous amount of waste it generates have made it a global issue. According to Chae *et al.* (2015), this synthetic organic polymer is utilized in numerous affordably priced and multipurpose products. Due to the substantial accumulation of plastic trash, the growing usage of plastics has resulted in serious environmental degradation. Conventional polyethylene disposal techniques, such as landfilling and burning, are frequently inefficient and increase secondary contamination. Microbial degradation is a new strategy to deal with this problem (Zhu *et al.*, 2024). Because the biodegradation process is safe for the environment and doesn't harm the ecosystem, it can be utilized as an alternate degradation method. The process by which microorganisms can break down synthetic polymers like polyethylene and polystyrene or natural polymers like cellulose and lignin is known as biodegradation (Kaseem *et al.*, 2012). *Trichoderma* species, such as *T. harzianum* and *T. asperellum*, have shown the capacity to break down polyethylene through enzymatic activity, particularly through the formation of laccase and manganese peroxidase. These enzymes aid in the degradation of polyethylene polymers, causing treated plastics to significantly lose weight and undergo structural alterations. According to studies, *Trichoderma* may break down up to 40% of treated polyethylene in a lab setting. This can be verified by sophisticated analytical methods including Fourier-transform infrared spectroscopy and scanning electron microscopy (Sowmya *et al.*, 2014). Furthermore, applying *Trichoderma* improves soil nutrients and aids in the decomposition of plastic, providing two environmental advantages (Zhu *et al.*, 2024). One viable, environmentally beneficial way to reduce plastic pollution is to incorporate *Trichoderma*-based biodegradation into waste management plans. This strategy offers a workable and scalable way to solve the plastic pollution problem since it promotes soil fertility and lessens the persistence of plastic in the environment, both of which are in line with global sustainability goals.

Keyword: Environmental pollution, Eco-friendly, *Trichoderma*, Soil health.

Introduction

Plastic is one of the most widely used and practical materials created by humans. Because of its exceptional stability and prolonged endurance, it plays a crucial role in everyday life, from the kitchen to the industrial level (Ogunbayo *et al.*, 2019; Sangale *et al.*, 2019). According to the biodegradability of plastic, polymers, which are made up of big molecules, are divided into biodegradable and non-biodegradable polymers (Thomas. 2022). The main focus of this work is synthetic polymers. Globally, the seven most popular types of synthetic plastic are used. According to Baheti (2021) and Hardin (2021), these include polycarbonates, acrylic, polylactic acid (PLA), high-density polyethylene (HDPE), polyethylene terephthalate (PET), fibers, nylon, low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Plastic is used for a number of different purposes in many industries, such as packaging modules, commodities, and food wrapping. Due to its non-biodegradability, persistence, and stubborn nature, polyethylene caused severe environmental contamination worldwide, impacting our ecosystem (Mukherjee *et al.*, 2014). According to a recent study, between 300 and 400 million tons of plastics derived from fossil fuels are produced annually worldwide and seep into the environment (Ghatge *et al.*, 2020). According to Wilkes and Aristilde (2017), plastics' high molecular weight along a structural chain of polymers and hydrophobicity make them resistant to degradation. There are several ways to break down these polymers, including photodegradation, incineration, thermo-oxidative degradation, catalytic degradation, and biodegradation. However, exposure to high temperatures causes plastic to burn, releasing harmful chemicals into the atmosphere and posing health risks, like cancer and lung diseases (Pramila and Vijaya Ramesh, 2011). The biodegradation approach is generally preferred over other degradations because of its eco-friendly procedure

and pollution-free mechanism. Generally speaking, this biodegradation of plastics entails the growth of fungi on the plastic's surface, where the fungi use the plastic as food while being influenced by ambient elements like pH and temperature.

Biodegradation of Polyethylene

One of the most popular synthetic plastics is polyethylene (PE), partly because of its durability and adaptability. However, these very characteristics lead to serious environmental problems: PE accumulates steadily in landfills and natural ecosystems, contributing significantly to the world's plastic pollution, and is extremely resistant to degradation. Conventional degradation and disposal techniques, like chemical processes, landfills, and incineration, are frequently expensive, insufficient, or detrimental to the environment (Sanniyasi *et al.*, 2021).

A more environmentally friendly option is provided via polyethylene biodegradation. The strong carbon bonds in the polymer are broken by microbes like bacteria, fungi, and algae using their enzymatic machinery. This process reduces the molecular weight of the polymer and permits additional breakdown and assimilation. Under aerobic or anaerobic circumstances, complete mineralization transforms PE into harmless byproducts like carbon dioxide and water. Although encouraging, polyethylene biodegradation often proceeds slowly in the absence of an abiotic or chemical preparation that increases the plastic's accessibility to microorganisms (Montazer *et al.*, 2020).

Mechanism of polyethylene degradation by *Trichoderma*.

Trichoderma fungus have shown great promise in the breakdown of polyethylene, especially *Trichoderma harzianum* and *Trichoderma asperellum*. *Trichoderma* comprises of a large number of filamentous fungal strains that are rhizocompetent and may be found in a wide range of habitats with varying climatic zones (Ningshen *et al.*, 2025). Studies reveal that fungi may utilize polyethylene as a carbon source and enzymatically degrade it, contributing to plastic breakdown in both terrestrial and aquatic environments.

- *Trichoderma* spores or hyphae first stick to the polyethylene's surface. The fungus then forms a biofilm called hydrophobin, which creates a confined environment rich in fungal cells and released enzymes such as laccases, lignin peroxidase, manganese peroxidase, and alkane hydroxylase. These enzymes partially break down the polymer and increase its hydrophilicity by introducing oxygen-containing functional groups (such as hydroxyl, carbonyl, and carboxyl groups). PE becomes vulnerable to additional enzymatic attack as a result of the surface developing pits, fissures, and a roughened texture.
- By targeting the oxidized functional groups and C-C bonds, these enzymes accelerate the cleavage of the oxidized PE chains into even smaller molecules, such as oligomers and monomers (usually 10-20 carbon atoms). The fragments of the breakdown get small enough for entry of microbial cells.
- Microbial cells absorb the minor byproducts of PE decomposition, such as acetic acid and carboxylic acids. These compounds are broken down inside the cells by metabolic processes such as β -oxidation and the tricarboxylic acid (TCA) cycle, which produces biomass and energy.
- The biodegradation process is completed when the absorbed pieces are completely transformed into microbial biomass, carbon dioxide (CO₂), and water (H₂O) (Sowmya *et al.*, 2014).

Some findings on *Trichoderma* fungi's capacity to degrade polyethylene :

Using methods like thermogravimetric analysis (TGA), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM), which revealed structural alterations and fungal colonization on polyethylene surfaces, *Trichoderma harzianum* was able to achieve approximately 36% weight reduction of polyethylene in liquid media after one month and approximately 10% weight loss in soil after two months (Ahmed *et al.*, 2025).

In soil, *Trichoderma harzianum* mostly uses a biofilm-mediated oxidative pathway to break down polyethylene, while *Aspergillus niger* and other fungus use extracellular enzymes like lipase and esterases in liquid media. This implies that the degradative effect of *Trichoderma* depends on the environment and can be maximized by focusing on particular habitats. When used correctly, *Trichoderma asperellum* improves soil fertility and carbon sequestration in addition to demonstrating the capacity to degrade polyethylene. (Ahmed *et al.*, 2025)

The hydrocarbon backbone of polyethylene is oxidized to smaller monomers by enzymes such as laccases and peroxidases. The ability of *Trichoderma* species to biodegrade plastic is improved by the synthesis of

enzymes. Other polymers, such as PBAT, have been observed to be broken down by *Trichoderma* fungi, and the presence of herbicides may have an impact on their degradative activity. They may, however, also take up microplastic particles, which could have an impact on the processes of degradation (Varshney *et al.*, 2023).

Table 1: Potential effects of *Trichoderma* spp. on polyethylene degradation.

Sl. no	<i>Trichoderma</i> species	Types of plastic	Degradation %	Reference
1	<i>Trichoderma viride</i>	Polyethylene (HDPE)	25% (soil, 90 days); 18% (liquid medium, 30 days)	Verma and Gupta. 2018
2	<i>Trichoderma harzianum</i>	Polyethylene (PE, including LDPE & HDPE)	Up to 36% (LDPE, liquid medium, 1 month); 42% (HDPE, soil, 90 days); 25% (HDPE, liquid medium, 30 days)	Ahmed <i>et al.</i> , 2018
3	<i>Trichoderma asperellum</i>	Polyethylene (LDPE)	Degradation confirmed (4.15 % weight loss after 30days)	Zhu <i>et al.</i> , 2024
4	<i>Trichoderma harzianum</i>	Polyethylene LDPE	10.0% (soil, 2 months)	Ahmed <i>et al.</i> , 2025
5	<i>Trichoderma harzianum</i>	LDPE	36.0 ± 0.21% weight reduction in 1 month in liquid medium	Ahmed <i>et al.</i> , 2025

Conclusion

Trichoderma species offer a viable biological remedy for the worldwide problem of plastic pollution caused by polyethylene. The development of extracellular hydrolytic enzymes, oxidative enzyme activity that breaks C-C bonds in the polymer chain, and the generation of biofilms that improve surface colonization and degradation efficiency are some of the complementing mechanisms that drive the biodegradation process. Following *Trichoderma* treatment, studies have shown quantifiable decreases in polyethylene molecular weight, surface erosion, increased carbonyl index, and decreased tensile strength, confirming true biodegradation as opposed to fragmentation. However, before *Trichoderma*-based biodegradation can be scaled for industrial use, several important obstacles must be overcome. Because of its high molecular weight, hydrophobicity, and crystallinity, polyethylene is naturally resistant, which restricts its rate of disintegration. The development of cost-effective bioreactor systems for large-scale application, the isolation and engineering of *Trichoderma* strains with improved enzyme production and polyethylene affinity, the optimization of co-culture systems combining *Trichoderma* with bacterial consortia for synergistic degradation, thorough toxicological evaluations of degradation products, and the integration of *Trichoderma* biopesticides/biofertilizer applications with plastic waste management in agricultural systems should be among one of the primary objectives of future research.

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From Field to Phone: Transforming Agriculture through IGKV Digital Ecosystem



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Abstract

Digital agriculture is transforming conventional farming systems by integrating Information and Communication Technology (ICT), Artificial Intelligence (AI), and mobile-based advisory platforms into agricultural production and management practices. In Chhattisgarh, Indira Gandhi Krishi Vishwavidyalaya has emerged as a leading institution in promoting digital agriculture through the development of farmer-centric mobile applications and institutional e-governance platforms. The present paper reviews the major ICT-enabled applications developed by the university, namely Crop Doctor 2.0, Millet Doctor, e-Krishi Panchang, e-Haat App, and Sankhya App, and examines their role in strengthening smart farming systems, agro-advisory services, market linkage, and institutional management. Crop Doctor 2.0 utilizes Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Natural Language Processing (NLP), and computer vision technologies for automated diagnosis of crop pests, diseases, and nutrient deficiencies. Millet Doctor supports climate-resilient millet cultivation and tribal farming communities through localized agronomic advisories. e-Krishi Panchang integrates block-level meteorological data with traditional agricultural calendars to guide climate-responsive farm operations, while e-Haat App strengthens digital market connectivity through direct farmer-to-buyer transactions and transparent price discovery mechanisms. Sankhya App functions as an institutional Enterprise Resource Planning (ERP) and decision-support system for university governance and data-driven planning. Collectively, these applications represent an integrated digital ecosystem contributing toward precision agriculture, improved extension outreach, sustainable resource management, and digitally empowered farming communities in Chhattisgarh.

Keywords: ICT in Agriculture, Digital Agriculture, Smart Farming, Mobile Applications, Crop Advisory, IGKV, Chhattisgarh.

1. Introduction

Agriculture continues to play a vital role in the Indian economy by contributing significantly to national income, employment generation, and food security (Government of India, 2024). The agriculture and allied sector contribute nearly 18–20 per cent to the Gross Value Added (GVA) and supports the livelihood of more than half of the rural population in India (Economic Survey of India, 2024). In Chhattisgarh, agriculture remains the backbone of rural socio-economic development, with over 70 per cent of the population dependent on farming and allied activities (Government of Chhattisgarh, 2023). The state is also popularly known as the “Rice Bowl of India” because of its rich agro-biodiversity and extensive rice cultivation. Recent advancements in Information and Communication Technology (ICT) have created new opportunities to transform traditional agriculture into a precision-oriented and technology-driven system (FAO, 2022).

Digital agriculture has emerged as an important approach for improving productivity, resource-use efficiency, climate resilience, and market access in farming systems (World Bank, 2022). The rapid increase in smartphone usage, internet connectivity, and mobile-based advisory services has accelerated the adoption of ICT tools among farmers (Meera et al., 2021). Government programmes such as Digital India, e-NAM, and m-Kisan have further strengthened the rural digital framework and improved access to real-time agricultural information (Government of India, 2023). In Chhattisgarh, the adoption of digital agricultural technologies is steadily increasing due to improved digital infrastructure, extension awareness, and institutional support from agricultural universities and government agencies (Patel and Verma, 2022).

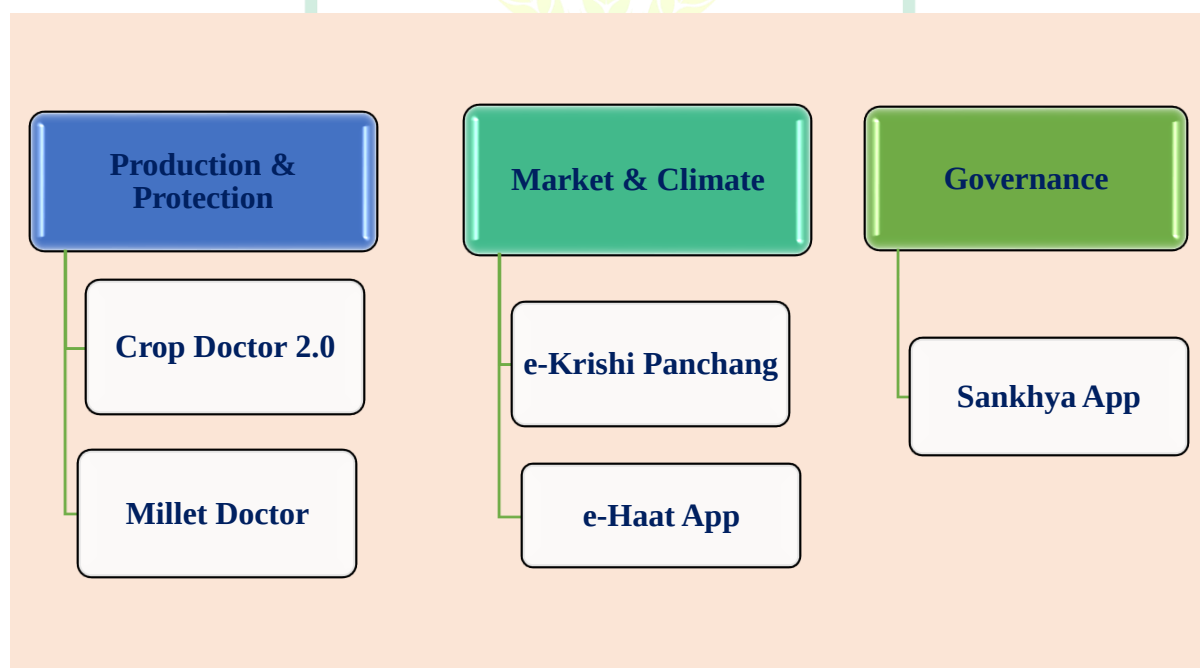
Recognizing this transition, Indira Gandhi Krishi Vishwavidyalaya has emerged as a leading State Agricultural University in agricultural digitalization and e-governance (Sahu, 2022). In collaboration with the National Informatics Centre and Indian Institute of Technology Bhilai, IGKV has developed several ICT-enabled applications such as Crop Doctor 2.0, Millet Doctor, e-Krishi Panchang, e-Haat App, and Sankhya App. These platforms provide services related to crop diagnostics, climate-smart advisories, market linkage, and institutional management. Crop Doctor 2.0 and Millet Doctor offer image-based diagnosis for pests, diseases, and nutrient deficiencies, while e-Krishi Panchang provides season-wise agro-meteorological advisories. The e-Haat App strengthens direct farmer-to-buyer market connectivity, whereas Sankhya App supports ERP-based governance and institutional decision-making.

Collectively, these applications represent a significant advancement toward precision agriculture and data-driven farming systems in Chhattisgarh (Sharma and Singh, 2020). They help farmers access timely scientific advisories, improve farm management, reduce production losses, and strengthen market access and extension outreach (Kumar et al., 2021). Among these platforms, Crop Doctor 2.0 has emerged as the most widely adopted application with more than 760,000 registered users across the state. Therefore, the present paper reviews the major ICT-enabled applications developed by IGKV and examines their contribution toward strengthening digital agriculture, promoting smart farming practices, and enhancing agricultural advisory services in Chhattisgarh.

2. Classification and digital ecosystem architecture of IGKV Applications

IGKV Digital Ecosystem Architecture

2.1 Advisory and Diagnostic Applications



These applications provide real-time solutions for crop-related issues such as pests, diseases, and nutrient deficiencies.

2.1.1 Millet Doctor App

Millet Doctor is a bilingual (Hindi and English), Unicode-enabled Android application developed for farmers and students, with a special focus on climate-resilient small millets such as ragi, kodo, and kutki. The application functions as an integrated advisory platform for small millet cultivation, enabling users to upload images of affected crops and receive diagnostic support for diseases, insect pests, and nutrient deficiencies. Designed to promote sustainable cropping systems and support the resurgence of indigenous millets, the platform also aims to empower native tribal farming communities through accessible, location-relevant agronomic guidance.



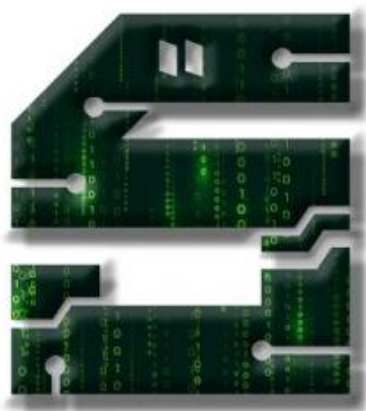
2.1.2 Crop Doctor 2.0 (Rank 1 – Highest Adoption & Primary Utility): Recognized as the cornerstone of Indira Gandhi Krishi Vishwavidyalaya's public digital ecosystem, Crop Doctor 2.0 has achieved the widest outreach with more than 760,000 registered farmers and nearly 300,000 direct application downloads (**IGKV Annual Report, 2024 and or 2026**). Developed in collaboration with Indian Institute of Technology Bhilai, the platform functions as an advanced AI-driven smart farming application providing diagnostic and advisory services for major crops, including paddy, pulses, oilseeds, and vegetables. The application integrates Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Natural Language Processing (NLP), and computer vision technologies to automate the localized identification of insect pests, crop diseases, and nutrient deficiencies through mobile image uploads. Furthermore, the platform synchronizes with regional land records to deliver hyper-customized advisory services to registered farmers. It also disseminates information related to agricultural schemes, farm implements, and agri-news, thereby serving as a comprehensive digital decision-support system for modern agriculture (Sivakumar et al., 2022).



2.2 Institutional Management and Analytics

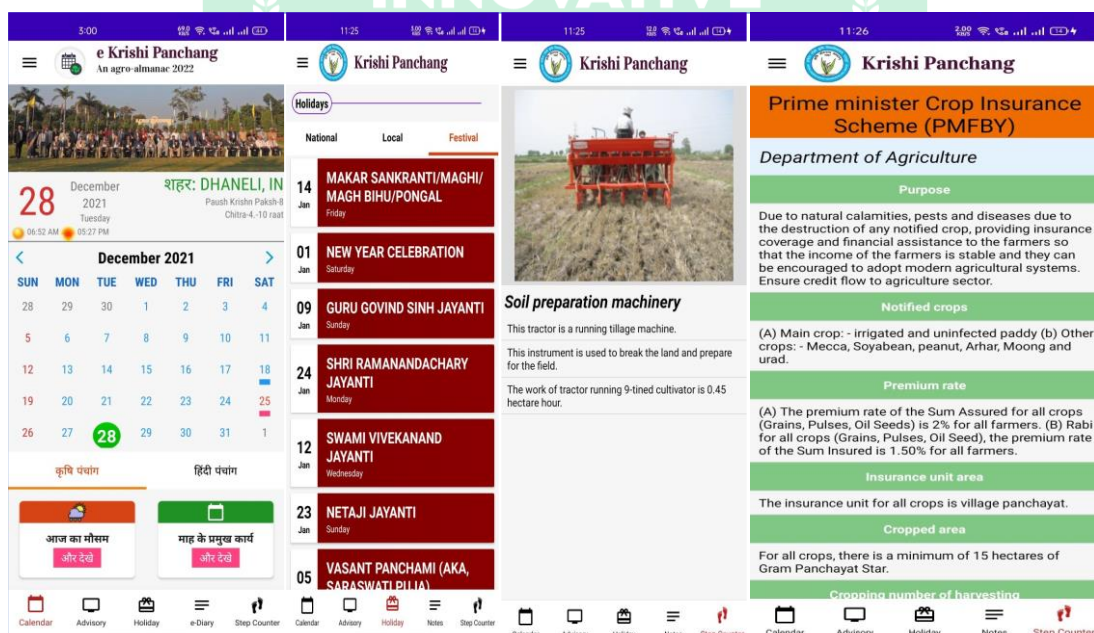
2.2.1 Sankhya App: Sankhya App is an institutional Enterprise Resource Planning (ERP) and decision-support platform developed to strengthen data-driven governance and administrative efficiency across Indira Gandhi Krishi Vishwavidyalaya and its constituent colleges. The application integrates analytical dashboards with real-time institutional metrics, including financial management records, human resource data, staff demographics, student enrolment statistics, academic lifecycle records, and governance indicators. Designed to support evidence-based planning and transparent administration, the platform enables university administrators to monitor

institutional performance, optimize resource allocation, and improve policy implementation. Additionally, the inclusion of gender-disaggregated datasets enhances inclusive planning and informed decision-making within the higher agricultural education system (Sahu, 2022).



2.3 Planning and Agro-Advisory Tools

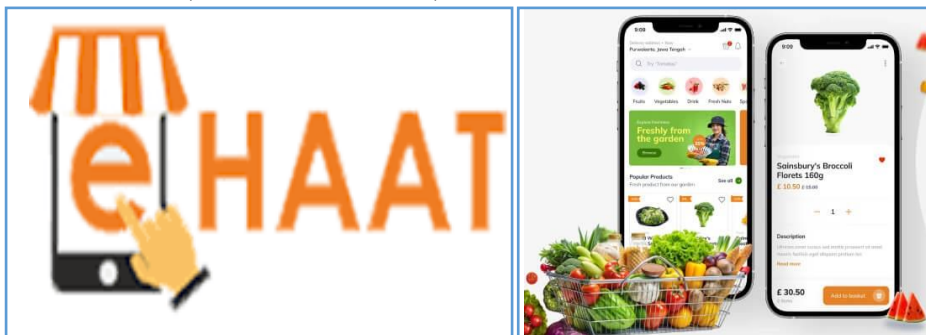
2.3.1 e-Krishi Panchang: it is a geofenced digital agro-meteorological almanac that harmonizes traditional agricultural calendrical intelligence with real-time, block-level meteorological data provided by the Indian Meteorological Department (IMD). The platform delivers block-wise, season-wise, and crop-specific advisories to support timely and efficient agricultural operations. By integrating localized weather forecasts, traditional farming knowledge, auspicious timings (muhurats), festivals, and crop management schedules, the system assists farmers in planning sowing, irrigation, plant protection, and harvesting activities in a climate-responsive manner. Widely utilized for operational farm decision-making, the platform strengthens localized and preventive agricultural planning through geofenced micro-climate intelligence (Sivakumar et al., 2022).



2.4 Market Linkage and E-Commerce Platforms

2.4.1 e-Haat App: The e-Haat App is a geospatially enabled digital marketplace designed to facilitate direct business-to-business (B2B) and business-to-consumer (B2C) transactions between farmers and buyers. Functioning as a bridge between rural producers and markets, the platform provides real-time information on commodity prices, demand trends, product availability, and transparent price discovery mechanisms. Integrated with geo-tagging and map-based interfaces, the application enables efficient identification and location of

agricultural produce, thereby improving supply chain coordination and market accessibility. By establishing direct farmer-to-buyer transaction channels and minimizing dependence on exploitative intermediaries, the platform enhances farmers' income, strengthens market transparency, and promotes better price realization for agricultural commodities (Sivakumar et al., 2022).



3. Comparative Analysis of Applications

The digital applications developed by Indira Gandhi Krishi Vishwavidyalaya serve diverse yet complementary roles within an integrated agricultural digital framework. Crop Doctor 2.0 is the most advanced and widely adopted platform, utilizing Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Natural Language Processing (NLP), and computer vision technologies for automated diagnosis of crop pests, diseases, and nutrient deficiencies across major crops. In contrast, Millet Doctor focuses specifically on climate-resilient small millets such as ragi, kodo, and kutki, providing localized agronomic advisories and diagnostic support for tribal and rain-fed farming communities. e-Krishi Panchang functions as a geofenced agro-meteorological advisory platform that integrates real-time weather data from the India Meteorological Department with traditional agricultural calendars to support climate-responsive farm planning. Meanwhile, e-Haat App acts as a geospatially enabled B2B/B2C digital marketplace that strengthens market connectivity through direct farmer-to-buyer transactions, transparent price discovery, and efficient supply chain management. Unlike the farmer-oriented applications, Sankhya App primarily supports institutional governance through ERP-based analytics, administrative monitoring, and evidence-based decision-support systems. The application aggregates governance metrics, financial records, human resource information, and academic lifecycle data to improve administrative efficiency within the university framework. Collectively, these applications integrate advisory, planning, marketing, and governance functions, thereby strengthening precision agriculture, digital extension services, smart farming practices, and sustainable agricultural development in Chhattisgarh.

4. Key Features of Applications

S. No	Application Name	Platform	Target Users	Key Features	Scope	Technology	Language	Developed By
1	Millet Doctor	Android App	Farmers, Students	Image-based diagnosis, advisory	Small millets	ICT-based	Hindi & English	IGKV+NIC
2	Sankhya App	Mobile/Web	Administrators	Data analytics, MIS	Institutional	Data analytics	English	IGKV
3	e-Krishi Panchang	Mobile/Web	Farmers	Crop calendar, advisories	Location-based	Agro-advisory	Hindi	IGKV
4	e-Haat App	Mobile/Web	Farmers, Buyers	Marketplace, price trends	All crops	GIS-based ICT	Hindi & English	IGKV
5	Crop Doctor 2.0	Android App	Farmers	AI-based diagnosis	Major crops	AI, ML, DL, NLP	Hindi & English	IGKV+NIC

5. Conclusion

The digital applications developed by Indira Gandhi Krishi Vishwavidyalaya demonstrate the growing importance of Information and Communication Technology (ICT) in strengthening modern agriculture and

institutional governance. Platforms such as Crop Doctor 2.0 and Millet Doctor provide real-time diagnostic and advisory support, improving precision farming and climate-resilient crop management. e-Krishi Panchang enhances climate-responsive agricultural planning through localized agro-meteorological advisories, while e-Haat App improves market access and transparent price discovery for farmers. Sankhya App contributes to efficient institutional administration through ERP-based governance and analytical decision-support systems. Collectively, these applications form an integrated digital ecosystem that supports smart farming, technology dissemination, and sustainable agricultural development in Chhattisgarh. The increasing adoption of these platforms highlights the potential of AI-driven and ICT-enabled solutions in empowering farmers, improving extension outreach, and accelerating the transition toward digitally connected agriculture.

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The Hidden Life of Fruits After Harvest: Scientific Basis of Quality and Shelf Life



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Abstract:

Fruits continue to function as living systems after detachment, and their post-harvest behaviour is governed by complex physiological and biochemical interactions. The progression from maturity to over-ripeness is influenced by metabolic intensity, hormonal regulation, and environmental conditions. Factors such as temperature, humidity, and atmospheric composition critically determine the rate of quality deterioration and nutrient retention. Advances in post-harvest technology, including controlled storage environments and eco-friendly preservation methods, have enhanced the ability to manage these changes effectively. A systematic understanding of these mechanisms is essential for minimizing quantitative and qualitative losses, improving storage efficiency, and ensuring a consistent supply of high-quality fruits.

Keywords: Post-harvest physiology, Fruit ripening; Ethylene regulation; Shelf life; Nutritional quality

1. Introduction

Fruits are highly perishable biological commodities whose quality and nutritional value are strongly influenced by processes occurring after harvest. Contrary to the common assumption that physiological activity ceases once fruits are harvested, they remain living tissues that continue to undergo a wide range of biochemical and metabolic changes. These post-harvest processes play a crucial role in determining shelf life, sensory attributes and nutritional composition. With increasing global concern regarding food losses and the need to supply high-quality produce to consumers, understanding the scientific basis of post-harvest behaviour has become essential. This article highlights the key physiological changes in fruits after harvest and scientific approaches for managing them effectively.

2. Physiological activity of fruits after harvest

Respiration and metabolic activity

Respiration is one of the most important physiological processes influencing the post-harvest life of the fruits. It involves the breakdown of stored substrates such as sugars and organic acids to release energy required for maintaining cellular functions. The rate of respiration directly associated with the rate of deterioration. Fruits with higher respiration rates, such as strawberries, mangoes and bananas, tend to have shorter storage lives, whereas fruits like apples and citrus exhibit slower respiration and can be stored for longer durations. Therefore, controlling respiration rate is a primary objective in post-harvest management to delay senescence and extend shelf life.

3. Ripening and senescence processes

Ripening after harvest

Ripening is a genetically regulated and highly coordinated process that enhances the edibility and overall acceptability of fruits. It encompasses the series of biochemical and structural transformations that collectively contribute to desirable sensory attributes. During ripening, starch is progressively converted into soluble sugars, resulting in increased sweetness. Simultaneously, chlorophyll degrades while pigments such as carotenoids and anthocyanins are synthesized, leading to the characteristic colour development. The softening of fruit tissues

occurs due to the enzymatic degradation of cell wall components, particularly pectic substances, which reduces structural integrity. In addition, the synthesis of volatile compounds contributes to the development of distinctive flavour and aroma. In climacteric fruits, these ripening-associated changes are closely linked with a marked increase in respiration and ethylene production. The physiological behaviour allows such fruits to continue ripening even after harvest, making post-harvest handling and storage conditions critically important.

4. Senescence and quality decline

Senescence represents the final stage of fruit development and is characterized by progressive and irreversible deterioration. This phase involves loss of membrane integrity, disruption of cellular organization and decline of enzymatic regulation. As senescence advances, there is a reduction in nutritional quality and an increased susceptibility to microbial invasion. The transition from ripening to senescence is a delicate phase and its effective management is essential for maintaining post-harvest quality and extending shelf life.

5. Role of ethylene in post-harvest changes

Ethylene is a naturally occurring plant hormone that plays a central role in regulating ripening and senescence, particularly in climacteric fruits. Even at very low concentrations, ethylene is capable of initiating and accelerating a range of ripening-related processes. Its action influences colour development, softening and synthesis of flavour compounds. After harvest, ethylene may accumulate within storage environments, leading to uneven or premature ripening. Such uncontrolled exposure can negatively impact fruit quality and market value. Therefore, effective management of ethylene is a critical component of post-harvest technology. This includes its removal or absorption from storage systems, the use of inhibitors that block ethylene action and the application of controlled or modified atmospheric conditions. Proper regulation of ethylene not only ensures uniform ripening but also contributes significantly to extending storage life.

6. Moisture loss and textural deterioration

Moisture loss through transpiration is a major factor contributing to post-harvest deterioration of fruits. As water is lost, fruits gradually undergo shrivelling, wilting, and a reduction in firmness, all of which adversely affect their visual appeal and market acceptability. In parallel, enzymatic degradation of pectic substances and other structural carbohydrates leads to further softening of tissues. To minimize these undesirable changes, post-harvest practices focus on maintaining high relative humidity, reducing mechanical damage during handling, and employing suitable packaging materials. These measures collectively help in preserving the structural integrity and freshness of fruits during storage and transportation.

7. Nutritional Changes During Post-Harvest Storage

Post-harvest handling and storage conditions have a significant influence on the nutritional composition of fruits. The extent and nature of these changes depend on several factors, including temperature, oxygen availability and duration of storage.

- **Vitamin Stability**

Vitamin C, also known as ascorbic acid, is particularly sensitive to oxidative degradation during storage. Its concentration tends to decline over time, especially under conditions of elevated temperature and exposure to oxygen. However, the use of optimized storage conditions, such as low temperature and controlled atmospheres, can effectively slow down this degradation and help retain nutritional quality.

- **Bioactive Compounds**

Fruits are an important source of bioactive compounds, including phenolics, flavonoids, and carotenoids, which contribute to their antioxidant properties. Interestingly, post-harvest stress conditions may, in some cases, stimulate the synthesis of certain phenolic compounds as part of the fruit's natural defense response. Consequently, changes in nutritional quality during storage are not always uniform and are influenced by the type of fruit as well as the storage environment.

- **Microbial Spoilage and Post-Harvest Diseases**

Microbial spoilage constitutes one of the major causes of post-harvest losses in fruits. Fungal pathogens are particularly significant and often infect fruits through mechanical injuries or latent infections that originate in the field. The high moisture content and nutrient-rich nature of fruits create favourable conditions for the rapid growth of microorganisms. Modern approaches to managing post-harvest diseases emphasize integrated strategies that

combine proper sanitation, temperature and humidity control, and the use of biological control agents. In addition, natural antimicrobial compounds are increasingly being explored as safer alternatives to synthetic chemicals. These approaches aim to enhance food safety while minimizing environmental and health concerns.

8. Temperature and Atmospheric Control

- **Cold Storage**

Low-temperature storage remains one of the most effective methods for extending the shelf life of fruits. By reducing temperature, metabolic activities such as respiration and ethylene production are significantly slowed, along with microbial growth. However, improper temperature management can lead to physiological disorders such as chilling injury, particularly in tropical and subtropical fruits, thereby limiting their storage potential.

- **Modified and Controlled Atmosphere Storage**

The manipulation of atmospheric composition, particularly through the reduction of oxygen and the elevation of carbon dioxide levels, provides an additional means of controlling metabolic activity. Controlled atmosphere storage has been successfully applied for the long-term preservation of fruits such as apples, pears, and kiwifruit, enabling extended storage with minimal loss of quality.

9. Emerging Post-Harvest Technologies

Recent advancements in post-harvest technology are increasingly focused on sustainable and environmentally friendly approaches. Edible coatings and bio-based films have gained considerable attention due to their ability to act as semi-permeable barriers, thereby reducing moisture loss and regulating gas exchange. Furthermore, non-chemical techniques such as ozone treatment, irradiation, and the application of plant-derived extracts are being investigated for their potential to improve microbial safety and extend shelf life. These emerging technologies offer promising alternatives for enhancing post-harvest management while addressing concerns related to food safety and environmental sustainability.

10. Conclusion

The post-harvest phase represents a critical period in which fruits continue to undergo complex physiological and biochemical changes. Processes such as ripening, senescence, moisture loss, nutritional alterations, and microbial interactions collectively influence fruit quality and storage potential. A comprehensive understanding of these processes, combined with appropriate technological interventions, is essential for minimizing post-harvest losses and maintaining the nutritional and sensory quality of fruits. Strengthening post-harvest management practices is therefore crucial for improving the efficiency and sustainability of the food system.

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Impact of Moringa Leaf Powder Supplementation on the Nutritional Status of Rural Women: A Sustainable Strategy for Combating Hidden Hunger and Micronutrient Deficiencies



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Abstract

Malnutrition and micronutrient deficiencies remain major public health challenges among rural women in developing countries. Iron deficiency anemia, inadequate dietary diversity, and insufficient intake of essential micronutrients adversely affect women's health, productivity, and overall well-being. *Moringa oleifera*, commonly known as the drumstick tree, has gained global recognition as a nutrient-dense plant rich in proteins, vitamins, minerals, antioxidants, and bioactive compounds. Moringa leaf powder (MLP) represents a low-cost, locally available, and sustainable dietary supplement that can significantly improve nutritional outcomes among vulnerable populations. Several studies have demonstrated that regular supplementation with MLP contributes to improvements in hemoglobin concentration, micronutrient status, dietary quality, and overall nutritional health. This review critically examines the nutritional composition of moringa leaf powder, its role in addressing nutritional deficiencies among rural women, mechanisms underlying its health benefits, and opportunities for integrating moringa-based interventions into community nutrition and extension programs. The review also highlights current research gaps and future directions for large-scale implementation.

Keywords: *Moringa oleifera*, Rural Women, Anemia, Hidden Hunger, Micronutrient Deficiency, Functional Foods, Nutrition Security

1. Introduction

Women's nutritional status is a critical determinant of family health, agricultural productivity, and socio-economic development. In many developing countries, particularly India, rural women continue to face multiple nutritional challenges, including protein-energy malnutrition, iron deficiency anemia, vitamin A deficiency, and inadequate dietary diversity. These nutritional deficiencies adversely affect reproductive health, work efficiency, immunity, and quality of life. According to national health surveys, anemia remains highly prevalent among women of reproductive age despite ongoing public health interventions. Conventional supplementation programs often encounter limitations related to accessibility, compliance, affordability, and sustainability. Consequently, nutrition-sensitive approaches utilizing locally available nutrient-rich foods have received increasing attention.

Moringa oleifera Lam. is a fast-growing, drought-resistant tree belonging to the family Moringaceae. Native to the Indian subcontinent, it is widely cultivated throughout tropical and subtropical regions. Due to its exceptional nutritional composition, moringa has been described as a "miracle tree" and is increasingly recognized as a functional food with significant



potential for addressing malnutrition and hidden hunger. The leaves of moringa can be processed into powder and incorporated into traditional diets without major dietary modifications. The powder possesses high concentrations of protein, iron, calcium, potassium, β -carotene, vitamin C, vitamin E, and numerous phytochemicals with antioxidant properties. These characteristics make moringa leaf powder an attractive intervention for improving nutritional status among rural women.

2. Nutritional Composition of Moringa Leaf Powder

Moringa leaves are considered among the most nutrient-dense plant foods. Drying and powdering the leaves concentrate nutrients while extending shelf life and facilitating year-round consumption.

Table 1. Major Nutrients Present in Moringa Leaf Powder (per 100 g)

Nutrient	Approximate Content
Protein	25–30 g
Carbohydrates	35–40 g
Dietary Fiber	15–20 g
Calcium	1800–2200 mg
Iron	20–30 mg
Potassium	1200–1500 mg
Magnesium	300–400 mg
Vitamin A (β -carotene)	6000–7000 μ g
Vitamin C	15–25 mg
Vitamin E	70–80 mg

The nutritional richness of moringa makes it particularly suitable for addressing deficiencies of iron, calcium, and vitamin A, which are common among rural women.

3. Hidden Hunger and Nutritional Challenges Among Rural Women

Hidden hunger refers to deficiencies of essential vitamins and minerals despite adequate caloric intake. Rural women frequently experience:

- Iron deficiency anemia
- Calcium deficiency
- Vitamin A deficiency
- Low dietary diversity
- Insufficient protein intake

Factors contributing to these deficiencies include poverty, limited access to diverse foods, gender disparities in food distribution, low nutrition awareness, and seasonal food insecurity.

The consequences include:

- Fatigue and reduced productivity
- Poor maternal health outcomes
- Increased susceptibility to infections
- Reduced cognitive performance
- Impaired work capacity

Addressing hidden hunger requires sustainable food-based strategies rather than exclusive reliance on pharmaceutical supplementation.

4. Mechanisms Through Which Moringa Improves Nutritional Status

4.1 Improvement of Iron Status

Moringa leaves contain substantial amounts of iron. Additionally, vitamin C present in moringa enhances intestinal iron absorption, thereby improving hemoglobin synthesis and reducing anemia risk.

4.2 Protein Supplementation

Protein deficiency remains a concern among low-income households. Moringa leaf powder provides plant-based proteins and essential amino acids that support tissue maintenance and physiological functions.

4.3 Antioxidant Activity

Moringa leaves contain flavonoids, polyphenols, quercetin, chlorogenic acid, and carotenoids. These compounds reduce oxidative stress and contribute to improved immune function.

4.4 Enhancement of Dietary Diversity

Moringa powder can be incorporated into:

- Chapati flour
- Soups
- Dal preparations
- Khichdi
- Snacks
- Traditional recipes

This improves nutrient density without significantly altering food habits.

5. Evidence on Moringa Supplementation and Women's Health

Several studies have reported positive outcomes associated with moringa supplementation.

Benefits

- Increased hemoglobin concentration
- Improved iron status
- Better micronutrient intake
- Enhanced immunity
- Reduced fatigue and weakness
- Improved dietary quality
- Greater nutritional awareness

Community-based nutrition interventions involving moringa have demonstrated promising results in improving maternal nutrition and household dietary practices.

6. Role of Krishi Vigyan Kendras in Promoting Moringa-Based Nutrition

Agricultural extension institutions can play a pivotal role in scaling up moringa-based nutritional interventions through:

- Demonstrations of moringa cultivation
- Nutrition garden promotion
- Training programs for rural women
- Value-addition and processing demonstrations
- Development of moringa-based enterprises
- Awareness campaigns on anemia prevention

Integration of moringa into Nutri-Smart Village initiatives can significantly enhance community nutrition outcomes.

7. Challenges and Limitations

- Despite its potential, several challenges remain:
- Limited awareness among rural households
- Variability in processing methods
- Lack of standardized dosage recommendations
- Storage and quality concerns
- Limited commercialization channels

Addressing these challenges requires coordinated efforts involving researchers, extension agencies, public health institutions, and policymakers.

8. Future Research Directions

- Future studies should focus on:
- Randomized controlled trials among rural women.
- Bioavailability of iron and micronutrients from moringa.

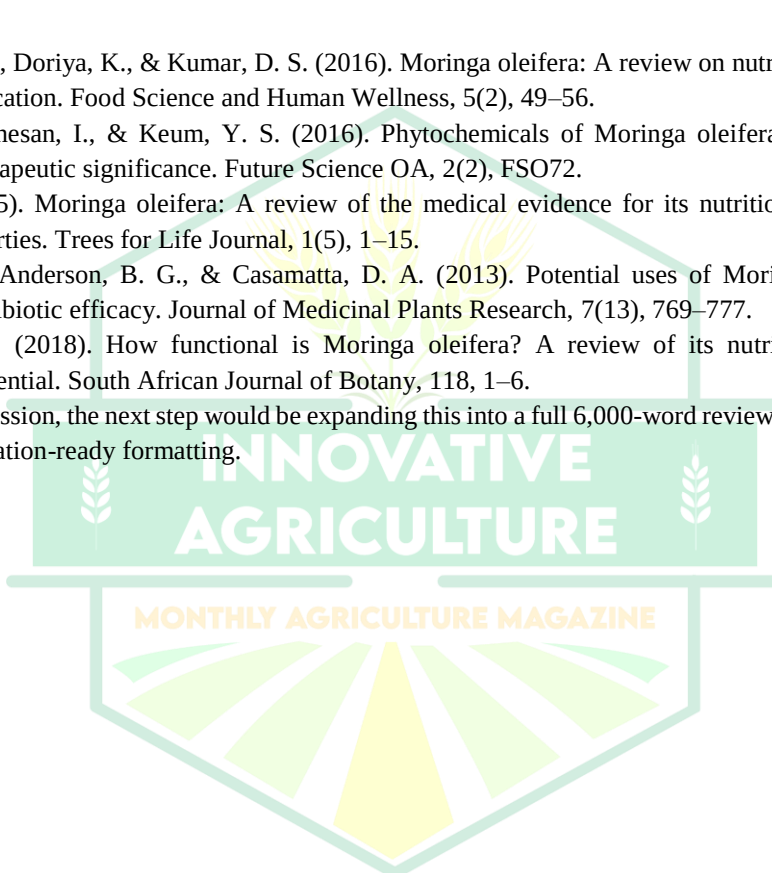
- Long-term supplementation studies.
- Development of moringa-fortified foods.
- Cost-effectiveness analyses.
- Integration with government nutrition programs.

9. Conclusion

Moringa leaf powder represents a sustainable, affordable, and locally available nutritional intervention capable of addressing hidden hunger and micronutrient deficiencies among rural women. Its exceptional nutrient profile, ease of cultivation, and compatibility with traditional diets make it a promising tool for improving nutritional security and women's health. Wider adoption through agricultural extension systems, nutrition education programs, and community-based interventions can contribute significantly to reducing anemia and enhancing rural livelihoods.

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- For a journal submission, the next step would be expanding this into a full 6,000-word review with 30+ references, figures, and publication-ready formatting.



Better Seeds, Better Harvests: Hybrid Seed Production Techniques



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Abstract

Hybrid seed production is an important technique of modern agriculture. It uses heterosis (hybrid vigor) to improve crop productivity, quality, and stress resistance. Hybrid seeds are produced under controlled pollination by crossing two different parental lines. To prevent self-pollination and ensure cross-pollination, special techniques are used, including manual emasculation or pollination, male sterility systems, self-incompatibility mechanisms, chemical hybridizing agents, and biotechnology-based approaches. These methods are applied in crops such as maize, rice, sorghum, sunflower, cotton, wheat, rapeseed- mustard and various vegetables for large-scale hybrid seed production. Hybrid seed production has played a major role in global food security by improving crop uniformity and yield. Recent advances in biotechnology and molecular breeding have made hybrid seed production more efficient and reliable, resulting in higher yields and better pest and disease resistance. This article discusses the principles, techniques, advantages, challenges, and prospects of hybrid seed production.

Keywords:

Hybrid seed production, heterosis, hybrid vigor, chemical hybridizing agents (CHA), controlled pollination, Genetic purity, parental line.

Introduction

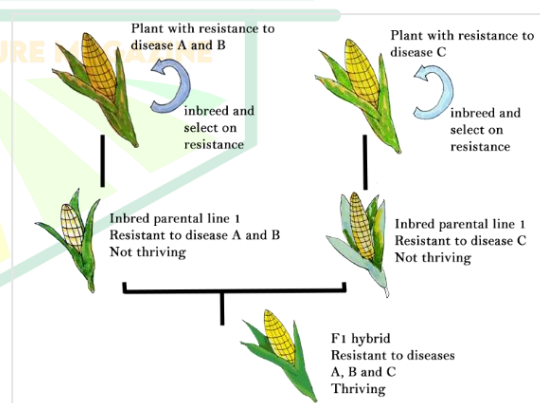
Hybrid seed technology has transformed modern Agriculture a lot, and with the help of these techniques, a variety of crops can be developed that are more productive and resistant to pests, diseases, and environmental stresses. Hybrid seeds are those seeds that are genetically different and are made by crossing pure parental lines. The F_1 generation obtained from these crosses shows better results than their parents. This phenomenon is known as heterosis or hybrid vigor.

The concept of hybrid breeding first became successful in maize, and after that, it was applied in rice, sorghum, pearl millet, cotton, sunflower, tomato, cabbage, and other vegetable crops. Hybrid varieties are popular among farmers because they provide high yield potential, uniform growth, and better adaptability.

For hybrid seed production, controlled pollination is very important so that male parent pollen fertilizes the female parent pollen. That's why different techniques have been developed, like manual emasculation, male sterility systems, self-incompatibility, and chemical hybridizing agents. Every technique has its own advantages and limitations, which depend upon crop species and its production scale.

Principles of hybrid seed production

Hybrid seed production is based on some basic skills, through which genetically pure and high-quality hybrid seeds are produced. The first step of seed production is the selection of suitable parental lines. These are usually



inbreeding lines that are developed by repeated self-pollination to achieve genetic uniformity. Selected parents should have desirable traits like high yield, disease resistance, and stress tolerance.

Another important requirement is the maintenance of genetic purity. Maintaining the genetic purity of parental lines is essential for producing uniform hybrids. This requires strict rouging of off-type plants, proper seed handling, and proper field management. Synchronization of flowering between male and female parents is also essential. Male and female parents should flower at the same time to ensure proper pollination. If flowering differs, sowing dates can be adjusted, or growth regulators may be used.

Isolation is equally important because hybrid seed production fields must be separated from other varieties of the same crop to prevent contamination through foreign pollen. Isolation can be maintained by distance, time difference in sowing, or physical barriers.

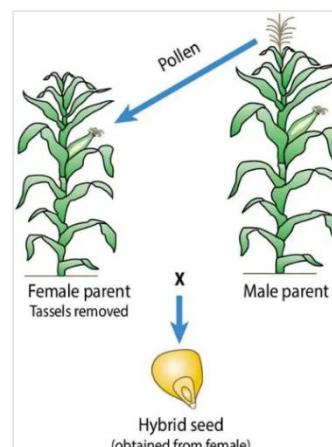


Figure 1: Schematic illustration of mustard hybrid seed production (created using AI)

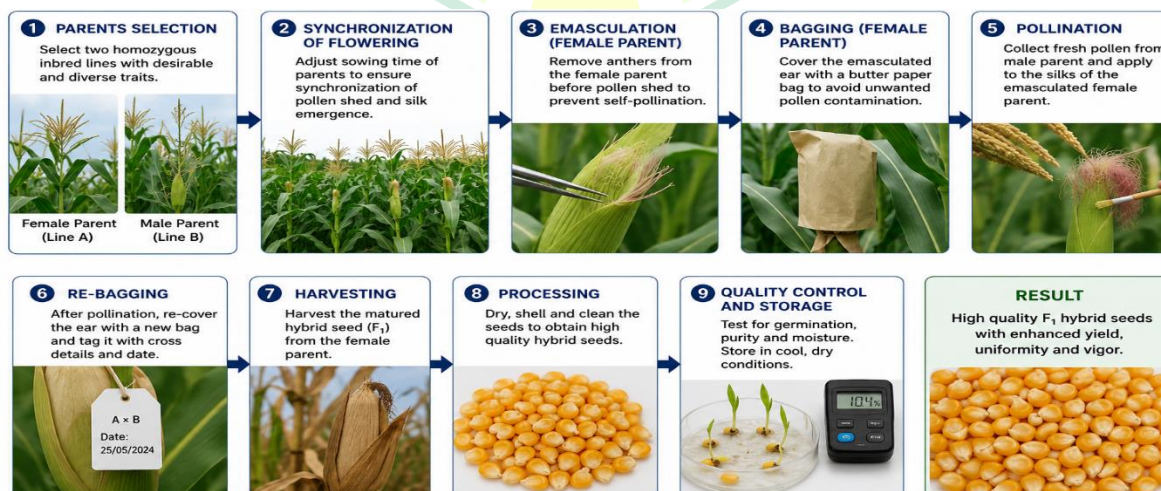


Figure 2: Schematic illustration of maize hybrid seed production (created using AI)

Techniques of hybrid seed production



Controlled pollination is the most critical step in hybrid seed production. One of the oldest and most reliable steps for hybrid seed production is hand emasculation and hand pollination. In this, the anthers of the female flower are removed before the release of the pollen so that self-pollination does not take place. After this, the pollen of the male parent is manually transferred to the stigma. These methods are commonly used in crops such as tomato, chilli, cotton, and brinjal. Although highly effective, it is labor-intensive, time-consuming, and costly for large-scale production.

Male sterility systems are widely used to reduce the need for manual emasculation. Male sterility refers to the inability of the plants to produce functional pollen. Genetic male sterility is controlled by the nuclear genes, whereas cytoplasmic male sterility is controlled by the cytoplasmic genes and shows maternal inheritance. Cytoplasmic male sterility is commonly used in crops like rice, sorghum, sunflower, and onion. In the cytoplasmic-genetic male sterility (CGMS) system, three types of lines are used: the A line, which is male sterile; the B line, which maintains the male sterility trait; and the R line, which restores fertility in the hybrid plants. This system has proven to be highly effective and widely used in commercial hybrid seed production.

Self-incompatibility is a natural mechanism in which pollen from the same plant or from a genetically similar plant is unable to fertilize the stigma. This prevents self-pollination and encourages natural cross-pollination. It is commonly utilized in crops such as cabbage, cauliflower, mustard, and radish for hybrid seed production. Some crops naturally possess floral mechanisms that encourage cross-pollination. Monoecious plants have separate male and female flowers on the same plant, while dioecious plants bear male and female flowers on different plants. These natural mechanisms are also useful in hybrid seed production.

Field management

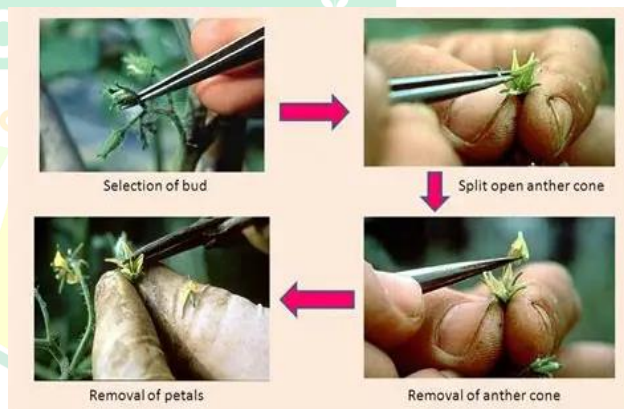
Proper field management is very important for achieving high seed yield and maintaining genetic purity. Fertile and properly prepared land should be selected for hybrid seed production. A proper ratio of male and female rows should be maintained to ensure effective pollination. Off-type plants should be removed regularly, and flowering synchronization must be carefully monitored. Timely harvesting, threshing, drying, and seed processing are also essential for maintaining seed quality and purity.

Role of biotechnology

Modern biotechnology has significantly improved hybrid seed production. Tissue culture techniques such as micropropagation, anther culture, and embryo rescue help in the rapid multiplication of parental lines. Molecular markers and marker-assisted selection have assisted breeders in identifying desirable genes and selecting superior parental lines more efficiently. Through genetic engineering, traits like male sterility, fertility restoration, and stress resistance can also be introduced into crop plants.

Advantages of hybrid seeds

Hybrid seeds offer several advantages over conventional varieties. They generally produce higher yields, exhibit better vigor, and show improved resistance to pests and diseases. They are also more tolerant of stresses such as drought, heat, and salinity. Hybrids usually show uniform growth and maturity, which is beneficial for harvesting and marketing. In vegetable crops, hybrid varieties often have better size, shape, color, and longer shelf life, increasing their market value.



Limitations and challenges

Hybrid seed production also has certain limitations. The process is often expensive because it requires skilled labor, controlled pollination, and proper maintenance of parental lines. Environmental factors such as temperature, rainfall, and wind can affect pollination efficiency. In some crops, suitable male sterility is not available. Moreover, farmers need to purchase new hybrid seeds every season, as seeds saved from hybrid crops usually do not maintain the same level of performance in the next generation.

Future prospects

The future of hybrid seed production is highly promising. Advanced technologies such as genomic selection, genome editing, speed breeding, and precision agriculture are making hybrid development faster and more accurate. Climate-resilient hybrids that can tolerate drought, heat, and diseases are expected to play a crucial role in meeting future agriculture and food security challenges.

Conclusion

Hybrid seed production is an important technology that has transformed modern agriculture. Exploiting heterosis, it helps in developing superior crop varieties with higher yields, better quality, and greater resilience. Techniques such as hand emasculation, male sterility systems, self-incompatibility, chemical hybridizing agents, and biotechnology have made hybrid seed production more efficient and commercially successful. In the future as well, this technology will continue to play a vital role in sustainable agriculture and global food security.

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Plant Extracts as Natural Nematicides: Future of Eco-friendly Crop Protection



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Abstract

Plant-parasitic nematodes are among the most destructive hidden pests of agricultural crops, causing severe yield losses throughout the world. The extensive use of chemical nematicides for their management has created environmental pollution, health hazards, destruction of beneficial soil organisms, and pesticide residue problems. In recent years, plant extracts have emerged as promising eco-friendly alternatives for nematode management. Botanicals derived from neem, papaya, marigold, garlic, castor, and nirgundi contain natural bioactive compounds capable of suppressing nematode populations and improving soil health. These plant-based products are biodegradable, economical, and safer for the environment. The present article discusses the importance of plant extracts as natural nematicides, their mode of action, commonly used botanicals, advantages, limitations, and future prospects in ecofriendly crop protection.

Keywords: Plant extracts, root-knot nematodes, eco-friendly agriculture, crop protection.

1. Introduction

Agriculture in the modern era faces the challenge of increasing crop production while maintaining environmental sustainability. Among the many pests affecting crop productivity, plant-parasitic nematodes remain one of the most neglected but destructive groups. These microscopic roundworms attack plant roots and interfere with the absorption of water and nutrients, ultimately reducing crop growth and yield. Root-knot nematodes belonging to the genus *Meloidogyne* are especially important because of their wide host range and severe economic impact on vegetables, fruits, ornamentals, and plantation crops.

Farmers often fail to identify nematode infestation because the above-ground symptoms resemble nutrient deficiency, drought stress, or fungal diseases. Consequently, nematodes continue to cause hidden damage beneath the soil surface. For several decades, chemical nematicides were widely used to control these pests. Although effective, continuous use of synthetic chemicals has led to serious concerns related to environmental contamination, groundwater pollution, toxicity to humans and animals, and destruction of beneficial soil microorganisms.

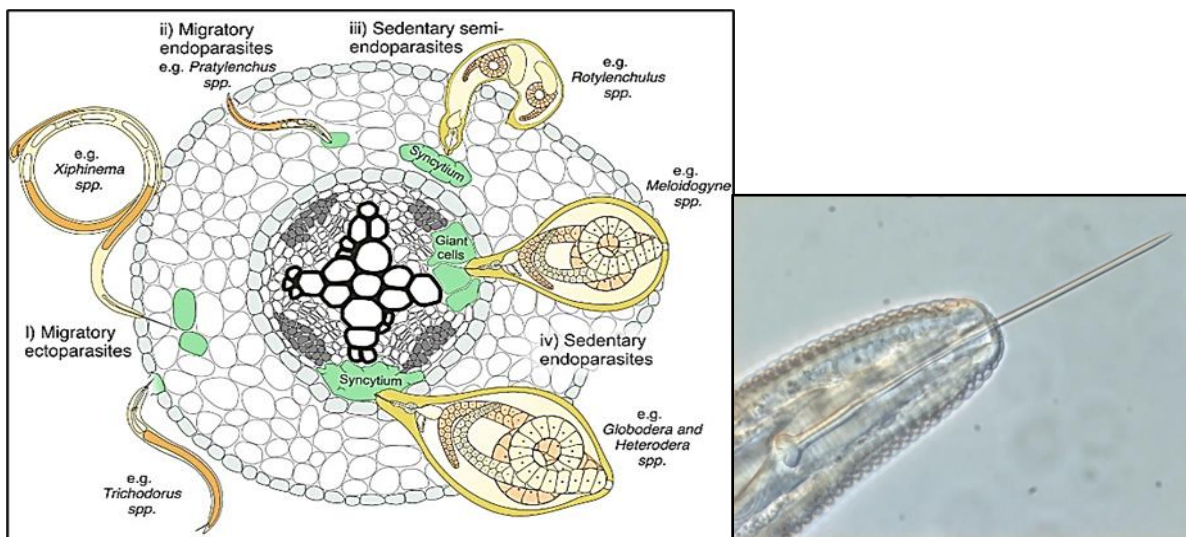
Growing awareness regarding sustainable agriculture and environmental safety has encouraged scientists to search for eco-friendly alternatives. Plant extracts have gained special importance because many plants naturally produce compounds that possess insecticidal and nematicidal properties. These compounds can inhibit egg hatching, suppress juvenile survival, and reduce nematode reproduction. The use of botanicals in pest management is deeply rooted in traditional agricultural practices, and modern scientific research has further validated their effectiveness against plant-parasitic nematodes.

2. Plant-Parasitic Nematodes and Their Damage

Plant-parasitic nematodes are microscopic worms living in soil and plant tissues. They feed on roots using a specialized needle-like structure known as a stylet. Through this stylet, they pierce plant cells and absorb nutrients, causing significant damage to the root system. Important nematodes affecting agricultural crops include root-knot nematodes, lesion nematodes, reniform nematodes, cyst nematodes, and burrowing nematodes.

The symptoms caused by nematodes are often difficult to diagnose accurately in the field. Infected plants commonly exhibit stunted growth, yellowing of leaves, wilting during hot weather, poor flowering, and reduced yield. Below-ground symptoms include root galls, lesions, rotting, and poorly developed root systems. Damaged roots are unable to absorb water and nutrients efficiently, resulting in weak and unproductive plants. In severe

infestations, nematodes may also interact with fungal and bacterial pathogens, forming disease complexes that further increase crop losses.



Different plant parasitic nematodes and their feeding behaviour on plant tissue

Stylet of a plant parasitic nematodes



Patchy symptoms in the field occur due to the uneven distribution of nematodes in the soil



Banana roots and rhizome infected with burrowing nematode

Tomato roots infected with root-knot nematode

Potato roots infected with golden cyst nematode

3. Need for Eco-friendly Nematode Management

The management of plant-parasitic nematodes has traditionally relied on chemical nematicides. While these chemicals provide rapid suppression of nematode populations, their indiscriminate use has generated several

environmental and health-related problems. Many synthetic nematicides are highly toxic and persist in soil for long periods, affecting non-target organisms including beneficial soil microbes, pollinators, and earthworms. Residual toxicity in food products and groundwater contamination have also become major concerns.

In recent years, ban on many chemical nematicides due to environmental regulations and growing demand for organic produce have reduced the use of hazardous chemicals in agriculture. As a result, researchers and farmers are increasingly turning toward safer and sustainable alternatives. Plant extracts have emerged as valuable tools in eco-friendly crop protection because they are biodegradable, locally available, and relatively safer for humans and the environment. Unlike synthetic pesticides, botanical extracts generally decompose rapidly and leave minimal harmful residues (Dubey *et al.*, 2010).

4. Plant Extracts as Natural Nematicides

Plants synthesize a wide range of secondary metabolites that help protect them against pests and pathogens. These natural compounds include alkaloids, phenols, terpenoids, flavonoids, tannins, and sulfur-containing substances. Many of these bioactive compounds exhibit strong nematicidal activity by affecting nematode survival, reproduction, feeding behaviour, and egg hatching.

4.1. Neem (*Azadirachta indica*): It is one of the most widely studied botanical sources for nematode management. Neem leaves, seeds, bark, and oil contain bioactive compounds such as azadirachtin, nimbin, and salannin that suppress nematode populations. Neem-based products inhibit egg hatching, reduce root gall formation, and interfere with nematode development. Neem cake incorporated into soil is commonly used in vegetable and horticultural crops for effective nematode suppression while improving soil fertility (Chitwood, 2002; Khan *et al.* 2008).



4.2. Papaya (*Carica papaya*): Papaya leaf extracts have also shown promising nematicidal properties. Papaya leaves contain enzymes, alkaloids, and phenolic compounds capable of suppressing root-knot nematodes. Application of papaya leaf extract has been reported to reduce gall formation and improve root growth in several vegetable crops (Oduor-Owino & Waudo, 1994).



4.3. Marigold (*Tagetes patula*): It is another important plant used for nematode management. The roots of marigold release compounds such as alpha-terthienyl that are toxic to nematodes. Marigold is often grown as an intercrop or trap crop in nematode-infested fields because it naturally reduces nematode populations in soil while improving biodiversity within the cropping system (Javed *et al.*, 2008; Hooks *et al.*, 2010).



4.5. Garlic (*Allium sativum*): Garlic possesses strong antimicrobial and nematicidal properties due to sulfur-containing compounds such as allicin. Garlic extracts suppress nematode mobility and egg hatching and help reduce root damage caused by root-knot nematodes (Oka *et al.*, 2000; Ntalli & Caboni, 2012).



4.6. Nirgundi (*Vitex negundo*): Medicinal plants like nirgundi have also attracted scientific attention for their pesticidal activity. The leaves of *Vitex negundo* contain flavonoids and essential oils that exhibit nematicidal effects. Studies have demonstrated that extracts from this plant reduce juvenile survival and suppress root-knot development, leading to improved plant growth and vigour (Gill *et al.*, 2001; Mokkapati *et al.*, 2024).



4.7. Castor (*Ricinus communis*): It is another plant traditionally used in pest management. Decomposition of castor residues in soil releases compounds harmful to nematodes and contributes to suppression of nematode populations (Ntali & Caboni, 2012).



5. Methods of Preparation and Application

Plant extracts can be prepared using simple methods that are suitable even for small-scale farmers. Fresh leaves or plant parts are collected, washed thoroughly, and ground into a paste. The material is then mixed with water and filtered through a muslin cloth to obtain the aqueous extract. Depending on the crop and nematode species, different concentrations are prepared and applied to the soil or plant roots. For laboratory and research purposes, methanolic extracts are commonly prepared to obtain a higher concentration of bioactive compounds. Fresh or shade-dried plant material is finely powdered and soaked in methanol (usually 80–100%) for 24–72 hours with occasional stirring. The mixture is then filtered, and the solvent is evaporated under reduced pressure using a rotary evaporator or allowed to evaporate at room temperature to obtain a crude extract. The concentrated extract is subsequently diluted to the desired concentration and used for in vitro or in vivo evaluation of nematocidal activity. Methanolic extraction is often preferred because methanol efficiently dissolves a wide range of phytochemicals, including alkaloids, flavonoids, phenolics, terpenoids, and essential oils that contribute to nematode suppression.

The extracts are commonly applied through soil drenching, seed treatment, root dipping, or incorporation into organic amendments. In some cases, plant residues are directly incorporated into soil, where decomposition releases bioactive compounds that suppress nematodes naturally. Repeated applications may be necessary because botanical extracts generally have shorter residual effects compared to synthetic chemicals.

6. Role in Integrated Nematode Management

Plant extracts are most effective when integrated with other sustainable management practices. The combination of botanicals with organic amendments, biological control agents, crop rotation, resistant varieties, and soil solarization can provide long-term suppression of nematode populations. Beneficial microorganisms such as *Trichoderma harzianum* and *Purpureocillium lilacinum* are often used alongside plant extracts to enhance nematode management.

Integrated approaches not only reduce dependence on synthetic chemicals but also improve soil structure, microbial activity, and overall plant health. Such systems contribute significantly to sustainable agriculture and environmental conservation.

7. Advantages of Plant-Based Nematicides

Plant-based nematicides possess several advantages over conventional chemicals. Their biodegradable nature minimizes environmental pollution and reduces the risk of toxic residues in food and soil. Since many botanical plants are locally available, farmers can prepare extracts at low cost using simple methods. Plant extracts are generally safer to beneficial soil organisms and fit well within organic and natural farming systems.

Another important advantage is the reduced risk of resistance development in nematodes. Unlike synthetic chemicals containing a single active ingredient, plant extracts contain complex mixtures of bioactive compounds that act through multiple mechanisms. This complexity makes it more difficult for pests to develop resistance.

8. Limitations and Challenges

Despite their promising potential, plant extracts also face certain limitations. Their effectiveness may vary depending on plant species, extraction method, environmental conditions, and nematode population levels. Botanical extracts often degrade rapidly in the environment, resulting in shorter residual activity and the need for repeated application.

Lack of standardized formulations and limited large-scale commercialization are additional challenges restricting wider adoption. Further scientific research is necessary to identify highly effective plant compounds, improve extraction techniques, and develop stable commercial formulations suitable for field application.

9. Future Prospects

The future of botanical nematicides appears highly promising in view of the increasing demand for sustainable and residue-free agriculture. Researchers are actively exploring nano-formulations, encapsulation technologies,

and combinations of plant extracts with beneficial microorganisms to enhance effectiveness and shelf life. Advances in biotechnology and natural product chemistry may lead to the development of highly efficient botanical formulations for commercial use.

Government initiatives promoting organic farming and reduced pesticide use are also expected to encourage the adoption of plant-based nematicides. As awareness about environmental safety continues to grow, botanical products are likely to become important components of integrated pest management programs worldwide.

10. Conclusion

Plant-parasitic nematodes continue to pose serious threats to agricultural productivity, often causing hidden but significant crop losses. Dependence on chemical nematicides is becoming increasingly unsustainable because of environmental and health concerns. Plant extracts provide an effective, economical, and environmentally safe alternative for nematode management.

Botanicals derived from neem, papaya, marigold, garlic, *Vitex negundo*, and other plants possess remarkable nematocidal properties capable of suppressing nematode populations while improving soil health. Their integration with biological control agents and organic amendments offers a sustainable pathway toward eco-friendly crop protection.

The future of agriculture depends not only on increasing production but also on protecting environmental health. Plant-based nematicides represent an important step toward greener, safer, and more sustainable farming systems.

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Livestock a Missing Link in Organic and Natural Farming for Long-Term Sustainability in India



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In the last two decades, Indian agriculture has seen a transformation in sustainability that the world's agriculture has never seen before. Organic farming has grown into an all-around 'buzzword' that captivated not just the government and entrepreneurs, but also the hearts and minds of everyone from the politicians to farmers. And more recently, the evolution of natural farming based on agribusiness has been driven by such initiatives of the government, which are a natural system of low costs, chemical-free farming that upholds our sense of ecology. However, we have failed to bring the agriculture sector a serious focus on livestock integration so that soil health, sustainability in general, and environmental resilience have also been better kept neglected. This is not a technical issue; it is still a structural weakness that threatens the future of organic and natural farming from the root if we keep going in a zero-energy and healthy manner. Livestock (particularly indigenous cattle) are not insignificant or peripheral to these farming philosophies; when they are factored into the system at large, they're foundational.

Organic Farming and Its Limitations

Organic farming was relatively open to sustainable farming (organic farming in India is all about the eradication of synthetic fertilizers and pesticides) and organic fertilizers of farmyard manure (FYM), compost, green manure, and biofertilizers. But when we look closer at it, we see that most inputs are livestock-based in nature, either directly or indirectly. For example, farmyard manure (cow dung) is mainly composed of cattle dung, urine, bedding, and leftover fodder. Likewise, vermicomposting, an extensive organic waste recycling model, relies on cattle dung as an underlying substrate for earthworms. However, the management of organic agriculture guidelines and practices are often at variance with the organic context of livestock input, which requires the animals to be raised without synthetic growth promoters and antibiotics. To provide real organic manure from these crops, they need to be grown and raised in organic conditions, with animals being fed organic feed and humane practices maintained. Sadly, that piece has been poorly understood. On this basis, food which we name organic usually will probably not be 100% organic, and it may be used without permission and organic in nature.

Natural Farming and Its Limitations

Natural farming approaches promoted under Zero Budget Natural Farming (ZBNF) and Bharatiya Prakritik Krishi Paddhati (BPKP) emphasize the use of indigenous knowledge, local resources, and eco-friendly agricultural practices. Central to these systems are preparations such as Jeevamrit, Beejamrit, and Ghan Jeevamrit, in which cow dung and urine serve as essential ingredients for enhancing microbial activity, improving soil fertility, and promoting plant health. Despite this strong dependence on livestock-derived inputs, the role of livestock in natural farming often remains that of an "unsung hero," receiving little recognition within the broader framework of natural farming policies and guidelines. This challenge is particularly evident in Northeast India and other tribal regions, where many crop farmers do not own livestock. In order to avail the benefits and incentives associated with natural farming schemes, farmers frequently procure cow dung and cattle urine from external livestock-rearing households. Such dependence on outside sources contradicts the principle of self-reliance that forms the foundation of natural farming and raises concerns regarding its long-term sustainability. While this system may continue temporarily under government-supported incentives, it is unlikely to remain viable in the long run. Therefore, for the sustained success and true sustainability of natural farming, livestock must be formally recognized and integrated as a core component of the natural farming framework.

The Structural Disconnect Between Crop and Livestock Farmers

Agricultural systems are built towards the very root and the nature of farming as far as they are concerned, and they are thus also very much interrelational. They are both based on such systems. Farm residues served as fodder,

while livestock provided manure and draught power. But the system has now become fragmented by modernization and specialization. Many of today's farmers are mostly in silos: Crop producers only work with plant power or farm equipment to farm, with little contact with livestock. Agricultural producers have no involvement with crop agriculture, but a farming approach of dairy, meat, or eggs for production. We find this much difference difficult for organic and natural agriculture, and with the contribution of livestock in that organic agriculture, we can see it is in question. When crop farmers are dependent on livestock farmers and do not have their own livestock to move their production on, the system becomes financially unsustainable over time for everyone in turn.

The Illusion of Sustainability.

Natural farming is viewed rather as a low-cost, self-renewing ecosystem. When farmers don't have animals on hand and demand input from other farmers, the system is pretty much like conventional agriculture but with different inputs. It would be very hard for the same farming system to be truly "natural" if we depend on those outside livestock farmers and do not have any livestock owners that sustain us or supply the basic food resources needed. What happens when government incentives to secure and process input are taken away? Many of the organic and natural farming programs have been initiated on these grounds owing to government support to feed livestock via subsidies and training. They're very inspiring and can't do well alone, not just through policy but for the long term, if the system turns into self-sustaining.

The Case for Livestock Integration.

The problem has to be fixed as one of the main reasons to involve livestock as part of organic and natural farming systems. We have to make sure that input authenticity is a guarantee for organic agriculture. For organic farming to be trusted, the source of inputs has to be traceable and within organic parameters. There has to be no mistake in organic livestock farming, which is to feed them all organic feed and manage the farm in a way that animals are fed organic feed. And there are so many healthy resources that can be recycled on land, for us at the farm level and in the ground, like manure, which is very important to help feed this protein chain. As a result, the soil is filled with valuable nutrients and microbial life because the dung and urine from livestock help the soil and are the foundation of the soils, not inputs from animals. Improved livestock integrated systems and crops will also reduce waste to a greater extent and allow efficient use of crop residues and reduce environmental damage. Farming systems that have a diverse approach with livestock can remain resilient to climatic and economic shocks. Livestock provide another source of income and work as a buffer during crop failures. Livestock rearing leads to opportunities at the local level, and rural livelihoods have to do with their employment opportunities in agriculture, especially for landless and marginal farmers. Integration of livestock is a way to keep farm systems steadier and more risk-free.

Policy Implications and Recommendations

There are policy measures to implement agriculture using livestock as agricultural products with organic and natural farming that would be helpful for the country to apply in any way that would be beneficial for sustainable farming processes and is also for livestock to be housed in organic and natural farming in food sources and livestock care and feed industry in an integrated way, etc. For organic and natural farming guidelines that deal with animal husbandry as an important aspect, they can be implemented, and there must be an overall reference of animal husbandry policy, animals in the system, feeding, and health care as important. Indigenous cattle breeds should be supplied by government programs if we want to give them to the beneficiary farmers. The local breeds have been bred to match the climate and hence have a perfect natural way to produce dung and urine into any farming input. Capacity Building and Training. With proper preparedness, farmers should be educated about organic farming and integrated farming, livestock management, fodder making, and other related activities on livestock farming. At the same time, the development of fodder resources should be included to facilitate livestock integration and to create organic fodder systems through pasture development and fodder crops. To promote integration, agricultural operators should have incentives for integrating farming practices rather than treating crop and livestock operations as separate organizations. The future of organic and natural farming in India is dependent on whether such concepts can develop into system-based approaches. Integrative livestock integration is more than a last step, but is at once a mandatory condition for sustainability. So it is that policymakers and

practitioners will fill the gaps from the past as livestock is key to sustainable agriculture and the development of this farming culture. So not only organic and natural are more trusted but also they'll be viable in the long run.

Conclusion

Organic and natural farming's development, I mean moving forward the direction of sustainable agriculture. But their current application underscores a critical deficiency— livestock has been marginalized. As critical inputs, livestock should now be included in such systems. And if not, organic and natural farming will simply exist as input-based models but more than likely self-feeding ones. Policy frameworks, practices, and beliefs need to come together to promote this holistic view of agriculture, understanding how crops and animals are inextricably linked. Only then can we become the essence of sustainability - ecologically sound systems with economic stability and justice as well as humane ones.



A Deep Dive into the Life of the Mandarin fish (*Synchiropus splendidus*)



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Abstract

The mandarin fish (*Synchiropus splendidus*) is also known as the Mandarin Dragonet, Green Mandarin, Psychedelic Fish, and Mandarin goby. It is considered one of the most beautiful, vibrant, and colorful fish in the world. This fish originates from the Pacific Ocean, particularly in coral reefs around the Philippines, Indonesia, Papua New Guinea, and parts of Australia. The mandarin fish's base coloration features vibrant electric blue, along with patterns of orange, yellow, greenish tones, as well as purple and turquoise. These colors are produced by a unique combination of chromatophores containing various pigments, including rare blue pigments. The mandarin fish lacks scales, and its skin is covered with a thick mucus layer. Mature individuals, particularly males, are larger than females. During mating, males and females emerge from hiding and swim upward in pairs or groups, performing a "mating rise." This fish undergoes external fertilization, with eggs released into open water columns. *Synchiropus splendidus* is currently listed as "Least Concern" by the International Union for Conservation of Nature (IUCN) because it is widely distributed and remains abundant in its natural range (IUCN 3.1) 2018. It is not targeted for food and reproduces well in the wild. However, it faces localized threats such as habitat loss (coral reef destruction), over-collection for the aquarium trade, and climate change. Continuous monitoring and reef conservation are necessary to prevent future decline.

Keywords: unique Characteristics, Breeding Behavior, Mating dance, Conservation and aquarium care

Introduction:

The Mandarin Fish, scientifically known as *Synchiropus splendidus*, is a tropical reef dweller that displays electric blue, orange, green, and yellow in swirling patterns. It is found in the Pacific's coral reefs, where its vibrant colors help in mating displays and serve as camouflage among corals and plants. Mandarin Fish are shy and spend most of their time close to the seafloor, hiding among coral rubble, algae, and seagrass beds. Its natural habitat is the coral reef (Rhyne *et al.*, 2012). The mandarin fish typically reaches about 30–60 mm in total length and is recognized by its characteristically outward-set eyes. They are most active during dusk and dawn, which is also when their courtship rituals occur. During mating, males and females perform a synchronized rise above the reef and release eggs and sperm into the water for external fertilization. Though currently listed as "Least Concern" by the IUCN, Mandarin Fish face localized threats, such as coral reef degradation, climate change, and over-collection for the ornamental fish trade. Increased captive breeding and reef conservation programs are helping to ensure the species remains abundant in its natural environment.

Physical appearance

The mandarin fish has the most complex and vibrant coloration pattern and typically reaches 6 to 7 centimeters in length, and the female is smaller than the male. The base color consists of alternating waves of electric blue and orange, overlaid with intricate patterns of green, purple, and turquoise. These colors are created by a unique combination of chromatophores containing various pigments, including rare blue pigments that are uncommon in vertebrates. The mandarin fish is not easy to maintain in captivity, due to its dietary requirements, other than by experienced aquarists (AMDA, 2000).

Skin Structure and Toxicity

A notable feature of the Mandarin fish is its lack of scales. Instead, its skin is covered with a thick mucus layer that contains toxic compounds, which provide protection against predators and parasites. This mucus includes

various bioactive substances, such as antimicrobial peptides and cytotoxic compounds, making the fish unpalatable.

The skin cells contain specialized organelles called iridophores and chromatophores that produce the brilliant colors through the reflection and absorption of light. The blue coloration, particularly rare in vertebrates, is produced by unique cellular structures containing cyanophores, making the Mandarin fish one of only a few vertebrate species capable of producing true blue pigmentation. The "dichromatic chromatophores" in the Mandarin fish's skin, which are single cells that contain both blue-producing cyanosomes and red-producing erythrosomes (Goda, M., *et al.*, 2013).

Sexual Dimorphism

Sexual dimorphism in *S. splendidus* is pronounced, particularly in mature individuals. Males are generally larger than females. These fish are broadcast spawners that exhibit complex courtship behaviors and precise timing of reproductive activities tied to lunar cycles and environmental conditions. Mandarin fish typically reach sexual maturity at 6-12 months of age, depending on environmental conditions and food availability

Male Characteristics:

Extended first dorsal fin spine that can be twice the length of the fish's body. More intense coloration, particularly during breeding periods. Broader head and more robust body structure. Prominent preopercular spines. More elongated and pointed anal fin. They have a more robust body structure and a broader head. A key feature is their extended first dorsal fin spine, which can be twice the length of the fish's body. Their coloration is also more intense, especially during breeding periods.

Female Characteristics:

Smaller overall size (typically 4-5 cm compared to 6-7 cm in males). More subdued coloration. Rounded first dorsal fin without the extended spine. More streamlined body profile. They have a more streamlined body profile and a rounded first dorsal fin without the long spine. Their coloration is more subdued compared to males.

An Enchanting Mating Dance

The courtship rituals of the Mandarin fish occur around dusk and dawn. During mating, males and females rise up from the reef together in a synchronized "mating rise". As they swim upward, they release eggs and sperm into the water column for external fertilization. As a pelagic spawner, *S. splendidus* releases buoyant eggs that hatch into delicate larvae, which are difficult to culture due to their tiny size and specialized feeding needs (Sadovy *et al.*, 2001; Wittenrich *et al.*, 2010).

Habitats and feeding behaviours

The mandarin fish is typically inhabiting coral rich areas in lagoons and sheltered reef slopes at depths ranging from 1 to 18 meters. *S. splendidus* exhibits highly specialized feeding behavior, functioning as a micropredator that targets small invertebrates living within coral reef substrates. The primary prey items like Copepods (various species of harpacticoid and calanoid copepods), Amphipods (small benthic species), Ostracods (seed shrimp), Polychaete worms (juvenile stages), Gastropod larvae and various other small crustaceans and invertebrate larvae. Feeding Methodology a "pick and peck" feeding strategy, using their small, protrusible mouths to extract prey from tight spaces within the coral matrix. Most feeding activity occurs during crepuscular periods (dawn and dusk) when many of their prey species are most active. However, some feeding also occurs during daylight hours, particularly in areas with adequate cover.

Aquarium trade:

The Mandarin Dragonet (*Synchiropus splendidus*) is a critically important species in the marine ornamental fish trade. Its brilliant colors drive high demand. The demand for the Mandarin Dragonet is exceptionally high due to its unique aesthetic qualities, making it a "dream fish" for many hobbyists. The availability of captive-bred mandarins has increased due to recent developments in commercial aquaculture, which has lessened the strain on wild populations (Rhyne *et al.*, 2011). Although there are still many obstacles to overcome, recent developments in captive breeding and live food enrichment techniques have increased husbandry success.

Conservation Status and Threats

Synchiropus splendidus is currently listed as "Least Concern" by the International Union for Conservation of Nature (IUCN), though this designation may not fully reflect the species' vulnerability to habitat degradation and

collection pressure. This is because the species is widely distributed and reproduces well in the wild. However, it faces localized threats like the destruction of its coral reef habitat, climate change, and over-collection for the aquarium trade. Mandarin fish are highly sought after in the marine aquarium trade due to their spectacular appearance. The main threat is overfishing and selective collection for the aquarium trade, particularly in the Indo-West Pacific (e.g., Philippines) Sadovy *et al.* (2001).

Many Mandarin fish populations benefit from protection within marine protected areas (MPAs) and coral reef reserves throughout their range. Key protected areas include:

1. Great Barrier Reef Marine Park (Australia)
2. Tubbataha Reefs Natural Park (Philippines)
3. Bunaken National Marine Park (Indonesia)
4. Palau National Marine Sanctuary
5. Various local and regional marine reserves.

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When Weather Enters the Kitchen: How Climate Shocks Drive Food Inflation in India



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1. Introduction: the new climate-price conversation

In an ordinary year, the price of onion, tomato, pulses or rice may look like a routine market signal. In a climate-stressed year, the same price becomes a warning light. A delayed monsoon can postpone sowing, a March heatwave can reduce wheat grain filling, excessive rain can damage vegetables just before harvest and a flood can break the road between the producing village and the urban wholesale market. The consumer sees only the final result: the weekly food bill rises.

India's inflation basket gives food a large social and political importance because food expenditure still occupies a substantial share of household budgets, especially among low-income families. The Economic Survey 2023-24 reported that food inflation based on the Consumer Food Price Index (CFPI) increased from 3.8% in FY22 to 6.6% in FY23 and 7.5% in FY24, during years when agriculture faced extreme weather events, lower reservoir levels and crop damage (Ministry of Finance, 2024). The April 2026 CPI release reported year-on-year CFPI inflation of 4.20%, with rural food inflation at 4.26% and urban food inflation at 4.10% (Ministry of Statistics and Programme Implementation [MoSPI], 2026).

This article explains how weather enters the kitchen: not through a single event, but through a chain of production, storage, transport, expectations and policy responses. The central point is simple. Climate shocks have become macroeconomic shocks because food prices link farmers, consumers, public stocks, fiscal costs and monetary policy.

Selected Food Inflation Indicators in India

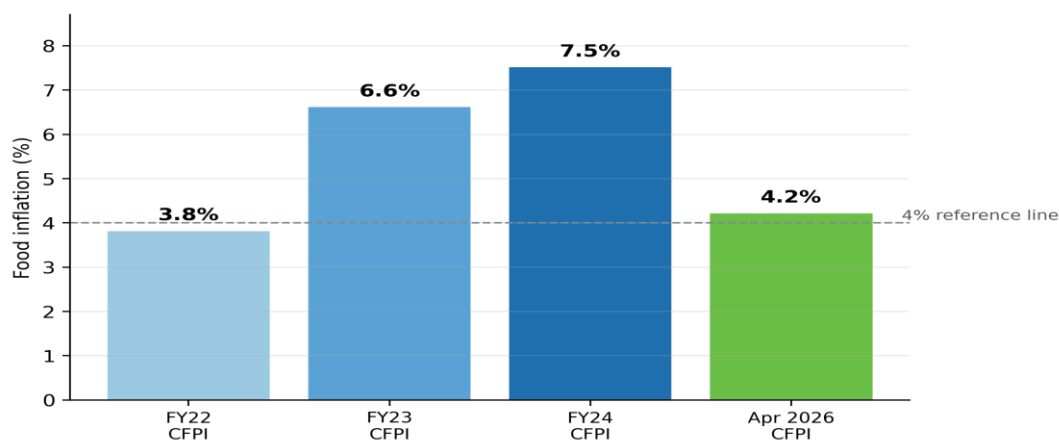


Figure 1. Selected food inflation indicators in India. Note: FY22-FY24 are CFPI values reported in the Economic Survey 2023-24; April 2026 is from the new CPI base 2024 release and is shown as a recent indicator rather than a continuous old-series observation.

2. How climate shocks become food inflation

A climate shock first affects the physical availability of food. Heat stress can reduce yields in cereals, pulses, vegetables and milk production; drought can lower irrigation availability and delay sowing; floods can damage standing crops and stored produce; and unseasonal rainfall can reduce quality, storability and shelf life. The second channel is market access. Even when total production is adequate at the national level, damaged roads, delayed arrivals, higher transport costs and wastage can tighten supply in consumption centres. The third channel

is expectations. If traders, consumers or policymakers expect shortage, inventory behaviour changes and prices can rise faster than actual scarcity.

The important insight is that weather creates both quantity risk and timing risk. A farmer may harvest less output, but a market may also receive the output late, in damaged condition or at a higher logistics cost. For perishable commodities such as tomato, onion, potato, green vegetables, fruits and milk, this timing risk is often enough to generate sharp retail spikes. The price effect is therefore not limited to the field; it is amplified by storage capacity, road connectivity, cold-chain availability and the credibility of market information.

Table 1. Climate shock channels and economic transmission

Climate shock	Immediate farm effect	Market-price channel	Likely vulnerable items
Heatwave	Lower yields, faster moisture loss, labour stress	Supply shortage and higher perishability	Wheat, vegetables, milk
Drought or rainfall deficit	Delayed sowing, lower reservoir recharge, irrigation stress	Reduced output and tighter stocks	Pulses, coarse cereals, oilseeds
Flood or excess rain	Crop submergence, post-harvest losses, transport disruption	Lower market arrivals and logistics premium	Rice, vegetables, fruits
Unseasonal rainfall/hailstorm	Quality loss near harvest, storage damage	Sharp short-run retail spikes	Onion, potato, tomato, fruits
Pest outbreak after weather anomaly	Higher crop losses and pesticide costs	Cost-push and supply-push inflation	Cotton, pulses, horticulture

The econometric evidence is also moving in this direction. Kumar (2026), using annual data for 1970-2024 and a local-projections framework, reports that climate shocks are reshaping India's food-price dynamics. Drought intensity raises cumulative food inflation in the medium run and peaks around the fourth year, while floods and storms show more heterogeneous short-run effects before later price pressures can reappear (Kumar, 2026). The implication is important: weather shocks do not always behave like one-month disturbances. Some work through multi-season supply, stock, labour and expectation channels.

3. A simple inflation equation for a popular understanding

For a non-technical reader, climate-sensitive food inflation can be represented as:

$$\pi_t^f = \alpha + \beta_1 \text{WeatherShock}_t + \beta_2 \text{SupplyGap}_t + \beta_3 \text{FuelCost}_t + \beta_4 \text{PolicyResponse}_t + \varepsilon_t$$

Here, π_t^f denotes food inflation at time t . WeatherShock captures heat, rainfall, drought or flood anomalies; Supply Gap captures the difference between expected and actual availability; FuelCost represents transport and energy costs; PolicyResponse includes buffer-stock release, import or export rules, price-stabilisation measures and monetary-policy stance. The equation is not a full forecasting model; it is a disciplined way to show that food inflation is jointly driven by nature, markets and policy.

In practice, economists may estimate this relationship through ARDL models, VAR models, local projections or machine-learning forecasts. Agricultural statisticians may add satellite vegetation indices, district rainfall anomalies, crop-cutting data, digital crop surveys, mandi arrivals and retail price observations. The policy value of such models is not mathematical elegance alone; it is the ability to identify stress early enough for corrective action before a local crop shock becomes a national kitchen shock.

4. Why India is especially exposed

India is highly exposed because agriculture remains monsoon-sensitive, food markets are geographically segmented and many commodities are perishable. A rainfall deficit in one producing belt may not be perfectly offset by surplus production elsewhere if storage, grading, processing and transport systems are weak. Similarly, a bumper harvest can still coexist with high retail prices when market arrivals are delayed or when urban supply chains face disruption.

The Intergovernmental Panel on Climate Change emphasises that climate risks are already affecting food systems, water security and human well-being, and that the scale of risk increases with warming (IPCC, 2023). For India, this means that inflation management can no longer treat climate as an external background condition. It must be embedded into price monitoring, crop planning and agricultural risk management.

Weather-to-Kitchen Transmission Pathway

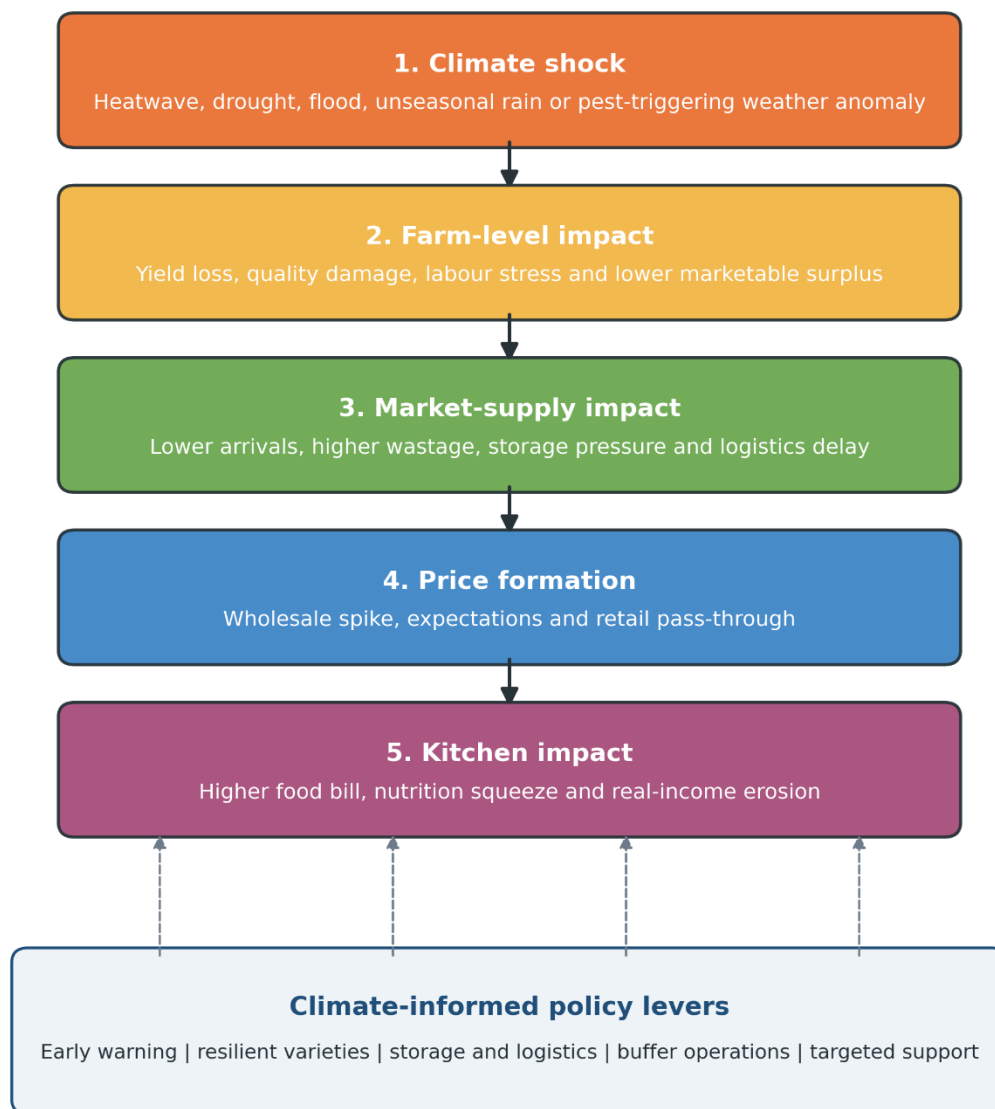


Figure 2. Professional weather-to-kitchen transmission pathway for food inflation.

Recent Indian experience strengthens this argument. The Centre for Social and Economic Progress notes that between 2022 and 2024 India faced record heat, erratic monsoons and persistent food-price pressures, with stress on wheat, rice, public stocks and inflation dynamics (Centre for Social and Economic Progress [CSEP], 2025). These are not isolated agricultural events; they affect the credibility of inflation forecasts, the fiscal cost of consumer relief and the real income of households.

A further reason for exposure is the asymmetry between farm-gate and retail markets. When production falls, retail prices may rise sharply; when production recovers, retail prices may not fall with the same speed because storage margins, transport costs and retail mark-ups adjust slowly. This asymmetry is visible in many perishables. It also explains why farmers and consumers can suffer at the same time: the farmer loses output or quality, while the consumer pays more for a smaller and less diverse food basket.

5. From farmer distress to household nutrition

The welfare effects of climate-induced food inflation are unequal. Farmers may not always benefit from high retail prices because crop loss reduces marketable surplus and because intermediaries, logistics costs and quality

discounts can absorb much of the price increase. Consumers, especially poor consumers, face an immediate squeeze because food demand is less flexible than many non-food items. When prices of pulses, milk, edible oils or vegetables rise, families may reduce dietary diversity before reducing calorie intake.

This is why the term “food inflation” understates the real problem. It is not only about a price index; it is about nutrition, health, gendered food allocation, school meals, wage negotiations and public distribution systems. In rural areas, the same household can be hit twice: first as a producer facing crop damage and then as a consumer buying costlier food. In urban areas, poor households are exposed because they buy almost all their food and have limited scope to substitute away from essential items.

The nutritional channel deserves special attention. A spike in cereal prices affects calorie security, but a spike in pulses, vegetables, fruits, milk or eggs affects protein and micronutrient security. Households may respond by shifting to cheaper staples, reducing meal diversity or postponing expenditure on health and education. Thus, climate-induced food inflation converts an environmental shock into a human-development shock. Any serious food-price policy must therefore protect both producer income and consumer nutrition.

6. What policy should do differently

The policy response must shift from reactive price control to climate-informed food-system management. Five interventions are central: early warning, climate-resilient production, storage and logistics, smart market intervention and integrated data systems. The old approach waits for price spikes and then releases stocks, changes trade rules or imposes restrictions. The new approach should combine weather intelligence, crop intelligence and market intelligence before the price spike becomes politically and nutritionally painful.

Table 2. Policy architecture for climate-sensitive food inflation management

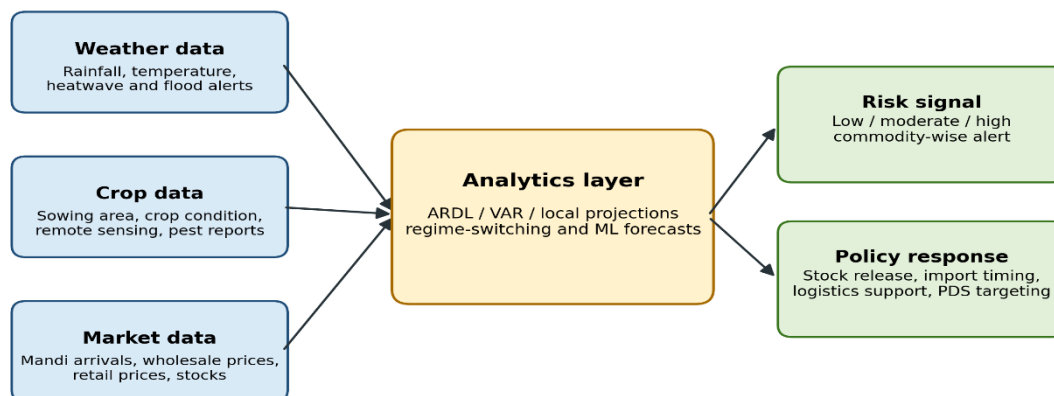
Policy area	Practical action	Expected inflation benefit
Early warning	Integrate IMD forecasts, crop condition, mandi arrivals and retail prices	Detect shortage before prices spike
Climate-resilient production	Heat-tolerant varieties, micro-irrigation, crop diversification, resilient seed systems	Reduce yield volatility
Storage and logistics	Decentralised cold chains, drying, grading, rural roads and rapid transport restoration	Reduce post-harvest loss and logistics premium
Smart market intervention	Rules-based buffer release, calibrated import/export decisions, transparent stock signals	Stabilise expectations
Data systems	Use digital crop surveys, farmer IDs, pest surveillance and remote sensing	Improve targeting and reduce information delay

India’s emerging digital agriculture infrastructure can strengthen this architecture. The Digital Agriculture Mission has created a large-scale foundation, including over 7.63 crore Farmer IDs and 23.5 crore crop plots surveyed, while the National Pest Surveillance System supports 66 crops and more than 432 pest types (Press Information Bureau, 2026). These systems should not remain administrative databases; they should feed into real-time food-inflation intelligence.

For econometricians and agricultural statisticians, the future task is to combine high-frequency weather data, satellite-based crop monitoring, mandi arrivals, wholesale prices, retail prices and household consumption data. Models such as ARDL, VAR, local projections, regime-switching models and machine-learning forecasts can identify whether a price rise is a temporary market fluctuation or an early sign of a climate-induced supply shock.

However, data alone will not stabilise prices. The system must be connected to action. If a rainfall deficit is detected in a pulse-producing belt, the response may include seed contingency planning, import timing, monitoring of private stocks and targeted communication to prevent panic. If unseasonal rain damages onion quality, the response may require rapid drying, storage support, movement from surplus regions and transparent retail monitoring. The goal is not to eliminate all price movement; it is to prevent avoidable volatility from becoming a welfare crisis.

A Practical Early-Warning System for Climate-Sensitive Food Inflation



Goal: detect supply stress before it becomes a household food-price shock

Figure 3. Data and econometric architecture for an early-warning system.

7. Conclusion: food-price stability is climate resilience

The kitchen is the final point of a long climate-economic chain. A heatwave in March, a dry spell in July, a flood in September or unseasonal rain in December can each travel through production, storage, transport and expectations before appearing as a higher household food bill. This is why climate shocks must be treated as central to agricultural economics, not as peripheral environmental events.

India's food-inflation strategy must therefore be redesigned around anticipation. Better irrigation, resilient seeds, diversified cropping systems, scientific storage, real-time crop statistics, credible stock information and targeted consumer relief are not separate policies; together they form an inflation-management system for a warming economy. In the coming years, the countries that manage food prices best will not be those that react fastest after the shock, but those that read the weather before it enters the kitchen.

For popular understanding, the message is direct. Food inflation is not merely a market number announced once a month; it is a story of monsoon timing, farm risk, transport bottlenecks, storage weakness, consumer vulnerability and policy preparedness. When the weather changes, the economy changes with it. The sooner India builds climate intelligence into agricultural statistics and food-price management, the more stable and nutrition-sensitive its growth path will become.

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Maintaining records is essential for livestock farms



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An essential management tool for monitoring individual animals and the performance of the entire herd is a livestock record-keeping register. By keeping an eye on births, reproduction, health, and output, it maximizes profitability. Maintaining accurate records is essential to managing a cattle business. Farmers must rely on their recollections when making decisions about their farming methods in the absence of written records. However, after a few days, months, or years, recollections might lose their accuracy. Therefore, if animals have some sort of identity or numbering, it will be easy to record their accomplishments. Animal identification and registration are therefore always necessary. There are several useful records such as production and financial transactions in the dairy enterprise. We must keep some helpful farm records if we want to understand what is going on on the dairy farm. Farm records resemble the progress report cards that students receive at school. Farmers can determine how successfully they are managing their farm in relation to other farmers if they have farm data. Additionally, they are able to recognize the advantages and disadvantages of their farming operations. Accurate data is also crucial when applying for government loans, borrowing money, and filing taxes.

Advantages of record keeping at farm:

- i. Records provide basis for evaluation of animals from past records hence helps in selection and culling animals.
- ii. Assists in creating animal pedigrees and historical records.
- iii. Helps in assessing the past records and designing better breeding plans to check inbreeding, selecting superior parents and helps in better replacement and culling practices.
- iv. Aids in bull progeny testing.
- v. Aids in the analysis of feeding costs and the advantages of animal product outputs. Thus, it aids in the development of cost-effective feeding plans for maximum output.
- vi. Assists in identifying aberrant circumstances or illness state in the herd that causes weight loss, decreased milk output, etc.
- vii. Assists in identifying frequent diseases in the herd so that timely preventative measures, like as vaccination and deworming, can be developed.
- viii. Assists in determining appropriate prices for animals intended for sale or acquisition.
- ix. Helps in overall better supervision and management of herd.
- x. Assists in determining the dairy farm's revenue and expenses (economics).
- xi. Aids in calculating the price of producing milk.
- xii. Useful for comparing labor and herd productivity with other farms.
- xiii. To analyze the herd's performance over time in order to calculate annual profit or loss and establish the farm's future objectives.

Types of records to be maintained at a dairy farm:

1. Livestock registration: The number of animals on the farm, their identity number, date of birth, sire and dam numbers, calf and sex, date of calving, date of purchase, date of sale/auction, and date of death are all recorded in this register.
2. Calving registration: This register keeps track of every calving that occurs on the farm. It keeps track of the calf's sex, date of birth, dam and sire numbers, and any additional information such as the calving type (normal or atypical).
3. Daily milk yield register: The cows' daily milk production performance is documented in this register.

4. Calf register: keeps track of the calf's number, sex, sire and dam numbers, birth weight, and other details at the farm.
5. Young stock growth record: this record keeps track of the young stocks' weight at various intervals.
6. Daily feeding register: This keeps track of how much concentrate, dry fodder, green fodder, and other feeds are fed to the animals each day.
7. Herd health registration: This register keeps track of sick animals' medical history, symptoms, diagnosis, course of treatment, and veterinarian's name.
8. Cow number, date of calving, date of heat and services, bull number, date of successful service, pregnancy diagnosis records, expected date of calving, actual date of calving, calf number, etc. are all kept in the cattle breeding register.
9. Animal History Sheet: This keeps track of the animal's number, breed, birth date, sire and dam numbers, lactation yield records, drying date, disposal/death date, reason for disposal, etc.
10. Register for the vaccination schedule of different diseases.

All above facts these are the best for animal farmer for future prospect of good and healthy livestock farm.



Seaweed farming as a climate resilient strategy for sustainable agriculture



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1. Introduction

Seaweeds are fast-growing marine macrophytes that play a crucial role in marine ecosystems. They account for 50% of global marine and coastal aquaculture production by weight, with over 99% currently grown in Asia. Approximately 48 to 119 million km² of the global ocean (24–60 times the size of Greenland) may be suitable for seaweed production. It is anticipated that cultivating just 2% of the ocean's surface area with seaweed species would double present agricultural food output in bulk tonnage. Seaweed provides essential ecosystem services, such as, habitat for marine organisms, renewable plastics as well as generating marine protein, carbon dioxide (CO₂) sequestration, and reduction of ocean acidification.

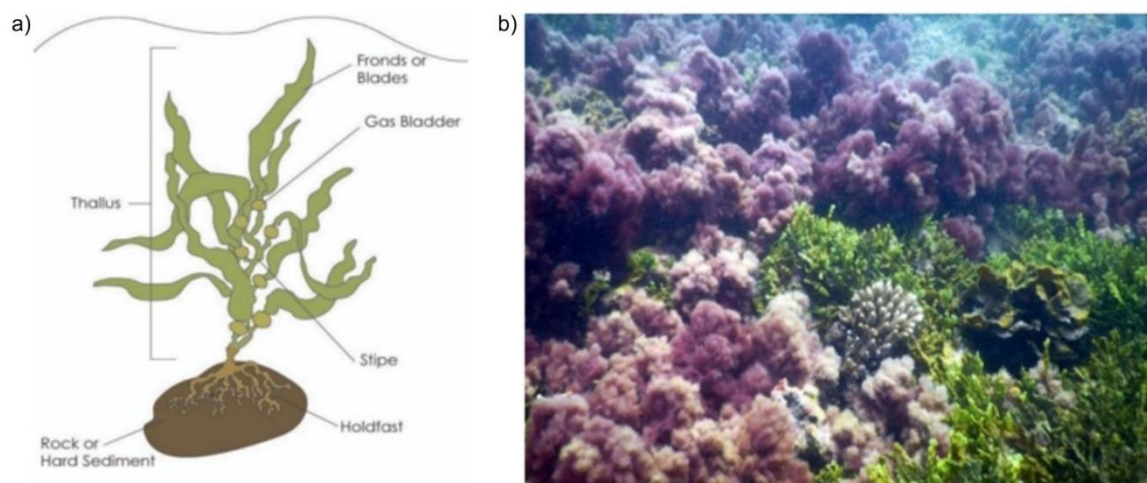


Fig 1. (a) Morphology of seaweed, (b) luxuriant seaweed in underwater

2. Types of seaweed

- Green (Chlorophytes) - presence of chlorophylls a and b
- Red (Rhodophytes) - presence of the pigments phycoerythrin and phycocyanin
- Brown (Phaeophyceae) - dominant on rocky shores

2.1 Seaweed distribution

At global scale, the seaweeds are distributed horizontally in different zonations viz. supra tidal, intertidal and subtidal regions of the seas and oceans. Green seaweeds are most commonly found in the intertidal zone and brown seaweeds inhabit the tidal or upper subtidal zones while red seaweeds grow in subtidal waters. The depth range for seaweeds is from the intertidal zone to the greatest depths (> 200 m) receiving enough light to support their growth (Duarte et al., 2017).

In India, a total of 844 seaweed species have been reported from India with a standing stock of 58,715 tonnes (Banerjee et al., 2020). It includes 216 species of Chlorophyta, 191 species of Pheophyta, 434 species of Rodophyta and 3 species of Xanthophyta. In India, Gujarat and Tamil Nadu coasts harbour the highest seaweed diversity (Ganesan et al. 2019). In 1980–90, the Central Salt and Marine Chemicals Research Institute (CSMCRI) estimated the total standing stocks of seaweeds as 97,400 tonnes wet wt. from the coast of Tamil Nadu, 7,500 tonnes wet wt. from the coast of Andhra Pradesh and 19,345 tonnes wet wt. from the Lakshadweep Islands.



Fig 2. Popular seaweed locations in India (Jaikumar et al., 2023)

2.2 Seaweed production and cultivation trends

2.2.1 Global scale

Global seaweed production reached 35.8 million tonnes in 2019, accounting for 97% of total production (FAO, 2021). Wild seaweed production has remained constant at 1.1 million tonnes, while cultivated seaweed has grown significantly. The increased output might provide the coastal population with 25% more food, 1.5 million tonnes of oil, 5 million tonnes of plant protein, and 125 million MWh of bioenergy. Expanding seaweed farming: Cultivating just 2% of the ocean's surface with seaweed could double present agricultural food output (Radulovich et al., 2015). Major seaweed farming trends (1950–2019): Increased 1000 times (from 34.7 thousand tonnes to 35.8 million tonnes)

- Brown seaweed: 3.1 million → 16.4 million tonnes
- Red seaweed: 1 million → 18.3 million tonnes
- Green seaweed: 31,000 → 17,000 tonnes (FAO, 2021).

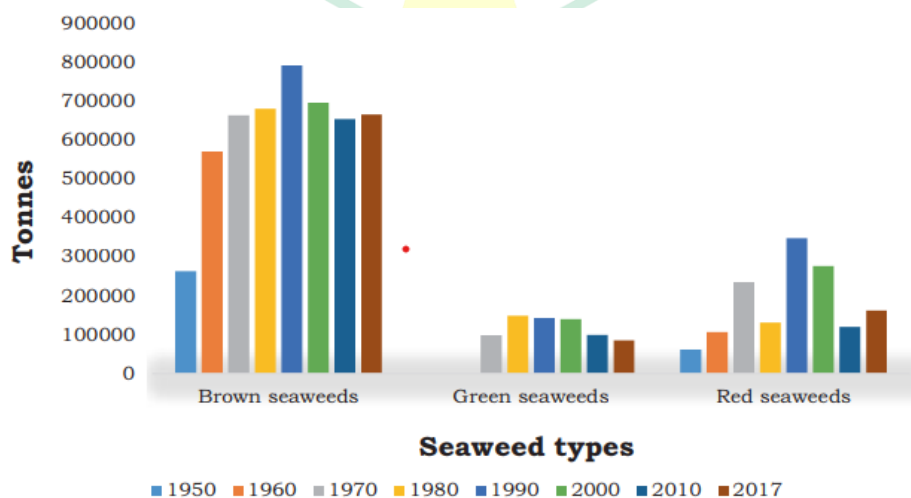


Fig 3. Global capture of seaweed production (Source: FAO 2018)

2.2.2 Indian scenario

India stands in 13th position in global seaweed production as the contribution of the Indian seaweed industry to global seaweed production accounts only for 5.3 tonnes (wet weight) (FAO, 2021). Demand for carrageenan is around 500 tonnes per year, for agar 400 tonnes per year, and for alginate 1,000-2,000 per year. But the production of carrageenan, agar and alginate in India is a mere 50-60, 150 and 250-600 tonnes per year respectively.

Pradhan Mantri Matsya Sampada Yojana scheme allocated six hundred and forty crores (640 Cr) for Seaweed Cultivation and Value Chain Development in India. The production target for the country from 2020-21 to 2024-25 is 11.2 lakh tonnes in wet weight from 13 states/union territories including Gujarat, Maharashtra, Goa, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, West Bengal, Karnataka, Puducherry, Lakshadweep, Andaman & Nicobar Islands, and Daman & Diu (Department of Fisheries, Govt. of India, Presentation).

3. Principle of seaweed farming

Seaweed farming is defined as the optimized culturing of seaweed crops in seawater for growth and ensuring continuous photosynthesis. Seaweed is plant-like species attached with a holdfast to shallow coastal waters, requires sunlight and substratum for its growth, but does not have root to supply nutrients, as whole body is involved in nutrient absorption and photosynthesis. Few brown seaweeds are free-floating because of their air-filled bladders (Milledge and Harvey, 2016). Hence the ability of seaweed to grow in the form of attachment to floating objects is the basis of seaweed farming

3.1 Steps in seaweed farming

1. Site selection - Long-spine sea urchins and turtles are causing physical damage to the farm or injuries to the farmers. The diseases, including “ice-ice,” are also a challenge for seaweed farming because it causes damage to the seaweed (Egan et al., 2014).
2. Species selection and preparation - based on the ultimate application (food, feed, hydrocolloid, biofuel, and bioactive compounds) and suitability of the environment.
3. Cultivation method selection - bottom monoline method, fixed bottom long-line method, floating bamboo method, bamboo raft method, mangrove stakes, net cultivation, and integrated multitrophic aquaculture method (Radulovich et al., 2015)
4. Maintenance at field, and
5. Harvest followed by drying

3.2 Advanced techniques in seaweed cultivation

Offshore cultivation method is a possible step toward large-scale expansion of seaweed farming and reduction of the impact of waste generated in aquaculture (Buck et al., 2018). The offshore cultivation techniques include integrated multitrophic aquaculture and macroalgal cultivation rig, which could reduce the pressure on coastal waters and provide void biomass.

3.2.1 Integrated multitrophic aquaculture (IMTA)

IMTA provides the coculturing of organisms from the different trophic levels at the same farm to minimize aquaculture waste. It provides cocultivation of fed species (finfish and shrimp) together with organic extractive species (mussels and oysters) work as

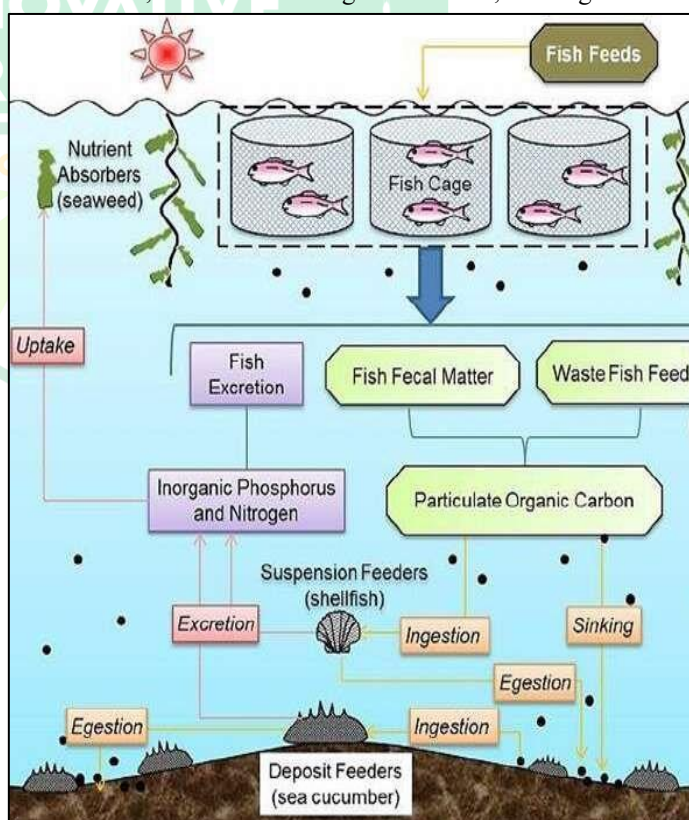


Fig 4. Process flow of Integrated multitrophic aquaculture (IMTA)

suspension-feeding and sea urchin and sea cucumber as deposit-feeding and inorganic extractive species seaweed (kelp) to create a more balanced ecosystem. The minerals are still being extracted from the water as seaweeds are collected from IMTA (Granada et al., 2018). The *Ulva lactuca* produced in IMTA considerably reduced the nitrogen loads from the water by assimilating about 74% of dissolved nitrogen and help in the growth of sea urchin (Shpigel et al., 2018).

3.2.2 Macroalgal cultivation rig

Vertical lines that help in switching over from one species to other in between the harvesting process. Multiple partial harvesting (four harvests for *Saccharina latissima* and three harvests for *Alaria esculenta*) are possible without reseeding to reduce the production cost. Further, rig comprises fixed lines in horizontal direction along with seed lines toward vertical direction arranged in the form of backbone (Buck et al., 2018).

4. Role of seaweed in climate change

4.1 Carbon sequestration

Seaweed is the best primary producer in marine ecosystems, with a net production of 1521 Tg carbon/year. Seaweed can sequester dissolved CO₂ at a daily rate of 80.5 mg/g wet weight (WW), with a CO₂ sequestration intensity of approximately 1,500 t CO₂/km²/year (Duarte et al., 2017). The potential carbon sequestration was 173 TgC per year ranging between 61 and 268 TgC/year (~11% of global net C-production). If just 0.03% of the ocean surface area is cultivated with seaweed, it could remove approximately 135 million tons of carbon per year, which equates to 3.2% of annual oceanic carbon input (Bjerregaard et al., 2016). Seaweed-based carbon sequestration strategies: a) restoring wild seaweed forests, b) expanding nearshore seaweed aquaculture, c) offsetting industrial CO₂ emissions using seaweed-based products, and d) sinking seaweed into the deep ocean to sequester CO₂.

Laminaria japonica, plays a notable role in the process of carbon sequestration. Macroalgae, including kelp, release dissolved organic carbon (DOC) into the seawater, comprising a substantial proportion of recalcitrant DOC (RDOC) that remains stable and can be sequestered for prolonged periods. This phenomenon enhances the significance of macroalgae in carbon sequestration processes (Li et al., 2022). *Gracilaria tikvahiae* (red seaweed) and *Saccharina latissima* (brown seaweed) rapidly assimilate carbon in Long Island Sound and the Bronx River Estuary of New York (Kim et al., 2017). Commercial seaweed harvest sequesters approximately 1.5 million tonnes of carbon per year, equivalent to 3.2% of the carbon released into seawater due to greenhouse gas emissions.

4.2 Ocean Acidification Mitigation and Marine Ecosystem Protection

Seaweed acts as a sponge for carbon dioxide, reducing ocean acidification (Duarte et al., 2017). Increasing the number of seaweeds utilize the high level of CO₂ for its growth. So, the CO₂ will not be available for the production of carbonate ion and hydroxyl ions, responsible for ocean acidification. Seaweed has a great intake and recycling of CO₂; kelp uses up five times more carbon than other land-based vegetation (Sinha et al., 2001). Large-scale seaweed farms increase oxygen levels and provide refuge from hypoxia, benefiting marine species (Duarte et al., 2017). Seaweed farming has been found to cause a net positive rise in pH and oxygen around farm operations, particularly during rapid growth phases (Campbell et al., 2019). Green seaweed *Chaetomorpha antennina* have demonstrated a beneficial impact by decreasing the rate at which marine bivalve shells dissolve when exposed to elevated CO₂ levels (Cui et al., 2021).

4.3 Agricultural Emission Reduction

Seaweed is utilized as an organic fertilizer, soil conditioner, and promote biostimulant properties, helping crops resist drought and diseases. Rich in essential nutrients like nitrogen, phosphorus, and potassium, as well as micronutrients and growth-promoting substances, seaweed contributes significantly to plant health. Farmers incorporate seaweed extracts into their agricultural practices through methods like foliar spraying, soil amendments, or hydroponic applications, resulting in improved plant growth, resilience to stress, and overall crop yield. Seaweed biochar and compost seaweed can improve soil quality and crop productivity, replacing synthetic fertilizers and reducing emissions (Zacharia et al., 2015).

Additionally, seaweed releases beneficial substances into the soil, stimulating microbial activity and enhancing nutrient availability for plants. Cultivating seaweed on 0.03% of the ocean surface could remove 30%

of introduced nitrogen (Bjerregaard et al., 2016; Kim et al., 2017). Seaweed removes inorganic nutrients from ocean water, mitigating environmental damage. The seaweed farming annually removes approximately 75,000tons of nitrogen and 9500tons of phosphorous from coastal waters (Xiao et al., 2017). The World Bank estimates that producing a global harvest of 500MT of seaweed by 2050 will consume 10MT of nitrogen from the water, which is 30% of the nitrogen expected for reaching the sea, and 15MT of phosphorus, which is around 33% of the phosphorus produced from manure and fertilizers.

4.4 Livestock Emission Reduction

Adding seaweed to cattle feed significantly reduces methane emissions: Just 2% of certain seaweed species in cattle feed can reduce methane emissions by up to 99% (Machado et al., 2016). Fermented seaweed enhances ruminant digestion, minimizing methane production.

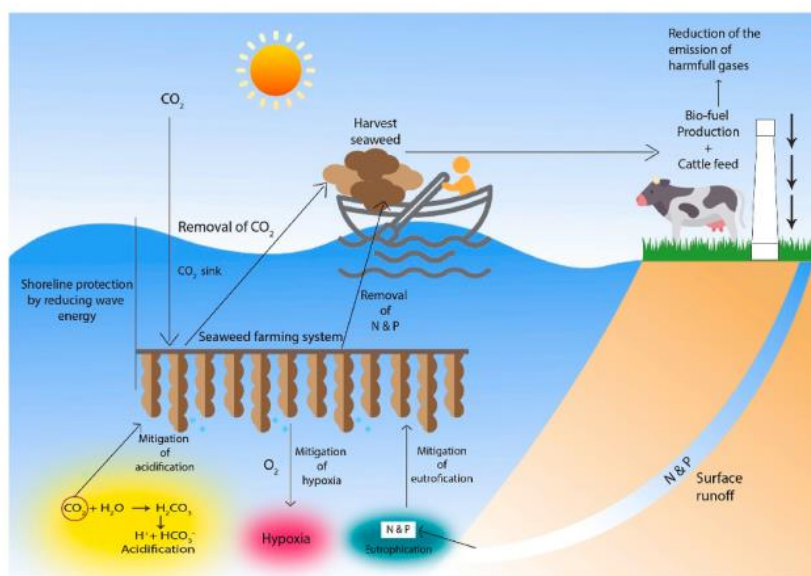


Fig 5. Benefits of seaweed farming in climate change mitigation and adaptation (Source: Duarte et al., 2017)

5. Conclusion

Seaweed farming plays a crucial role in climate change mitigation by sequestering carbon and reducing CO₂ emissions, producing biofuels as an alternative to fossil fuels, reducing agricultural emissions through livestock feed and soil enhancement, mitigating ocean acidification and improving marine ecosystems, and providing coastal protection against climate-induced disasters. Despite its challenges, proper management and strategic expansion of seaweed farming could provide significant environmental benefits and contribute to long-term climate resilience.

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SEHAT: Integrating Agriculture with Health



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India's progress in augmenting food grains production since independence has been unparalleled. From a food deficit nation to a food secure one, India now leads the world in production of many commodities. India is a top-three global food grain producer, frequently ranking 2nd in rice and wheat production and 1st in pulses and millets as of 2024-2025. With a record production of around 354-357 million tonnes for the 2024-25 agricultural year, India ranks behind China, securing a strong position in overall cereal production. Production of food grains has increased almost seven times from 50 million tonnes to more than 350 million tonnes at present ensuring a stable and secure supply for the population. Horticultural production has exceeded food grains production. In the country, the daily per capita net availability of food grains has reached to about 568 grams which translates to about 207.6 kg per person annually.

Despite a considerable improvement made in agricultural production and consequent food security, nutritional security has been a cause of concern for all. Nutritional security is a state where all individuals have consistent physical, economic, and social access to safe, nutritious food that meets dietary needs for an active, healthy life. It goes beyond food security (calorie availability) by focusing on dietary quality, nutrient intake, and the body's ability to utilize food, encompassing clean water and health services. The core pillars of Nutritional Security include Availability *i. e* sufficient, diverse, and nutritious food must be available; Accessibility *i. e* economic and physical means to obtain this food; Utilization *i. e* proper biological use of food through adequate diet, water, sanitation, and health care and Stability which means reliable access to nutrition at all times, unaffected by crises or seasons. Nutritional security results Holistic Health by reduction of malnutrition, including stunting (36% of children under 5 in India) and wasting (19%), which are linked to about 45% of deaths in children under 5. It also leads to economic productivity by boosting human capital, reducing illness-related lost productivity and lowering healthcare costs. It also prevents 'Hidden Hunger' by ensuring intake of essential micronutrients (iron, vitamin A, iodine) that prevent cognitive impairment and chronic diseases.

The world GHI score sat at 18.3, marking virtually no significant shift since 2016, placing the global hunger level firmly in the "moderate" category and pushing the 2030 Zero Hunger target out of reach. [Around 35.5 million children under the age of five were acutely malnourished. Of these, nearly 10 million suffered from severe acute malnutrition, a life-threatening condition. Over 150 million children suffered from chronic under-nutrition. India specifically recorded the highest number of wasted (low weight-for-height) children in this age bracket. India faces a 'serious' hunger problem ranking 102nd out of 123 countries in the 2025 Global Hunger Index with a score of 25.8. Despite being a top food producer, around 14% of the population suffers from serious hunger and the nation hosts roughly 25% of the world's undernourished people. Malnutrition is particularly high in women and children, with high rates of wasting and anemia. The hidden hunger is not only more prevalent in poorer countries in Asia and Africa, but it also exists in developed world and in countries like USA. Vitamin A deficiency worldwide was identified as a major problem worldwide until 1992. In 1992 scientists from John Hopkins University revealed that 1.3 to 2.5 million deaths among infants and preschoolers could be prevented every year if they just received enough vitamin A; no other nutritional interventions or improvements were needed. Deficiencies of various micronutrients, including vitamin A, zinc and iron are common in the developing world and affect billions of people. These can lead to amongst other symptoms, a higher incidence of blindness, a weaker immune system, stunted growth and impaired cognitive development. The poor, particularly the rural poor, tend to subsist on a diet of staple crops such as rice, wheat and maize, which are low in these micronutrients, and most cannot afford or efficiently cultivate enough fruits, vegetables or meat products that are necessary to obtain healthy levels of these nutrients.

SEHAT (Science Excellence for Health through Agricultural Transformation): To combat the menace of hidden hunger and malnutrition, Indian Council of Agricultural Research (ICAR) has come up with a landmark initiative called SEHAT (Science Excellence for Health through Agricultural Transformation). SEHAT is a landmark national mission launched by the Indian Council of Agricultural Research (ICAR) and the Indian Council of Medical Research (ICMR). It proactively links agriculture, nutrition, and public health to combat malnutrition and prevent diseases. The mission will work on four core strategies:

Crop Biofortification: It will shift focus from just food yield to nutritional value by promoting bio-fortified and traditional crops to alleviate 'hidden hunger'. The country has already started working on 'Biofortification'. It differs from conventional fortification in that biofortification aims to increase nutrient levels in crops during plant growth rather than through manual means during processing of the crops. Biofortification may therefore present a way to reach populations where supplementation and conventional fortification activities may be difficult to implement and/or limited. Some examples of biofortification include iron-biofortification of rice, beans, sweet potato, cassava and legumes, zinc-biofortification of wheat, rice, beans, sweet potato, maize and provitamin A carotenoid-biofortification of sweet potato, maize and cassava; and amino acid and protein-biofortification of sorghum and cassava. In the case of iron, WHO estimated that biofortification could help curing the 2 billion people suffering from iron deficiency-induced anemia.

Integrated Farming: Under SEHAT Integrated Farming will be encouraged through sustainable agricultural practices designed to build resilient and healthy food systems. Focus will now be on farming system approach. A farming system integrates crops, livestock, aquaculture, and agro-forestry to create a balanced, self-sustaining ecosystem. Output of one enterprise becomes input of other one. Sustainable agriculture optimizes this system using low-input, eco-friendly practices like crop rotation and natural pest management to protect natural resources, minimize pollution, and ensure long-term economic profitability.

One Health Approach: It will be based on a 'One Health Approach' collaborating across medical, veterinary, and agricultural disciplines to prevent zoonotic diseases, manage data, and improve pandemic preparedness. The One Health approach is an integrated framework designed to balance and optimize the health of people, animals, and ecosystems. It recognizes that human, animal and environmental healths are deeply interdependent and requires collaborative, multidisciplinary efforts across various sectors to address global health threats. One Health approach focuses on physical well-being, disease prevention, and ensuring populations are protected against outbreaks. Animal health protects livestock, domestic pets, and wildlife, while promoting sustainable agricultural and conservation practices and Environmental health maintains healthy ecosystems, clean water, clean air, and climate stability, which are foundational for all life.

Preventive Healthcare: It is another aspect of SEHAT wherein the national health strategy will be shifted from a reactive, curative model to a proactive one by improving dietary habits and nutritional security at the grassroots level. Preventive healthcare (or prophylaxis) consists of proactive measures including check-ups, screenings, and vaccinations designed to prevent illnesses, detect potential health issues early, and manage risk factors before symptoms develop. It aims to keep individuals healthy, improve long-term well-being, and reduce the need for more intensive, costly treatments later. Routine Screenings, Vaccinations & Immunizations: Annual Wellness Exams Lifestyle Counseling and Pediatric Care are essential part of it.

INTERKINGDOM DNA TRANSFER AND TUMORIGENESIS IN CROWN GALL DISEASE



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ABSTRACT

Crown gall disease is a widespread plant tumor disease caused by the soil-borne bacterium *Agrobacterium tumefaciens*. The pathogen induces neoplastic growth by transferring T-DNA from its tumor-inducing (Ti) plasmid into the host plant genome. Wound-released phenolics activate bacterial virulence genes, enabling T-DNA processing and delivery through a Type IV secretion system. Integration of T-DNA leads to expression of auxin and cytokinin biosynthesis genes, resulting in hormonal imbalance and uncontrolled cell proliferation. Opine synthesis genes further reprogram plant metabolism to support bacterial growth. Recent studies highlight the role of host transcriptional reprogramming, chromatin remodelling, and non-CG DNA methylation in tumor development. Beyond its pathological impact, *A. tumefaciens* serves as a powerful tool for plant genetic engineering. This manuscript reviews the biology, molecular mechanisms, host interactions, and biotechnological applications of crown gall disease.

Keywords: Crown gall, *Agrobacterium tumefaciens*, T- DNA, Ti- plasmid, tumor.

1. INTRODUCTION

Crown gall disease represents one of the most extensively studied plant diseases because it provides a natural example of interkingdom genetic transfer. The disease was first described in grapevines in France in the nineteenth century and later demonstrated to be caused by a bacterium by Smith and Townsend in 1907. Their work established the infectious nature of plant tumors and laid the foundation for molecular plant pathology. Unlike most plant pathogens that cause necrosis or tissue collapse and induces persistent tumor formation. Once plant cells are transformed, tumors continue to grow even in the absence of bacteria, indicating permanent genetic alteration. This discovery revealed that tumorigenesis results from stable integration of bacterial DNA into plant chromosomes.

2. SYSTEMATIC POSITION

Domain: Bacteria

Phylum: Proteobacteria

Class: Alphaproteobacteria

Order: Rhizobiales

Family: Rhizobiaceae

Genus: *Agrobacterium*

Species: *A. tumefaciens* (= *Rhizobium radiobacter*)

3. THE PATHOGEN

The bacterium is a gram (-) ve, soil inhabitant, rod shaped with presence of few peritrichous flagella. The genome size is about 5.7 Mbp. Its genome is multipartite, consisting of circular and linear chromosomes along with plasmids (Ti- Plasmid and Cryptic Plasmid). Pathogenicity depends on the presence of the tumor-inducing (Ti) plasmid. *Agrobacterium* causes crown gall of many woody plants. Primarily stone fruits, pome fruits, willows and grapes. *A. tumefaciens* carries Ti- plasmid which is responsible for tumor formation. Similarly, *A. rhizogenes* carries Ri- plasmid which is responsible for hairy root formation in apple.

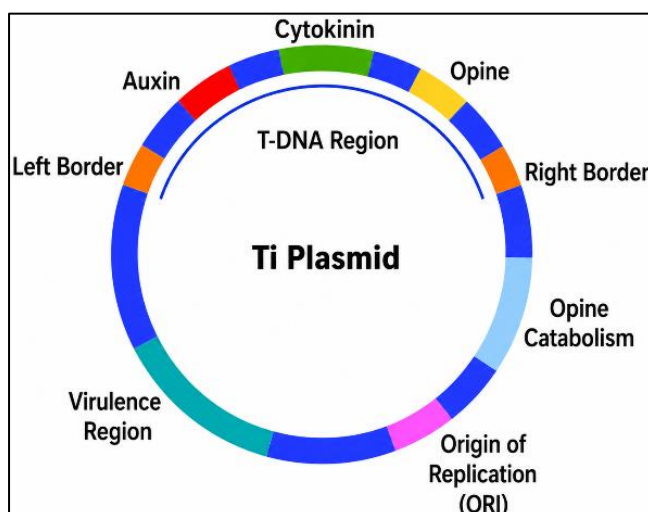
4. SYMPTOMS

- ❖ Crown gall first appears as small, round, whitish, soft overgrowths on the stem and roots, particularly near the soil line.
- ❖ As the tumors enlarge, their surfaces become convoluted, and the outer tissues become dark brown due to the death and decay of the peripheral cells.

- ❖ Irregular tumors sizes may reach upto 30 cm in diameter and upto 150 cm from the ground.



5. STRUCTURE OF Ti- PLASMID



The Ti plasmid contains:

- Origin of replication (ORI)
- Virulence (vir) region
- T-DNA region
- Opine catabolism

Origin of replication (ORI)- Initiates plasmid DNA synthesis. The components are repA, repB, repC and repV. In that repC is a replication initiator protein which binds to ORI.

Virulence (vir) region- Contains different virulence genes, each encodes different functions from signal sensing to integration of T- DNA in a host genome.

Functional Category	Genes
Signal sensing (Phenolic compound released from wounded plant cell)	virA, virG
T-DNA processing	virD₁, virD₂, virC₁, virC₂
T-strand protection from plant defence reactions	virE₁, virE₂
Initiate Type IV Secretion machinery through F- Pili	virB₁- virB₁₁, virD₄
Nuclear targeting & integration	virD₂, virE₂, virF

The vir region encodes approximately 11 operons (virA- virH), required for T-DNA excision, protection, transport, and integration.

T-DNA region- It is responsible for gall formation in host plant by carrying oncogenes and opine genes into the plant cell machinery.

The T-DNA region encodes:

- ❖ Auxin biosynthesis genes → *iaaM* and *iaaH*
- ❖ Cytokinin biosynthesis genes → *ipt*

- ❖ Opine biosynthesis genes- **nos** (Nopaline), **ocs** (Octopine) & **ags** (Agropine) **genes** [Depending on its strain type].

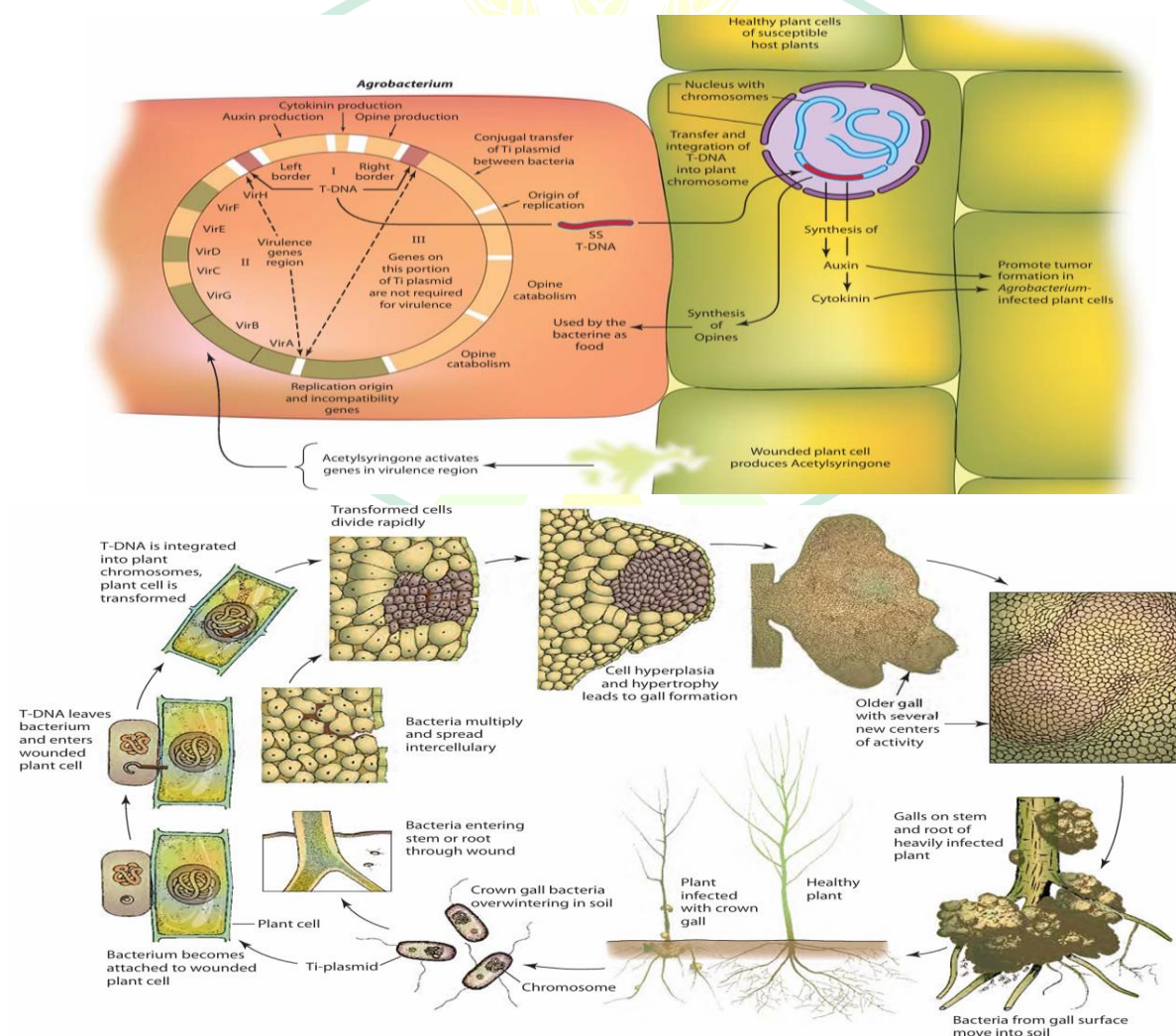
Opine catabolism- This region contains different catabolic operon (Nopaline type- **noc** genes, Octopine type- **ooc** genes and Agropine type- **acc** genes).

4. MOLECULAR MECHANISMS OF CROWN GALL FORMATION

Wound Recognition and Signal Perception: Infection begins at fresh wound sites (24 hrs). Wounded plant cells release phenolic compounds such as acetosyringone. These molecules are detected by the VirA sensor kinase, which activates the response regulator VirG, inducing transcription of other vir genes.

T-DNA Processing and Transfer: VirD₁ and VirD₂ introduce a site-specific nick at border sequences, generating a single-stranded T-DNA (T-strand). VirE₂ binds and protects the T-strand. The T-DNA protein complex is transported into plant cells via the Type IV secretion system (VirB₁- VirB₁₁[11 genes] and VirD₄). VirD₂ and VirE₂ contain nuclear localization signals that guide the T-complex into the nucleus, where integration occurs through host DNA repair pathways.

Integration and Oncogene Expression: T-DNA integrates semi-randomly into plant chromosomes. Expression of auxin and cytokinin biosynthesis genes leads to hormonal imbalance, resulting in hyperplasia (increased cell number), hypertrophy (increased cell size) and loss of growth regulation. Transformed cells also produce opines, which serve as exclusive nutrients for Ti plasmid containing bacteria. Importantly, high auxin and cytokinin levels alone are insufficient for transformation; stable genomic integration is essential for tumorigenesis.



DISEASE CYCLE

The bacterium overwinters in soil and plant debris. It infects through wounds caused by cultivation, grafting, or insects. Tumors release bacteria back into soil, completing the disease cycle. Secondary tumors may develop systemically, possibly originating from vascular tissues.

5. HOW THE BACTERIUM OVERCOMES PLANT DEFENSE?

Plant defense	Mechanisms used by <i>A. tumefaciens</i>
PAMP-Triggered Immunity (PTI)	Type IV Secretion System (T4SS) injects Vir effectors (VirE ₂ , VirE ₃ , VirD ₂).
Oxidative Burst (ROS Production)	Catalase (KatA), Superoxide dismutase (SOD), Peroxidases, VirE ₂ protects T-DNA from oxidative damage.
Cell Wall Fortification	Suppression of callose synthase signaling, mild secretion of pectinases & cellulases and infection at wound sites (for natural wall weakness).
Hypersensitive Response (HR) / ETI (Effector Triggered Immunity)	Lacks strong Avr proteins (weak ETI activation), Effectors interfere with HR signaling and maintains host cell viability.
SA (Salicylic Acid) mediated defense	Early auxin signaling suppresses SA pathway, Hormonal crosstalk manipulation leads to downregulation of defense genes.
JA (Jasmonic Acid) /ET (Ethylene) for wound response	Alters SA- JA balance toward susceptibility and hormonal reprogramming favors transformation.
Antimicrobial Compounds (Phytoalexins, phenolics and PR proteins)	Biofilm formation, efflux pumps and produce resistance enzymes.
Nutrient limitation (Eg. Iron)	Siderophore production to scavenge iron efficiently.
Growth restriction signals	T-DNA oncogenes (iaaM, iaaH → auxin; ipt → cytokinin) reprograms host cells.

6. BIOLOGICAL CONTROL

- ❖ A non-pathogenic strain (*A. radiobacter*) K84 produces agrocin 84, a bacteriocin inhibitory to pathogenic strains. The derivative strain K1026 prevents resistance transfer. Recent studies report that *Bacillus velezensis* and endophytic *Pseudomonas* spp. suppress crown gall through antibiosis, biofilm disruption, and induction of systemic resistance. These findings highlight sustainable disease management strategies.
- ❖ Disarmed Ti plasmids lacking oncogenes enabled development of binary vector systems.

7. RECENT TRANSFORMATION RESEARCH

A recent study by Ying Liu *et al.* (2022) established an efficient *Agrobacterium* mediated transformation system in *Brassica rapa* var. *rapa* using CRISPR/Cas9. The study demonstrated that *Agrobacterium*'s natural DNA transfer ability can be harnessed for precise genome editing, BrrWUSa gene enhances shoot regeneration, CRISPR/Cas9 was used to target BrrTCP4b and stable integration and targeted mutation were achieved in *Brassica*.

8. CONCLUSION

Crown gall disease remains a model system for studying host reprogramming, bacterial virulence, and interkingdom DNA transfer. Emerging multi-omics analyses reveal that tumor development is governed not only by hormonal dysregulation but also by chromatin remodeling and epigenetic control. Future research should focus on:

- ❖ Mechanistic details of T-DNA integration
- ❖ Host chromatin remodeling pathways
- ❖ Engineering hyper-efficient transformation strains
- ❖ Sustainable biocontrol integration

Understanding crown gall biology continues to bridge between plant pathology and biotechnology.

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Heavy Metal Analysis Using Digital Soil Mapping



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Abstract

Heavy metal contamination in soils has become a critical environmental issue due to rapid industrialization, urbanization, mining activities, agricultural intensification, and improper waste disposal practices. Toxic metals such as cadmium, lead, chromium, nickel, arsenic, mercury, copper, and zinc accumulate in soils and pose significant threats to ecosystems, crop productivity, groundwater quality, and human health. Traditional methods of assessing heavy metal contamination rely on extensive field sampling and laboratory analysis, which are often expensive, time-consuming, and spatially limited. Digital Soil Mapping (DSM) has emerged as an advanced geospatial approach for predicting and mapping heavy metal distribution using environmental covariates, remote sensing data, geographic information systems, and machine learning algorithms. DSM enables the creation of spatially continuous contamination maps with improved efficiency and accuracy. Modern techniques such as Random Forest, Support Vector Machine, Artificial Neural Networks, and geostatistical methods are widely employed for predictive modeling. Remote sensing platforms including satellite imagery, hyperspectral sensors, and unmanned aerial vehicles further strengthen contamination assessment capabilities. This paper discusses the principles, methodologies, data sources, modeling techniques, applications, challenges, and future prospects of heavy metal analysis using Digital Soil Mapping. The study highlights the importance of DSM in environmental monitoring, risk assessment, sustainable land management, and precision agriculture.

Keywords: Digital Soil Mapping, Heavy Metals, Remote Sensing, Spatial Analysis

1. Introduction

Soil is an essential natural resource that supports agricultural production, biodiversity, ecological balance, and human survival. However, increasing anthropogenic activities have significantly degraded soil quality worldwide. Among various soil degradation problems, heavy metal contamination has gained major attention because of its persistence, toxicity, non-biodegradable nature, and potential to accumulate in living organisms through the food chain. Heavy metals are naturally occurring elements with relatively high atomic weights and densities. Although certain metals such as zinc, copper, iron, and manganese are required in trace amounts for plant growth, excessive concentrations become toxic to plants, animals, microorganisms, and humans.

Industrialization, mining operations, sewage sludge application, excessive fertilizer and pesticide use, wastewater irrigation, vehicular emissions, and improper waste disposal are the major sources of heavy metal contamination in soils. Once introduced into the soil environment, heavy metals remain for long periods due to their low mobility and resistance to degradation. Contaminated soils reduce crop productivity, deteriorate soil fertility, affect microbial diversity, and increase health risks through food chain contamination.

Traditional heavy metal analysis involves field sampling followed by laboratory testing using techniques such as Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), and X-ray Fluorescence (XRF). Although accurate, these methods are labor-intensive, costly, and inadequate for representing spatial variability over large areas. Soil contamination is spatially heterogeneous due to differences in land use, topography, geology, and pollution sources. Therefore, there is a need for advanced spatial techniques capable of predicting contamination continuously across landscapes.

Digital Soil Mapping has emerged as a powerful approach for analyzing soil properties and contaminants using numerical models and spatial environmental data. DSM integrates field observations, remote sensing, terrain analysis, GIS, and predictive modeling techniques to generate high-resolution soil maps. The approach helps identify contamination hotspots, supports remediation planning, and improves environmental monitoring.

2. Heavy Metals in Soil

Heavy metals are metallic elements that occur naturally in the Earth's crust but become hazardous when accumulated in excessive concentrations. Common heavy metals found in contaminated soils include cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), mercury (Hg), arsenic (As), copper (Cu), and zinc (Zn). These metals originate from both natural and anthropogenic sources.

Natural sources include weathering of parent rocks, volcanic eruptions, and atmospheric deposition. However, human activities contribute significantly to elevated heavy metal concentrations in soils. Industrial emissions, mining and smelting operations, coal combustion, automobile exhaust, landfill leachates, sewage irrigation, fertilizers, pesticides, and electronic waste disposal are major anthropogenic contributors.

Heavy metals adversely affect soil health by altering microbial activity, reducing nutrient availability, and disrupting biochemical processes. Toxic metals may enter plant tissues and subsequently accumulate in animals and humans through the food chain. Long-term exposure to heavy metals can cause neurological disorders, kidney damage, respiratory diseases, and cancer.

The distribution of heavy metals in soil depends on various factors such as soil texture, pH, organic matter content, cation exchange capacity, climate, and topography. Understanding their spatial variability is essential for environmental risk assessment and sustainable land management.

3. Concept of Digital Soil Mapping

Digital Soil Mapping refers to the creation of spatial soil information using mathematical and statistical models that relate soil observations to environmental covariates. DSM is based on the principle that soil properties are influenced by soil-forming factors including climate, organisms, relief, parent material, time, and human activities.

The DSM framework generally involves soil sample collection, laboratory analysis, environmental covariate preparation, predictive modeling, spatial interpolation, validation, and map generation. Environmental variables used in DSM include elevation, slope, aspect, vegetation indices, rainfall, temperature, land use, geology, and spectral data derived from remote sensing.

DSM offers several advantages over conventional soil mapping methods. It reduces sampling costs, improves spatial coverage, increases mapping accuracy, and enables continuous prediction of soil properties. The integration of GIS and remote sensing technologies further enhances the efficiency of digital soil mapping.

In heavy metal studies, DSM predicts contamination levels across landscapes using observed heavy metal concentrations and environmental predictors. The resulting maps help identify contaminated zones, pollution sources, and vulnerable areas.

4. Role of Remote Sensing in Heavy Metal Analysis

Remote sensing plays a vital role in Digital Soil Mapping by providing spatially continuous environmental information. Satellite imagery, aerial photography, hyperspectral sensors, and UAV-based systems are widely used for soil contamination studies.

Satellite platforms such as Landsat, Sentinel, MODIS, and SPOT provide multispectral data useful for land use mapping, vegetation analysis, and soil property assessment. Spectral reflectance patterns can indicate soil contamination indirectly through vegetation stress, surface discoloration, and mineralogical changes.

Hyperspectral remote sensing is particularly effective for heavy metal analysis because it captures narrow spectral bands that provide detailed information about soil composition and mineralogy. Heavy metal contamination alters soil spectral characteristics, enabling indirect detection through spectral analysis.

Vegetation indices such as NDVI, SAVI, and EVI are commonly used to assess vegetation stress associated with contaminated soils. Stressed vegetation often exhibits reduced chlorophyll content and altered spectral responses.

Unmanned Aerial Vehicles provide ultra-high-resolution imagery for localized contamination assessment. UAVs are increasingly used for precision agriculture and environmental monitoring because they offer flexibility, rapid data acquisition, and detailed spatial information.

Remote sensing significantly reduces field survey requirements and enhances large-scale contamination monitoring capabilities.

5. Geographic Information Systems in DSM

Geographic Information Systems are essential tools in Digital Soil Mapping for storing, managing, analyzing, and visualizing spatial data. GIS integrates multiple layers of environmental information such as topography, land use, soil properties, climate, geology, and contamination data.

GIS enables spatial analysis of heavy metal distribution patterns and facilitates overlay analysis to identify relationships between contamination and environmental factors. Buffer analysis, hotspot detection, spatial interpolation, and risk zoning are commonly performed using GIS tools.

Digital Elevation Models derived within GIS environments help generate terrain attributes such as slope, aspect, curvature, and drainage patterns. These terrain variables strongly influence heavy metal transport and accumulation.

GIS also supports decision-making processes by generating contamination risk maps, suitability maps, and remediation planning tools. The integration of GIS with remote sensing and machine learning enhances the efficiency of environmental monitoring systems.

6. Soil Sampling and Laboratory Analysis

Accurate soil sampling and laboratory analysis are critical components of heavy metal mapping studies. Soil samples are generally collected using systematic, random, stratified, or grid-based sampling approaches depending on study objectives and spatial variability.

Sampling depth is important because heavy metal concentrations often vary vertically within the soil profile. Surface soils are commonly sampled because they are more exposed to anthropogenic pollution sources.

Laboratory analysis of heavy metals is performed using advanced analytical techniques such as Atomic Absorption Spectroscopy, ICP-OES, ICP-MS, and X-ray Fluorescence spectroscopy. These techniques provide precise measurements of metal concentrations.

Quality assurance and quality control procedures including duplicate samples, standard reference materials, and calibration standards are necessary to ensure data reliability.

The analyzed soil data serve as reference information for developing predictive Digital Soil Mapping models.

7. Environmental Covariates in Heavy Metal Mapping

Environmental covariates are variables used to predict heavy metal concentrations in DSM models. These variables represent environmental processes influencing contaminant distribution.

Topographic variables derived from DEMs include elevation, slope, aspect, curvature, topographic wetness index, and drainage patterns. These factors influence erosion, runoff, sediment deposition, and contaminant transport.

Land use and land cover data help identify anthropogenic pollution sources such as industrial zones, mining areas, urban settlements, and agricultural fields.

Climate variables including rainfall and temperature influence weathering, leaching, and metal mobility within soils.

Geological information and parent material data are important because natural background concentrations of heavy metals vary depending on rock composition.

Remote sensing-derived spectral indices provide indirect information about vegetation stress, soil moisture, and surface conditions associated with contamination.

The selection of relevant covariates significantly affects model performance and prediction accuracy.

8. Geostatistical Techniques in Heavy Metal Analysis

Geostatistics is widely used in Digital Soil Mapping to analyze spatial variability and predict soil contamination levels. Spatial interpolation techniques estimate unknown values at unsampled locations based on observed data.

Ordinary Kriging is one of the most commonly used interpolation methods. It assumes spatial autocorrelation among neighboring observations and generates smooth prediction surfaces.

Universal Kriging incorporates environmental trends into spatial prediction models. Co-Kriging uses secondary variables such as elevation or spectral data to improve prediction accuracy.

Regression Kriging combines regression analysis with geostatistical interpolation, integrating environmental covariates and spatial autocorrelation.

Variogram analysis is an essential component of geostatistics. Variograms describe the spatial dependence structure of heavy metal concentrations and help determine interpolation parameters.

Geostatistical methods are valuable for producing accurate contamination maps and quantifying prediction uncertainty.

9. Machine Learning Techniques in DSM

Machine learning algorithms have significantly improved the accuracy and efficiency of Digital Soil Mapping. These techniques can model complex nonlinear relationships between heavy metal concentrations and environmental variables.

Random Forest is one of the most widely used machine learning algorithms in soil mapping. It constructs multiple decision trees and combines their predictions to improve accuracy and reduce overfitting.

Support Vector Machine is effective for handling multidimensional datasets and nonlinear relationships. Artificial Neural Networks simulate biological neural systems and are capable of modeling highly complex patterns.

Gradient Boosting Machines and Extreme Gradient Boosting are advanced ensemble learning methods that provide strong predictive performance.

Deep learning approaches including Convolutional Neural Networks are increasingly applied to hyperspectral imagery and spatial datasets.

Machine learning models generally outperform traditional statistical methods when large datasets and multiple environmental variables are involved.

10. Applications of Heavy Metal Digital Soil Mapping

Heavy metal Digital Soil Mapping has numerous environmental, agricultural, and public health applications. One major application is contamination hotspot identification. DSM helps locate areas with elevated heavy metal concentrations requiring immediate intervention.

Environmental risk assessment is another important application. Contamination maps help evaluate ecological risks, human exposure risks, and food safety concerns.

In agriculture, DSM supports precision farming practices by identifying contaminated agricultural lands and guiding appropriate crop management strategies.

Urban planning agencies use heavy metal maps to regulate industrial development, landfill placement, and waste disposal activities.

DSM also assists in monitoring mining impacts, assessing industrial pollution, and evaluating remediation effectiveness.

Government organizations and environmental agencies increasingly use DSM for sustainable land management and environmental policy development.

11. Challenges in Heavy Metal Mapping

Despite its advantages, heavy metal analysis using DSM faces several challenges. One major challenge is the availability of high-quality soil data. Sparse sampling and inconsistent laboratory methods can reduce model reliability.

Spatial heterogeneity of contamination complicates predictive modeling. Heavy metal concentrations may vary significantly over short distances.

Remote sensing limitations such as cloud cover, spectral mixing, and limited penetration depth affect contamination detection accuracy.

Machine learning models often require large datasets and substantial computational resources. Overfitting and model uncertainty may also occur.

Selection of appropriate environmental covariates remains difficult because different variables influence contamination differently across regions.

Another challenge is the lack of standardized methodologies for Digital Soil Mapping studies, making comparison among studies difficult.

12. Future Prospects

Future advancements in Digital Soil Mapping are expected to improve heavy metal analysis significantly. High-resolution satellite imagery, hyperspectral sensors, and UAV technologies will enhance contamination detection capabilities.

Artificial intelligence and deep learning methods are likely to revolutionize predictive soil mapping by handling large multidimensional datasets more efficiently.

Integration of Internet of Things sensors, real-time monitoring systems, and cloud computing will enable dynamic soil contamination assessment.

Big data analytics and geospatial artificial intelligence will facilitate rapid environmental decision-making and precision land management.

The development of open-access soil databases and collaborative research initiatives will improve data availability and model standardization.

Future DSM studies are expected to contribute significantly to sustainable agriculture, environmental protection, climate resilience, and public health management.

13. Conclusion

Heavy metal contamination of soils has become a serious environmental and public health concern worldwide. Traditional methods of contamination assessment are often expensive, labor-intensive, and spatially limited. Digital Soil Mapping has emerged as an advanced and efficient approach for predicting and visualizing heavy metal distribution across landscapes using remote sensing, GIS, geostatistics, and machine learning techniques.

DSM enables continuous spatial prediction of contamination levels and helps identify pollution hotspots, assess environmental risks, and support remediation planning. The integration of satellite imagery, hyperspectral data, terrain analysis, and advanced predictive models has greatly improved mapping accuracy and efficiency.

Machine learning algorithms such as Random Forest, Support Vector Machine, and Artificial Neural Networks have revolutionized soil contamination modeling by capturing complex nonlinear relationships among environmental variables. Similarly, geostatistical methods continue to play an important role in spatial interpolation and uncertainty analysis.

Despite several challenges including data limitations, spatial heterogeneity, and model uncertainty, DSM offers immense potential for sustainable environmental monitoring and land management. Future advancements in artificial intelligence, remote sensing technologies, and big data analytics are expected to further strengthen heavy metal analysis capabilities.

Overall, heavy metal analysis using Digital Soil Mapping represents a modern scientific approach that supports precision agriculture, environmental protection, public health safety, and sustainable resource management.

The Modern Age Paradigm of Integrated Pest Management



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- The Food and Agriculture Organization of the United Nations (FOA) defines integrated pest management as careful consideration of all available pest control methods and subsequent integration of appropriate measures that deter the development of pest populations and keep pesticides and other inter-ventions to levels that are economically justified and minimize risks to human health and the environment. Earlier models of integrated pest management (IPM) focused on ecological aspects of pest management.
- The recent developments in agricultural technology, modern communication tools, changing consumer trends, increased awareness for sustainably produced food systems, and globalization of trade and travel, there seems to be a need to revisit the IPM paradigm as appropriate for modern times. A new model, built on earlier models based on ecological and economic aspects, is expanded and reconfigured to include management, business, and sustainability aspects and emphasize the importance of research and outreach.

Integrated pest management: a historical perspective

- ✓ In the 1940s with development of synthetic pesticides, the whole scenario of crop pest management changed. It began with the introduction of alkyl thiocyanate insecticides, and then the discovery of remarkable insecticidal properties of DDT in 1939 by Paul Muller.
- ✓ DDT was followed by the manufacture of other chlorinated hydrocarbons, including aldrin, endrin, heptachlor and recognition of the herbicidal activity of the phenoxyacetic acids-MCPA (2-methyl-4 chlorophenoxyacetic acid) and 2,4-D (2,4-dichlorophenoxyacetic acid).
- ✓ Due to over reliance on synthetic pesticides from the late 1940s to mid-1960s, the period has been called “the dark ages” of pest control. However, in the late 1950s, entomologists began to identify the problems associated with extensive and intensive use, misuse, and abuse of insecticides and pesticide resistance, secondary pest outbreaks, hazards of toxic residues in food commodities and biomagnifications, environmental pollution, and killing of nontarget beneficial organisms.
- ✓ The first integrated control program was devised for managing spotted alfalfa aphid, *Therioaphis maculata* (Buckton), on alfalfa grown for hay purposes.
- ✓ Shortly after IPM concept first appeared, Rachel Carson’s book “Silent Spring” in 1962 was published, which explored the effects of pesticide overuse on environment and non-target species. Hence, the public awareness was raised and thereby the concept “integrated control” became popular in both scientific literature and practice.
- ✓ The future aim of IPM programs should be fundamental structural changes through effective understanding of ecological processes and synergy between crops.

What aspect modern age paradigm of IPM

➤ Management aspect	⇒ I. Pest management
➤ Business aspect	⇒ II. Knowledge
➤ Sustainable aspect	⇒ III. Planning
	⇒ IV Communication

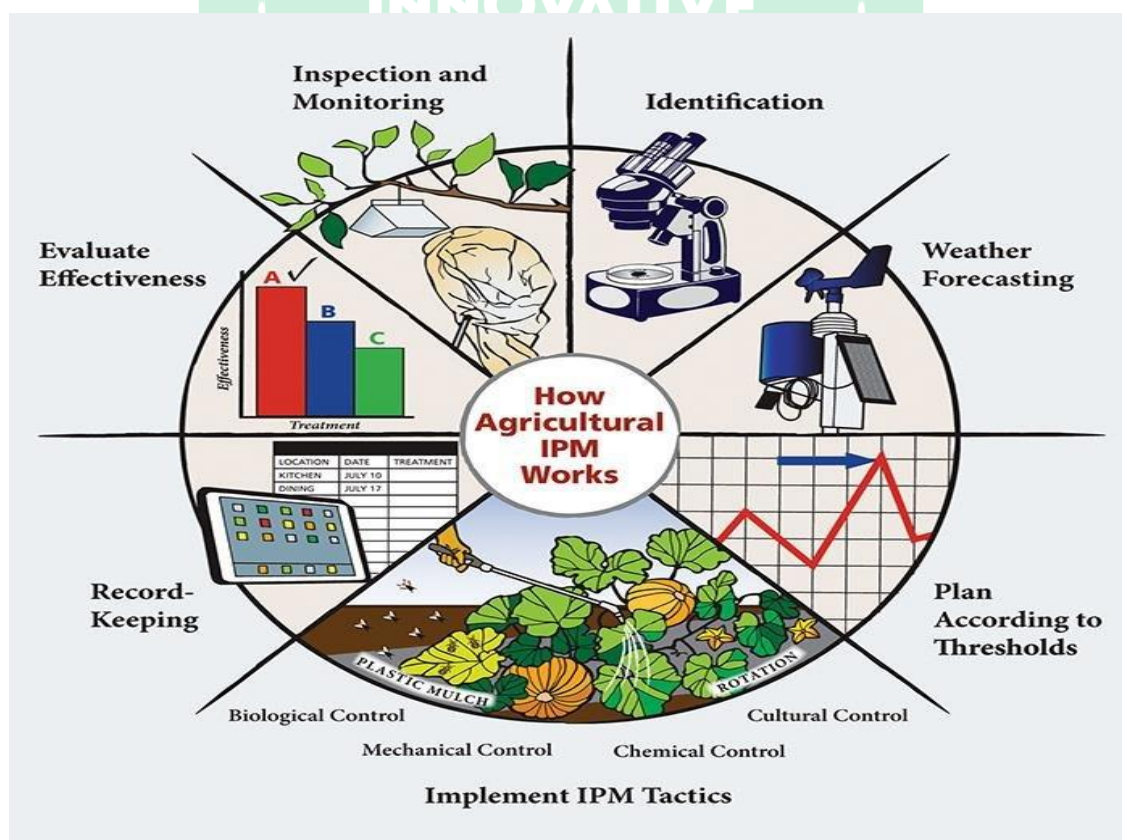
Pest Management:-

- (i) Host plant resistance
- (ii) Cultural control
- (iii) Biological control

- (iv) Behavioral control
- (v) physical and mechanical control
- (vi) Microbial control
- (vii) chemical control



A new IPM paradigm with its various components



Host Plant Resistance

A strategy that involves the use of pest-resistant and pest-tolerant cultivars developed through traditional breeding or genetic engineering (Douglas 2018). These cultivars possess physical, morphological, or biochemical characters that reduce the plant's attractiveness or suitability for the pest to feed, develop, or reproduce successfully. These cultivars resist or tolerate pest damage and thus reduce the yield losses. This option is the first line of defense in IPM

Cultural Control

1. Adopting good agronomic practices that avoid or reduce pest infestations and damage refers to cultural control.
2. Choosing clean seed or plant material is critical to avoid the chances of introducing pests right from the beginning of the crop production.
3. Adjusting planting dates can help escape pest occurrence or avoid most vulnerable stages.

Example-

- (a) Early planting of cowpea reduced aphid, thrips, and pod bug infestations in Uganda and the legume pod-borer (*Maruca vitrata*), the legume flower thrips (*Megalurothrips sjostedti*), and the pod sucking bug (*Clarigralla tomentosicollis*) in Nigeria.
- (b) Plant density or row spacing will also have an impact on pest infestations. Modifying irrigation practices, fertilizer program, and other agronomic practices can create conditions that are less suitable for the pest.
- (c) Increased plant nitrogen can exacerbate arthropod infestations. Destroying crop residue and thorough cultivation will eliminate breeding sites and control soil-inhabiting stages of the pest.
- (d) Plowing is also an important control option to destroy the crop residue and expose the soil-inhabiting stages of several vegetable pests. Crop rotation with non-host or tolerant crops will break the pest cycles and reduce their buildup year after year.

Biological Control:-

- To address invasive pest issues, classical biological control approach is typically used where natural enemies from the native region of the invasive pest are imported, multiplied, and released in the new habitat of the pest. The release of irradiated, sterile insects is another biological control technique that has been effectively used against a number of pests.
- CBC has been carried out widely over a variety of target organisms, but most commonly against insects, using parasitoids and predators and, occasionally, pathogens. Until 2010, 6158 introductions of parasitoids and predators were made against 588 insect pests, leading to the control of 172 pests. About 55% of these introductions were made against pests of woody plants. Establishment rates of natural enemies and success rates were higher in CBC projects targeting pests of woody plants than other pests. Since the introduction of the vedalia beetle.

Behavioral Control:-

- The behavior of the pest can be exploited for its monitoring and control through baits, traps, and mating disruption techniques. Baits containing poisonous material will attract and kill the pests when distributed in the field or placed in traps.
- Pests are attracted to certain colors, lights, odors of attractants or pheromones. Pheromone lures confuse adult insects and disrupt their mating potential, and thus reduce their offspring.

Physical or Mechanical Control:-

- This approach refers to the use of a variety of physical or mechanical techniques for pest exclusion, trapping (in some cases similar to the behavioral control), removal or destruction.
- Modifying environmental conditions such as heat or humidity in greenhouses, steam sterilization or solarization. Installation of bird perches in the field for allowing birds to sit and feed on insect pests and their immature stages viz., eggs, larvae and pupae.
- Installation of visual or physical bird deterrent such as reflective material or sonic devices or bird scarer in the field as per requirement

Microbial Control:-

- Using entomopathogenic bacteria, fungi, microsporidia, nematodes, or viruses, and fermentation byproducts of some microbes against arthropod pests, plant parasitic nematodes, and plant pathogens generally come under microbial control.

Chemical Control:-

- Chemical control typically refers to the use of synthetic chemical pesticides. However, to be technically accurate, chemical control should include synthetic chemicals as well as chemicals of microbial or botanical origin.
- Although botanical extracts such as azadirachtin and pyrethrins, and microbe-derived toxic metabolites such as avermectin and spinosad are regarded as biologicals, they are still chemical molecules, similar to synthetic chemicals, and possess many of the human and environmental safety risks as chemical pesticides.
- Chemical pesticides are categorized into different groups based on their mode of action and rotating chemicals from different mode of action groups is recommended to reduce the risk of resistance development. Government regulations restrict the time and amount of certain chemical pesticides and help mitigate the associated risks. All the management options need careful consideration and application to avoid potential risks.
- For example, several pest developed resistance to transgenic crops with *Bacillus thuringiensis* toxin proteins and planting non transgenic plants along with resistant plants has been recommend, among other strategies, to reduce the resistance development.

Knowledge and Resources:-

- (i) Pest
- (ii) Available control option
- (iii) Tools and technology

The knowledge of various control options, pest biology and damage potential, and suitability of available resources enables the grower to make a decision appropriate for their situation.

- **Pest**
Identification of the pest, understanding its biology and seasonal population trends, damaging life stages and their habitats, nature of the damage and its economic significance, the vulnerability of each life stage for one or more control options, host preference and alternate hosts, predictability of pest occurrence based on the environment, cropping trends, farming practices, and other influencing factors, and all the related information is critical for identifying an effective control strategy.
- **Available Control Options**
Because not all control options can be used against every pest, the grower has to choose the ones that are ideal for the situation. For ex-ample, systemic insecticides are more effective against pests that mine or bore into the plant tissue. Pests that follow a particular seasonal pattern can be controlled by adjusting planting dates. Commercially available natural enemies can be released against some, while mating disruption works well against others.
- **Tools and Technology**
This is an important component where diagnostic and preventive or curative decisions are made based on available and affordable control options. A particular pest can be controlled by certain options, but they may not all be available in a particular place, for a particular crop, or within the available financial means. For example, the release of natural enemies may be possible in high-value specialty crops, but not in large acreage field crops.
- Regulatory guidelines that limit the use of certain pesticides or promote the use of others can have a major influence on IPM implementation. Many countries have phased out broad-spectrum pesticides and fumigants. Recent concern for pollinator health has also led to restrictions on the use of certain pesticides.

III Planning and Organization

- (i) Action
- (ii) Managing information

(iii) Monitoring

(i) Corrective Actions

Taking a timely action is probably the most important aspect of IPM. Even with all the knowledge about the pest and availability of resources for its effective management, losses can be prevented only when corrective actions are taken at the right time. Good farm management will allow the grower to act in a timely manner.

(ii) Managing Information

A good recordkeeping about pests, their damage, effective treatments, seasonal fluctuations, interactions with environmental factors, irrigation practices, plant nutrition, and other related information from year to year will build the institutional knowledge on a farm and prepares the grower to take preventive or curative actions.

(iii) Pest-monitoring

Monitoring is also important to avoid calendar-based pesticide applications especially at lower pest populations that do not warrant treatment. For example, sampling based fumigation along with improved sanitation and other practices can be an economical alternative to calendar based fumigation of heat in elevators. However, drone assisted aerial imagery for pest-detection and identification or to locate areas that are exposed to biotic or abiotic stressor can improve the monitoring efficiency and precision.

Communication

- Good communication to transfer the individual or collective knowledge for the benefit of everyone is the last component of the new IPM model. Modern and traditional communication tools can be used for outreach as researchers develop information about endemic and invasive pests, emerging threats, and new control strategies.
- With public
- Among growers
- Within the group
- Staying informed

Communication With the Public:-

- Public demand is influenced by retail marketing strategies, concerns for food safety based on pesticide regulations in their region, and a lack of knowledge on food production among other factors.
- They indicated a change in their knowledge and a potential change in their behavior in making food choices following the discussions and field tours. Educating public will help their understanding of and preference for organic, conventional, or sustainably produced food as well as influence policy and regulatory decisions in their regions to ensure food safety and security

Communication Among Growers

- Pests do not have boundaries and can spread to multiple fields when they are not effectively managed throughout the region. Although certain crop production and protection strategies are considered proprietary information, sharing knowledge and resources with each other will improve pest control efficacy and benefit the entire grower community.

Staying information:-

- Growers and pest control professionals should stay informed about existing and emerging pests and their management options. Science-based information can be obtained by attending extension meeting, webinars, or workshops, reading the newsletter, trade, extension, or scientific journal article, and keeping in touch with researchers and other professionals through various communication channels.

Business aspect:-

- In an ideal system, consumer, producer, and seller would maintain a harmonious balance of food production and sale. In such a system, food is safe and affordable to everyone, there will be food security all over the world, and both growers and sellers make a good profit with minimal risk to the environment in the process of food production.

Sustainability Aspect- :

- IPM is an approach to ensure economic viability at both consumer and producer level, environmental safety through a balanced use of all available pest control options, and social acceptability since IPM-based food is safe and affordable.

Pros and cons of integrated pest management program-:

- ✚ The key benefits of integrated pest management to farming and society include.
- ✚ IPM emphasizes understanding the agroecosystem, integration of new management skills and the new concepts for pest management to protect our environment and make sure the uninterrupted safe and nutritious food supply for the growing world population.
- ✚ IPM, besides sustaining biodiversity, slows the development of resistance of pests to synthetic pesticides.
- ✚ It improves profitability to farmer as pest management costs are reduced.
- ✚ It reduces risk of crop loss by a pest and long-term answers to pest problem.
- ✚ In spite of benefits of IPM stated so far, there are also some drawbacks to it:
- ✚ IPM involves more technicalities and decision-making.
- ✚ An IPM program requires a higher degree of planning and management
- ✚ It requires more resources as a substitute to pesticides.

Conclusions

- Earlier IPM models are designed from the scientific perspective with a focus on ecological, environmental and evolutionary aspects of pest management to reduce or prevent economic losses. There was limited scope to include the human, social, business, and communication aspects of the total equation in the previous models that may be deficient in effective promotion and implementation of IPM.
- Several examples discussed in this paper showed the influence of these factors on development, outreach, and successful implementation of IPM practices around the world. Since IPM is a part of agriculture, which is a consumer-oriented enterprise, and agriculture is a part of global trade, which is influenced by several other factors, IPM is redefined for the modern times where advanced agricultural technologies and communication tools play a critical role in food production and consumption.
- The new IPM model provides a template for focusing on different areas of the paradigm and to encourage collaboration among different disciplines. This new model is expected to guide IPM strategies around the world to develop and implement sustainable agricultural practices to ensure profitability for the growers, affordability to consumers, and food security to the growing world population

Alien Insect Pests in India: Current status, Threats and Solutions



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- ✚ Alien insect pests are **non-native** or **exotic organisms** that occur outside their natural adapted habitat. They are abundant in natural range. Wide distribution in different habitat. They have fast growth, early maturity and high reproduction and have ability to go without food and water.

✚ Pathways of Spread

- Commercial shipping
- Ships
- Planes
- Trains
- Vehicles
- People movers

✚ Factors Responsible For Growing Alien pests numbers in India

- Expansion of geographical range, climate change : insect – pests are expected to extend their geographical range which leads to increase tropical insects and sudden outbreak of insect- pests. Temperature is single most important environmental factors influencing insects behaviour , distribution, reproduction. With 2°C temperature increase ,insects might experience one to five additional life cycles per seasons, e.g. *Helicoverpa armigera* continuously expanding in North India on cotton.
- Increase in international trade, modernization in agriculture. Geographic barriers without much quarantine have enhanced chances of introduction of alien insect pests into agroecosystem. National level legislation to prevent or control alien insects has not increased, as of 2010 only half of the world to the Convention on Biological Diversity had enacted national legislation against alien insect pests.

✚ CURRENT STATUS OF THE ALIEN INSECT PESTS IN INDIA

- **Sugarcane woolly aphid**, *Ceratovacuna lanigera* appeared in pestiferous form with alarming speed of spread was recorded in Sangli district of Maharashtra, in Belgaum district of Karnataka with total of 15.5% area under sugarcane is presently infested with highest infestation in Sangli (25.29%).
- **Thrips** *Parvispinus* warrants special attention in India as it is a potentially damaging plant pest in states of Andhra Pradesh, Chhattisgarh, Karnataka, Kerala, Tamil Nadu. Survey have been conducted to monitor the species, a total of 849 specimens were examined from five states viz, Andhra Pradesh(194), Chhattisgarh(94), Karnataka(378), Kerala(27) Tamil nadu(156). Serious damage was recorded in Andhra Pradesh, Chhattisgarh, Karnataka on *Capsicum annum* & in Tamil Nadu on *Mangifera indica*. Nearly 12000 acre of Capsicum was affected by thrips in Guntur districts alone during the current cropping season.
- **Papaya mealybug** *Paracoccus marginatus* was first observed on papaya crop in Jammu and till now rapid spread among horticulture crops. It was necessary to take immediate steps to limit the yield and crop losses.
- **Western flower thrips**, *Frankliniella occidentalis* reported for first time from Kolkata. WFT transmit tomato spotted wilt virus.
- **Tomato pin worm**, *Tuta absoluta* on Tomato & Potato was observed for first time in Pune & Ahmad nagar, Nasik region & six districts of Karnataka in 2014. This pest has been classified as most serious threat for tomato production with (50-87%) plants affected. If *T. absoluta* invades rest of world, the tomato pest management cost may arise up to 500 millions per year.

- ❖ **Rugose spiraling whitefly**, *Aleurodicus rugioperculatus* had been reported on coconut palm, mango, guava at Kottayam district, Kerala in India through accidental introduction. It produces honey dew which results in development of sooty mould. The severity of infestation ranged from 25-40% on leaf in banana. Complete drying of leaves was also noticed in several places of Tamil Nadu.

List of invasive pests in India

1889	Woolly apple aphid
1911	San Jose scale
1914	Diamond back moth
1915	Lantana bug
1921	Cottony cushion scale
1937	Potato tuber moth
1970	Pine woolly aphid/ Adalgid
1988	Subabul psyllid
1990	American serpentine leaf miner
1990	Coffee berry borer beetle
1994	Spiralling white fly
1997	Coconut eriophyid mite

1999	Silver leaf whitefly
2004	Cotton mealybug
2005	Lotus Lily midge
2006	Eucalyptus gall wasp
2006	Erythrina gall wasp
2008	Papaya mealybug
2012	Banana mealybug
2012	Madeira mealybug
2014	Tomato Pinworm
2015	Western flower thrips
2016	Rugose spiralling whitefly
2018	Fall armyworm
2019	Neotropical whitefly

Extent of damage by *T.absouluta*

State	% Fruit Damage
Tamil Nadu	0.5-13.5
Karnataka	2-100
Maharashtra	>50
Gujarat	5-12

Current Status of Fall Army Worm in Rajasthan

- This is a new invasive pest in this zone, infestation has been reported in some of the popular hybrid and sweet corn. Fall army worm, *Spodoptera frugiperda* is emerging as the most destructive pest of Maize in India. It rapid spread to more than 90% of maize – growing areas within a span of 16 months presents a major challenge to small holder maize farmers, maize based industry, as well as food and nutritional security. It is an economically destructive, highly mobile important pest. FAW has been reported in state of Karnataka, Andhra Pradesh, Maharashtra, Tamil Nadu but recently it has been reporting for the first time in Southern Rajasthan on winter maize crop in Banswara and Dungarpur district. It reduces corn grain yield up to 30% in these districts of Rajasthan.

Threats from alien insect pests in the twenty-first century

- Invasive alien insect pests are primary threat to global biodiversity, economics and human livelihoods, increasing globalization facilitates alien insect arrival & environmental changes and climate change facilitates alien establishment.
- One-sixth of the global land surface is highly vulnerable to alien insect pests including substantial areas in developing economies.

- One major source of threat is international trade as primary source of introduction of alien insects pests as contaminants in goods and packing materials. Pets & plant trades are primary mechanisms for introduction of insects pests and pathogens.
- The relative threats from alien insects pests that countries around world will face in the future differ markedly from current threats levels, as alien insects pests are currently potentially severe elements due to environment change in economically developing regions as food production systems are often fragile
- It should be noticed that twenty-first century threat level are based on trade & transport levels between 2000-2009 and will be globally high in the world's. (Regan early et al. 2016)
- Western flower thrips, *Frankliniella occidentalis* reported for first time from Kolkata. WFT transmit tomato spotted wilt virus.

Solutions:

- An important first step of solution is to identify those alien insect pests that may become invasive, these may be put on a "blacklist" and prohibited entry under national legislation.
- Preventing the International movement of invasive alien insect pests and coordinating a timely and effective response to invasion requires cooperation and collaboration among government, economics sectors, non government organizations and international organizations.
- At the national level consolidated and coordinated action is required.
- Insurance mechanism and liability regulation for the spread of alien insect pests are almost non-existent. Government should be encouraged to cooperate with the insurance sector to find solutions.

New Technological Solutions Available in India

- **SPLAT:** Specialized Pheromone and Lure Application Technology-is one of the effective and flourishing technologies for insects pests control mainly in foreign countries, though it is infant in India many trials under process in major agriculture institutes. The principle behind this is mating disruption and attract and kill strategy.
- **Pest Forewarning System:** quantification of crop-pest weather relationship is most imperative to understand and to predict the incidence of insect pest well in advance. This model will enable us to predict the incidence to increase the preparedness of farmers and to plan the pest control measure in an appropriate way and pest forewarning system will reduce indiscriminate use of insecticides.
- **Remote Sensing:** techniques like hyper spectral and multi spectral imaging are useful in detecting crop stresses, pest infestation, disease development. Currently this technology for monitoring of all kind of pests in developing country like INDIA for monitoring pest outbreaks caused by major pest like Locust, rice yellow stem borer, coconut rhinoceros beetles etc.
- **RNAi- A New Tool for Insect Pests Management:** a well known gene silencing mechanism which operates at cellular level & triggered by double stranded RNA can be another approach for development of next generation insect-resistant transgenic plants. Few reports shown successful application of RNAi especially for Coleoptera, Hemiptera & Lepidoptera.

THE GENERIC PLAN FOR A NEW INVASIVE



Conclusion

- We revealed a clear need for proactive invasion strategies in areas with high poverty levels & high biodiversity.
- International sharing of information on alien insect pests & management expertise could greatly help in management priorities in region that have little capacity to tackle alien insect pests.
- Invasion of alien insects was the result of globalization and alien insect pests caused substantial damage to the native flora and fauna.
- Hence it is necessary to know the recent invasion of alien insect pests in order to protect the crops from economic loss.



ROLE OF OSTRACODS IN MONITORING COASTAL POLLUTION



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Abstract

Severe anthropogenic stresses, such as industrial discharge, agricultural runoff, and coastal urbanization, are increasingly affecting coastal ecosystems. These settings deteriorate quickly, and biomonitoring techniques are sensitive and affordable. Ostracods offer a complex representation of environmental health because of their benthic lifestyle, extensive range, and high sensitivity to physicochemical changes. We investigate the direct relationships between gradients of heavy metals, hydrocarbons, and organic enrichment and important ecological metrics as species diversity, population density, and assemblage alterations. The study also emphasizes how important it is to consider ostracod valve morphology more especially, the frequency of carapace abnormalities as an obvious indicator of ecotoxicological stress. Ostracods' calcified carapaces, which not only bioaccumulate trace metals for geochemical research but also survive remarkably well in sediment cores, are a special and significant benefit of using them. By establishing pre-industrial historical baselines, this fossilization potential enables researchers to differentiate between current anthropogenic impacts and natural environmental variability. Emphasizes the need to incorporate ostracod-based multi-proxy studies, which provide a highly accurate and temporally contextualized method for evaluating coastal degradation, within conventional frameworks for coastal management and conservation.

Keywords: Ostracod, Bioindicator, Monitoring.

Introduction

Some of the planet's most prolific and delicate ecosystems are found around the coastal region, which act as the interface between terrestrial and marine environments, they are the main consumers of anthropogenic waste, includes nutrient enrichment, developing contaminants including microplastics, heavy metal contamination, and petroleum hydrocarbons. These contaminants endanger food web stability and biodiversity as they build up in the benthic region. The long-term biological effects of these stresses are frequently not captured by conventional chemical monitoring of water and sediment, although it does provide a snapshot of present circumstances. As a result, a key component of contemporary environmental management is the use of bioindicators, through their presence, behaviour, or physical state which, reflect the health of their surroundings. The Class Ostracoda (Subphylum Crustacea) is one of the many types of marine microorganisms, and it has become useful tool for assessing coastal health. Ostracods, sometimes known as "seed shrimp," are tiny crustaceans that are shielded by a bivalved, calcified carapace. In coastal and estuary environments, they occupy a wide range of niches, mainly the sediment-water interface, where contaminants frequently settle and concentrate. They serve as early warning systems for ecological change due to their sensitivity to changes in the environment.

Phylum classification of Ostracods

Kingdom	:	Animalia
Phylum	:	Arthropoda
Sub phylum	:	Crustacea
Super class	:	Oligostraca
Class	:	Ostracoda

Ostracods

Ostracods are tiny Crustaceans with calcified shells, inhabit the benthic zone, live in sedimentation and on dead phytoplankton. Fish eat these critters, which are benthic macroinvertebrates. Ostracods have a variety of uses in pollution research. When the environment deteriorates, their community structure which is determined by species richness, abundance, and diversity predictably changes. Chemical stresses have an impact on their physical development with sublethal pollution levels frequently cause calcification mistakes or morphological abnormalities in their shells. Ostracods shells are made of low-magnesium calcite, that serve as permanent geochemical archives of water chemistry by incorporating trace elements from the surrounding water during the moulting process. Ostracod valves' high potential for preservation in the geological record offers a "paleo-perspective" compared to other bioindicators.

Most importantly, ostracod valves great preservation potential in the geological record offers a "paleo-perspective" that most other bioindicators are unable to provide. Researchers can reconstruct pre-pollution baselines by examining ostracod assemblages in vertical sediment cores. Setting reasonable restoration goals and differentiating between natural environmental oscillations and harm caused by humans depend on the ability to compare current "impacted" states with past "pristine" states. The potential importance of these tiny sentinels in international coastal conservation efforts, examines the mechanisms by which ostracods react to coastal contaminants, and assesses the techniques currently employed in ostracod-based biomonitoring.

Ostracods and its morphology

The Ostracods have shortened body and a bivalve shell made of chitin, which is mostly impregnated in the majority of species with calcium carbonate. They have eight pairs of appendages without growth lines, and the head has four pairs of appendages that helps with swimming, walking, and feeding then it has two pairs of thoracic appendages which are useful for feeding, creeping, and cleaning the shell during their younger period. They undergo eight stages of moulting on the shape, function, and size of the instar collected or the presence of juveniles. Because of their hard shells nature, they are mostly free-plankton.

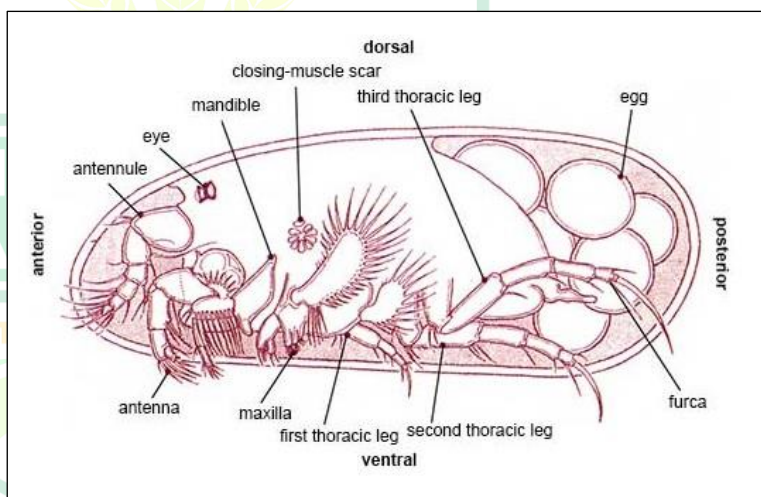


Fig. 1: Morphology of Ostracod

Uses of ostracods in environment monitoring

- 1. Acts as an environmental Bioindicators:** The conventional bioindicator groups like copepods, ostracods are frequently more sensitive to anthropogenic pressures such as water pollution, heavy metals, pesticides, oil spills, and radioactive pollutants. They are helpful in tracking ecological effects including eutrophication and determine the variations in water quality.
- 2. As excellent fossil records:** Ostracods have a remarkable fossil record that dates back about 500 million years because of their calcitic bivalve shells. Since they are the most prevalent fossil arthropod, extremely useful for paleoclimate research for recreating historical habitats (depth, temperature, and salinity).
- 3. High Habitat Adaptability and Resilience:** Ostracods flourish in nearly every type of aquatic environment, including freshwater, brackish, marine, subterranean, and transient ponds. They can withstand harsh temperatures, low oxygen levels, and excessive salinity.
- 4. "Tough Eggs" (Dormancy):** They can recolonize temporary water bodies as soon as water reappears since their eggs can survive for many years even after being totally dry.

5. **Aquarium upkeep and as natural food source:** By consuming algae and debris, they serve as a natural cleanup team in aquatic hobbies. Additionally, they provide amphibians and fish with an abundance of live, high-protein food that improves their health.

6. **Distinctive biological and evolutionary features:** The animal kingdom's largest sperm by volume is produced by ostracods. Certain marine species, such as *Vargula*, are bioluminescent; it produces a luminous mucus as a protection mechanism and create a blue light for mating displays.

7. **Low-cost monitoring tool:** They are an affordable option for various environmental studies because of their small size and great abundance in nature, which allow the collection of precise environmental data from very minimum samples (such as one cubic centimetre of sediment). It allows quick detection of environmental changes over short period of time.

Ostracods in waste monitoring

Ostracods are used as effective bioindicator for monitoring urban and agriculture waste impact in coastal areas. These are highly sensitive to environmental changes like salinity, pollution and nutrient levels which are influenced by runoff from cities and agriculture lands. In coastal ecosystem urban wastewater discharge and agriculture runoff release much contamination like heavy metals, pesticide fertilizer release excess nutrients leads to eutrophication and habitat degradation. Ostracods assemblies respond to these stresses through change in their species and composition, abundance and shell morphology. In contaminated areas, pollution-tolerant species may predominate while sensitive species were diminished. They are also helpful for both current monitoring and historical reconstruction of pollution patterns in their calcified shells that can retain geochemical traces, Therefore Ostracods evaluate the long term effect of human activity and offers significant information on the ecological health of coastal environment.

Environmental parameters for ostracods development

Ostracods are strongly influenced by a range of environment parameters makes them as valuable indicators for aquatic ecosystem

1. Salinity

Ostracods are highly sensitive to changes in salt concentration and adapted to specific salinity ranges such as freshwater, brackish or marine ecosystems. These salinity fluctuations caused by tidal cycle, freshwater inflow, evaporation and runoff from urban areas which significantly affects ostracods communities. Some species are stenohaline, while others are euryhaline that can survive under wide variation, affects their osmotic balance, reproduction and shell development leading to shift in their species composition.

2. Temperature

- Ostracods generally inhabit water ranging from near freezing condition to about 30-35°C, but each species have optimum temperature for their growth, reproduction and calcification.
- Significant variations in ostracod density and diversity may be explained by seasonal or depth-water temperature variations.
- Certain species, including *Candonaneglecta*, appear to benefit from low temperatures.
- In fresh water environment, temperature after metabolic rate, lifecycle duration and seasonal population dynamics to specific climate zones.

3. Concentrations of dissolved oxygen

Ostracods required sufficient oxygen for their respiration, metabolism and reproduction. In hypoxic conditions, many species experienced reduced activity, slower growth and lower reproductive success, while in anoxic condition, leads to forced migration or death of ostracods. While certain species that inhabit shallow muddy ponds, such *Candona candida*, *Paracyprideisfennica*, and *Cypria ophthalmic*, may withstand low oxygen concentrations for brief periods of time, others, like *Darwinulastevensoni*, are extremely vulnerable to oxygen deprivation.

4. pH

In ostracods, pH influences physiological process such as shell formation, ion balance and metabolic activity. Certain species can withstand a broad pH range of 4.6 to 13 and other species found in extremely acidic waters. The majority of freshwater ostracods prefer alkaline or slightly acidic environments. Because calcium intake for

carapace calcification is challenging in acidic conditions, ostracod species are typically absent at pH 5. In acidic water, shell dissolution becomes more, declined reproduction rate and reduce species diversity.

5. Levels of nutrients

Nutrient like nitrate and phosphate indirectly affect the ostracods by regulating the food sources availability like algae, organic matter. High nutrient enriched system, excess organic matter decomposition leads to O₂ depletion that impacts the ostracods species growth. Certain ostracod species are extremely vulnerable to elevated levels of certain contaminants. Certain *Herpetocypris* species are highly disturbed by phosphates, whereas *Candonaneglecta* is significantly impacted by nitrate levels. Some species, such as *Ilyocypris inermis*, are absent from disturbed habitats with high nutrient levels.

Ostracods application in environment monitoring

- **Paleoenvironmental reconstruction:** Ostracods are employed to recreate historical water and climate conditions. Data on temperature, salinity, and dissolved oxygen are obtained from their shell chemistry, which includes stable isotopes and trace elements like Mg/Ca and Sr/Ca.
- **Biostratigraphy and Oil Exploration:** Ostracods are good indicator for fossils record that are essential for correlating rock strata and dating sedimentary layers in oil exploration, especially in marginal marine and non-marine facies.
- **Environmental Bioindicators:** Ostracods are useful for evaluating the health of ecosystems because they are extremely sensitive to anthropogenic stressors including heavy metal pollution, eutrophication, and agricultural runoff.
- **Paleoceanography and Paleolimnology:** Ostracods are employed in lake studies to evaluate long-term climate change, and in ocean-drilling cores for ocean-climate research that evaluating thermohaline circulation.
- **Paleoecology and Aquaculture:** Planktonic ostracods are utilized in biology to investigate evolutionary patterns and act as food sources in aquatic ecosystems for their growth and development.
- **Geochemical Proxies:** Ostracods are especially crucial in freshwater research where other carbonate-producing species, such as foraminifera, are not present.

Conclusion

Ostracods are useful bioindicators for tracking the condition of coastal ecosystems. Their extreme susceptibility to environmental stressors shows up in different, ranging from organic enrichment and ocean acidification to heavy metal contamination and industrial effluent. Ostracod populations exhibit obvious reactions to polluted environments, such as changes in species diversity, population declines, and most notably, morphological abnormalities and irregular calcification in their protective carapaces. Ostracods special capacity to absorb contaminants and trace elements into their calcitic shells creates a lasting geochemical record. By examining fossilized assemblages in sediment cores, this feature enables researchers to reconstruct previous pollution timelines in addition to evaluating the quality of water and current sediment treat. These microscopic crustaceans provide a macroscopic perspective on the health of the coastal ecosystem. Policymakers and marine conservationists can obtain a more accurate, data-driven knowledge of anthropogenic consequences by incorporating ostracod-based biological and geochemical investigations into larger waste environmental monitoring programs for sustainable management to develop successful remediation solution.

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Overcoming Yield Plateaus in Pulses: Constraints, Breakthroughs and Future Horizons



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Abstract

Pulses are indispensable to global food security, sustainable farming systems, and human nutrition. Despite their environmental and nutritional benefits, stubborn yield stagnation—often referred to as the "yield barrier/yield plateau"—continues to affect pulse production globally, particularly across smallholder farms in developing regions. This comprehensive article examines the biological, environmental, and socio-economic hurdles that limit leguminous crop productivity. It evaluates cutting-edge technological innovations, including speed breeding, genomic selection, CRISPR-based gene editing, and nano-agrochemicals, that are transforming modern pulse cultivation. Finally, it presents a strategic blueprint designed to translate laboratory breakthroughs into stable, high-yielding field outcomes, paving the way for a more climate-resilient agricultural future.

Keywords: Pulses, Food security, Yield constraints, Breeding approaches

1. The Paradox of Pulses: Global Significance vs. Production Inefficiencies

Pulses, including chickpea (*Cicer arietinum*), pigeonpea (*Cajanus cajan*), mungbean (*Vigna radiata*), and lentil (*Lens culinaris*), are foundational pillars of nutritional security and ecological sustainability. As nutrient-dense superfoods, they provide a vital, low-cost source of plant-based protein, dietary fiber, vitamins, and minerals for billions of people worldwide. Beyond their dietary importance, legumes are crucial for soil health. Through symbiotic biological nitrogen fixation (BNF) powered by *Rhizobium* bacteria, pulses capture atmospheric nitrogen, reducing the need for synthetic, fossil-fuel-dependent nitrogenous fertilizers. This natural process improves soil structure, reduces greenhouse gas emissions, and breaks pest cycles when integrated into crop rotations.

Despite these clear advantages, global pulse production faces an agronomic paradox. While cereal yields (such as wheat, rice, and maize) saw massive leaps during the Green Revolution due to intensive breeding and input-rich management, pulses were largely pushed onto marginal, rainfed lands with poor soil fertility. Consequently, the global average yield of pulses has remained stagnant for decades, fluctuating between a modest 800 to 1,100 kg per hectare. This is only a fraction of their estimated genetic potential. As climate change accelerates, causing unpredictable weather and new pest pressures, breaking this yield barrier has evolved from a local agricultural goal into an urgent prerequisite for global food stability.

2. Deconstructing the Yield Plateaus: Multi-Dimensional Challenges

The persistent yield stagnation in grain legumes is caused by an overlapping mix of biological, environmental, and socio-economic factors.

2.1. Biological and Physiological Constraints

- **Indeterminate Growth Habits:** Many traditional pulse varieties exhibit indeterminate growth, where vegetative and reproductive phases occur simultaneously. This creates internal competition for photosynthates between developing leaves and expanding pods, leading to poor harvest indices and uneven grain ripening.
- **High Rate of Flower and Pod Abortion:** Legumes produce a large number of flowers, but up to 70–80% of them naturally drop before producing mature pods. This massive loss is caused by hormone imbalances, vascular limitations, and environmental stress during critical growth stages.

- **Narrow Genetic Base:** Domestication bottlenecks have severely restricted the genetic diversity available in modern cultivated pulse germplasm. This narrow genetic foundation limits breeders' capacity to select for high productivity and robust stress resilience.

2.2. Environmental and Climate-Induced Stress Factors

- **Abiotic Pressures (Drought, Salinity, Thermal Extremes):** Because pulses are typically grown on rainfed lands, they frequently encounter terminal drought and heat stress during the reproductive phase. This accelerates plant aging and cuts grain-filling short. Additionally, poor drainage can lead to waterlogging, which disrupts root respiration and halts nitrogen fixation.
- **Biotic Threats (The Pathogen and Pest Complex):** Pulses are highly vulnerable to a wide range of destructive pests and pathogens. Fungal diseases like Fusarium wilt, Ascochyta blight, and dry root rot, alongside destructive field insects such as the pod borer (*Helicoverpa armigera*), can cause complete crop failures if left unmanaged.

2.3. Agronomic and Socio-Economic Barriers

- **Marginal Land Cultivation:** Pulses are rarely grown on prime agricultural land. Instead, they are relegated to resource-poor soils with severe macro and micronutrient deficiencies, particularly zinc, boron, and phosphorus.
- **Poor Adoption of Modern Inputs:** Smallholder farmers often look at pulses as low-input, secondary crops. This leads to the widespread use of poor-quality, farm-saved seeds, minimal use of specialized protective biologicals, and a lack of protective irrigation.

3. Technocentric Innovations: Overcoming Yield Plateaus

The transition from conventional cross-breeding to precision molecular breeding has opened up new pathways to overcome the biological limitations of legumes.

3.1. Genomics-Assisted Breeding (GAB) and GWAS

The completion of high-quality genome sequences for crops like chickpea, pigeonpea, and mungbean has completely changed the breeding landscape. Genome-Wide Association Studies (GWAS) and Marker-Assisted Selection (MAS) allow researchers to pinpoint specific Quantitative Trait Loci (QTLs) tied to crucial yield attributes. Rather than waiting seasons for traits to manifest, breeders can now screen seedlings via DNA profiling to confirm the presence of genes for drought tolerance or disease resistance, saving valuable years of field validation.

3.2. Speed Breeding and Artificial Intelligence

Traditional pulse breeding takes 10 to 12 years to deliver a stable field cultivar. Speed breeding bypasses this constraint by using fully controlled indoor growth facilities with extended photoperiods (22–24 hours of continuous LED light) and precise temperature curves. This environment accelerates the plant's growth rate, allowing scientists to harvest up to six generations of a pulse crop per year instead of just one. When paired with AI-driven phenotyping drones, breeders can quickly scan thousands of test lines to pick out the top performers.

3.3. CRISPR-Cas9 and Advanced Gene Editing

Clustered Regularly Interspaced Short Palindromic Repeats (**CRISPR-Cas9**) offers a precise tool to modify specific plant genes. Rather than adding foreign DNA, CRISPR can tweak a plant's native genes to fix performance flaws:

- **Reducing Pod Shattering:** Deactivating the genes responsible for pod wall tension ensures pods stay intact until mechanical harvesting.
- **Architectural Modification:** Modifying hormone pathways helps transition plants to a semi-dwarf, determinate structure, optimizing their harvest index.
- **Detoxification:** Turning off specific metabolic pathways can reduce anti-nutritional compounds, such as neurotoxins in grass pea (*Lathyrus sativus*), making them safer alternative crops for dry regions.

4. Next-Generation Agronomy and Sustainable Crop Management

Unlocking a plant's genetic potential requires pairing high-quality seeds with advanced, resource-efficient field management strategies.

4.1. Precision Rhizobiology and Microbiome Engineering

The performance of a leguminous crop depends directly on its underground partnerships. Modern agronomy is moving away from basic, generic *Rhizobium* inoculants toward **Microbiome Engineering**. By selecting native, climate-hardy strains of Nitrogen-Fixing Bacteria and **Phosphate-Solubilizing Microorganisms (PSMs)**, scientists can create customized biological coatings for seeds. These specialized microbes stay active across a wider temperature range and in high-salinity soils, keeping the nitrogen-fixation process running smoothly even during dry spells.

4.2. Nano-Agrochemicals and Targeted Plant Nutrition

Traditional bulk fertilizer applications often fail to help pulses because the nutrients leach away before the plant can use them. **Nano-fertilizers** solve this problem by encapsulating vital nutrients within microscopic structures:

- **Nano-Urea and Nano-DAP:** These provide slow, controlled-release nutrient delivery through foliar sprays, minimizing chemical waste.
- **Nano-Zinc and Nano-Boron:** Delivering these key micronutrients at the nano-scale boosts enzyme activity, triggers pollen germination, and drastically reduces flower drop.

4.3. High-Density Planting and Smart Mechanization

Developing uniform, determinate pulse varieties allows farmers to adopt high-density planting designs. This approach maximizes the number of productive plants per acre and creates quick canopy cover that suppresses weeds naturally. Designing specialized, lightweight harvesters also reduces harvest losses and lowers manual labor costs, making pulse farming a more profitable venture.

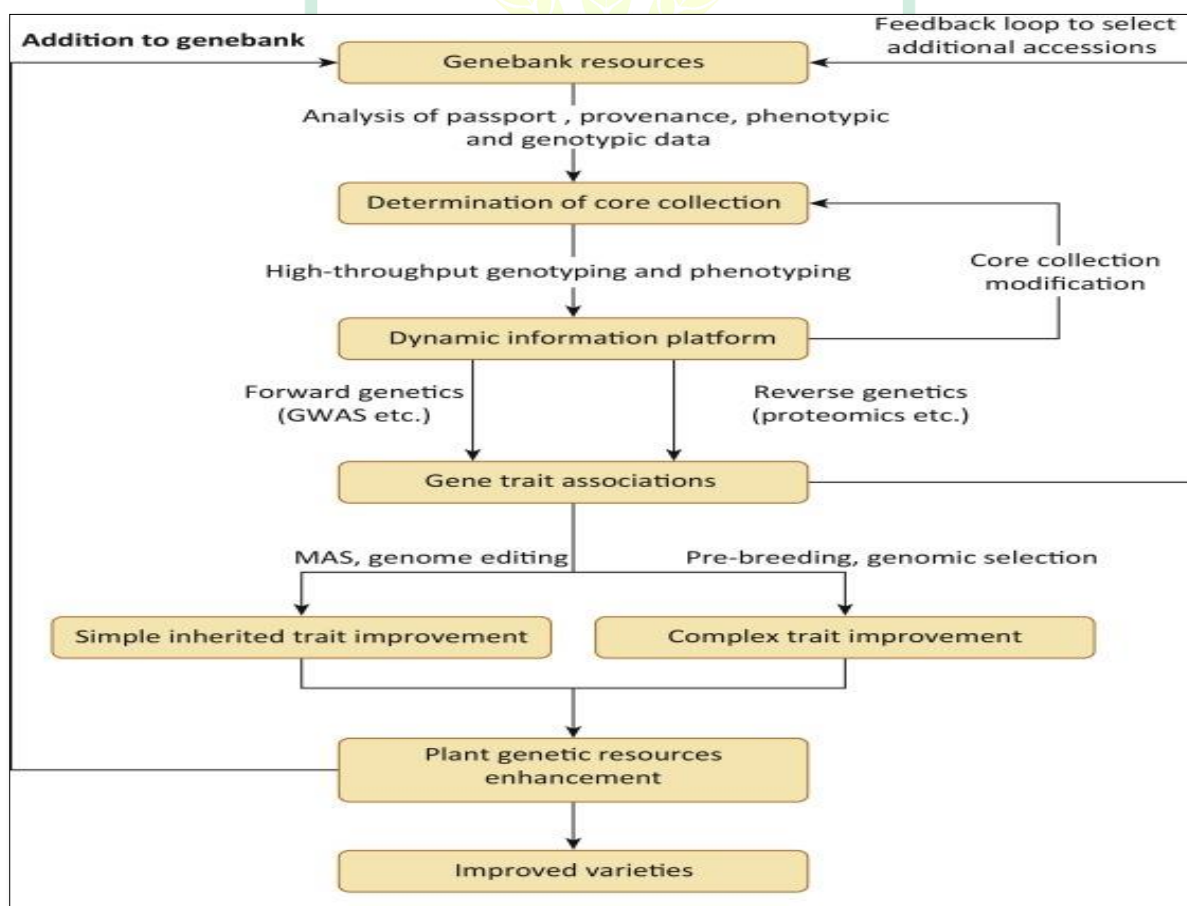


Fig 1. Flowchart illustrates the systematic workflow of genomics-assisted crop breeding, tracing the process from raw genebank resources through dual genetic screening pathways to produce improved crop varieties via precise feedback loops.

5. The Future Horizons: A Policy and Strategic Framework for the Future

To truly break the yield barrier on a global scale, laboratory discoveries must be systematically translated into practical, accessible field solutions for smallholder farmers.

5.1. Creating Resilient Seed Systems

The finest laboratory-engineered seed is useless if it stays trapped in a research center. Governments and private entities must co-invest in local seed networks to multiply and distribute new, high-yield varieties quickly. This ensures that farmers can easily access certified, stress-hardy seeds within a couple of seasons of their official release.

5.2. Policy Incentives and Financial Security

To motivate farmers to dedicate fertile land to pulses rather than conventional cereals, policy frameworks require adjustments:

- **Reliable Pricing:** Implementing minimum price guarantees helps shield smallholder farmers from sudden market price drops.
- **Climate Insurance:** Offering low-cost crop insurance tied to regional weather data protects farmers against climate-driven losses.

5.3. Upgrading Value Chains and Post-Harvest Infrastructure

Up to 15–20% of pulse harvests are lost after picking due to poor handling, pests, and damp storage conditions. Setting up regional processing centers equipped with temperature-controlled silos and modern drying equipment can preserve crop quality, cut down on post-harvest waste, and ensure farmers receive premium prices for their yields.

6. Conclusion

Breaking the yield barrier in pulses is an ecological, economic, and social imperative. Future progress will depend on effectively harnessing wild germplasm, developing climate-resilient and pest-resistant varieties, strengthening seed systems, and promoting pulse-based cropping systems at scale. Equally important is strong policy backing and sustained investment in pulse research and development. While biological complexities and climate extremes present real challenges, the integration of new breeding technologies like CRISPR-Cas9 and speed breeding, along with advanced nano-nutrition, offers a clear path forward. By supporting these scientific tools with resilient local seed systems, fair policy incentives, and modern post-harvest infrastructure, the global agricultural community can transform pulses from a marginal crop into a highly productive, sustainable asset. Taking these steps will secure a climate-resilient food system and protect the livelihoods of smallholder farmers for generations to come.

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Unmasking the Global Crisis of Arsenic contamination in Aquatic Ecosystems: Sources, Impacts and Mitigation Strategies



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Abstract

Aquatic ecosystem contamination by arsenic is a serious environmental and public health concern, especially in developing nations that are rapidly becoming more industrialized and urbanized. Anthropogenic activities, biogenic transformations and geogenic processes all contribute to the entry of arsenic into water bodies. Arsenic is mostly found in aquatic environments as As (III) and As (V), which are highly mobile and toxic, having detrimental effects on human health as well as ecological disturbances. Long-term exposure to contaminated water has negative effects on aquatic food chains and agricultural productivity in addition to cardiovascular, neurological, renal and carcinogenic effects. Sensitive arsenic detection and speciation are made possible by efficient monitoring using spectrophotometric, electrochemical and hyphenated analytical techniques. The efficacy of mitigation techniques such as oxidation, coagulation–flocculation, adsorption, ion exchange, membrane technologies and phytoremediation varies to evaluate sustainable mitigation techniques and highlights current monitoring methods for controlling arsenic pollution in aquatic ecosystems.

Keywords: Arsenic Toxicity, Aquatic Ecosystems, Groundwater Contamination, Biomarkers & Speciation, Adsorption, Phytoremediation.

Introduction

Rapid urbanization and industrialization in developing nations caused an increase in the concentration of organic and inorganic materials, which resulted in the excessive discharge of industrial waste into rivers and canals (Pawar et al., 2022). Human life depends on water and the problem of water security has a direct effect on society and the standard of living of its citizens. Water use has increased due to modern lifestyles, industrial development and population growth. Water safety is often threatened by chemicals and microbial contamination (Dilpazeer et al., 2023). Chromium (Cr), lead (Pb), zinc (Zn), arsenic (As), copper (Cu), nickel (Ni), cadmium (Cd), mercury (Hg) and other hazardous metals are being released into water bodies more frequently, which is concerning (Pawar et al., 2022). Large amounts of the metalloid element arsenic (As) are present in aquatic environments as a result of both natural and human activity. As a major environmental pollutant with a high risk of human poisoning, it presents a serious threat to public health. Public health officials around the world are therefore concerned about it (Sankhla et al., 2024).

The 20th most common metalloid in the Earth's crust, arsenic has an atomic number of 33. It is present in the environment as arsine, methylarsenic acid, dimethylarsinic acid, arsenic acid, arsenites and arsenates. The most common forms of arsenic are ions like arsenic (III) and arsenic (V). It is extensively dispersed and mostly carried by water to the environment (Mahamallik & Swain 2023). Groundwater arsenic pollution in India has been considered the world largest and most devastating natural disaster for more than thirty years. One of the global hotspots for this groundwater crisis is India. The crisis has tragically ended in many areas of northern and eastern India. Seven districts in the Indian state of West Bengal alone suffered severe damage (Koley, 2022). Arsenic pollution of groundwater exceeds the allowable limit of 0.05 mg/l, according to toxicological studies (Sankhla et al., 2018). Arsenic is considered as one of the dangerous elements found in the environment and exposure to it can lead to major health problems such as respiratory, neurological, hematological, cardiovascular and renal disorders. Reliable water sources, appropriate treatment technologies and appropriate government guidelines are all necessary to address the problem and issues related to arsenic contamination. To eliminate arsenic from water, researchers have used a variety of treatment techniques. The treatment approach

should be accessible to use on a large scale, economical and free of secondary pollutants (Mahamallik & Swain, 2023).

Physiochemistry of arsenic

Because of its broad range of chemical reactivity, arsenic can form covalent bonds and alloys with other elements. Inorganic arsenic compounds are solid at room temperature and are not anticipated to turn volatile. While most organic arsenic compounds are normally solids at room temperature, with some being gases or liquids due to their low boiling points, the water solubility of inorganic arsenic compounds ranges from excellent to nearly non-existent. Chemically, arsenic compounds fall into two categories: inorganic and organic. Inorganic arsenic comes in two varieties pentavalent (As V) and trivalent (As III). Arsenic oxide is the most significant of all the element's compounds. Although arsenic occurs naturally in the environment, the mineral arsenopyrite is the main commercial source of arsenic. The most prevalent oxidation states of arsenic are +5 (found in stable inorganic oxy-compounds called arsenates V) and +3 (found in the most prevalent organo-As compounds, known as arsenites III) (Sankhla et al., 2024).

Sources of arsenic contamination

Sources of Arsenic Contamination

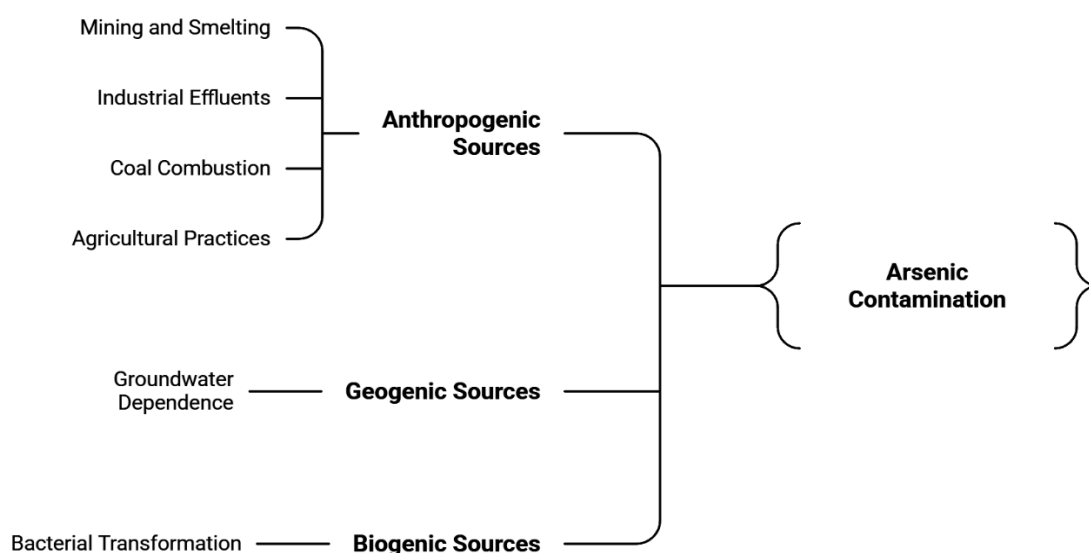


Fig. 1 Sources of Contamination

Anthropogenic sources

The main anthropogenic sources of arsenic contamination are industrial processes and human activity, which cause significant environmental and public health problems. There are many different sources that fall under the anthropogenic category, some of which are mentioned below:

1. **Mining and smelting:** These activities have the potential to release large amounts of arsenic into the air and water, detrimental to the health of nearby residents and contaminating surrounding ecosystems.
2. **Industrial effluents:** Wastewater containing arsenic can be released into rivers and streams as a result of industrial processes, such as the manufacturing of chemicals, metals and semiconductors. This is a major worldwide concern.
3. **Coal combustion:** When coal is burned to produce energy, arsenic is released into the atmosphere, which greatly contaminates water, soil and other environmental resources.
4. **Agricultural practices:** One of the main causes of soil and water contamination, particularly in areas with intensive agricultural activities, is the use of pesticides and herbicides containing arsenic.

Geogenic sources

Natural geological processes that release arsenic into the environment without direct human intervention are the source of geogenic sources of arsenic contamination. In areas where communities mainly depend on groundwater for drinking, geogenic arsenic contamination presents a serious problem.

Biogenic sources

Living things and natural biological processes are linked to biogenic sources of arsenic contamination. For example, some bacteria have the ability to change arsenic from less toxic to more toxic forms, which can contaminate groundwater (Bhat et al., 2024).

Impacts of arsenic contamination

Health impacts on humans

Long-term exposure to arsenic is a major health risk, particularly in areas where the main source of water for drinking has been contaminated groundwater. Numerous health issues are linked to prolonged exposure:

1. **Residential proximity:** Long-term exposure to arsenic-contaminated water sources increases the risk of chronic health problems in communities.
2. **Vulnerable groups:** People with weakened immune systems, children and pregnant women may be more susceptible to the negative health effects of arsenic exposure.
3. **Mitigation challenges:** Putting into practice efficient mitigation strategies is difficult, particularly in areas with limited resources, which increases the health risks related to arsenic contamination (Bhat et al., 2024).

Impacts on aquatic ecosystems

- Ecosystem disruption: Aquatic ecosystems can become less diverse, have different species compositions, and have altered food chains as a result of arsenic pollution in water bodies.
- Soil contamination due to irrigation: When water contaminated through arsenic is used for irrigation, it can accumulate in the soil and disrupt agricultural development. Additionally, it may enter the food chain and pose a health risk to humans (Mahamallik & Swain, 2023).
- Contamination of the food chain: When arsenic gets into aquatic environments, it can contaminate the food chain, which could have an adverse impact on higher trophic level (Bhat et al., 2024).

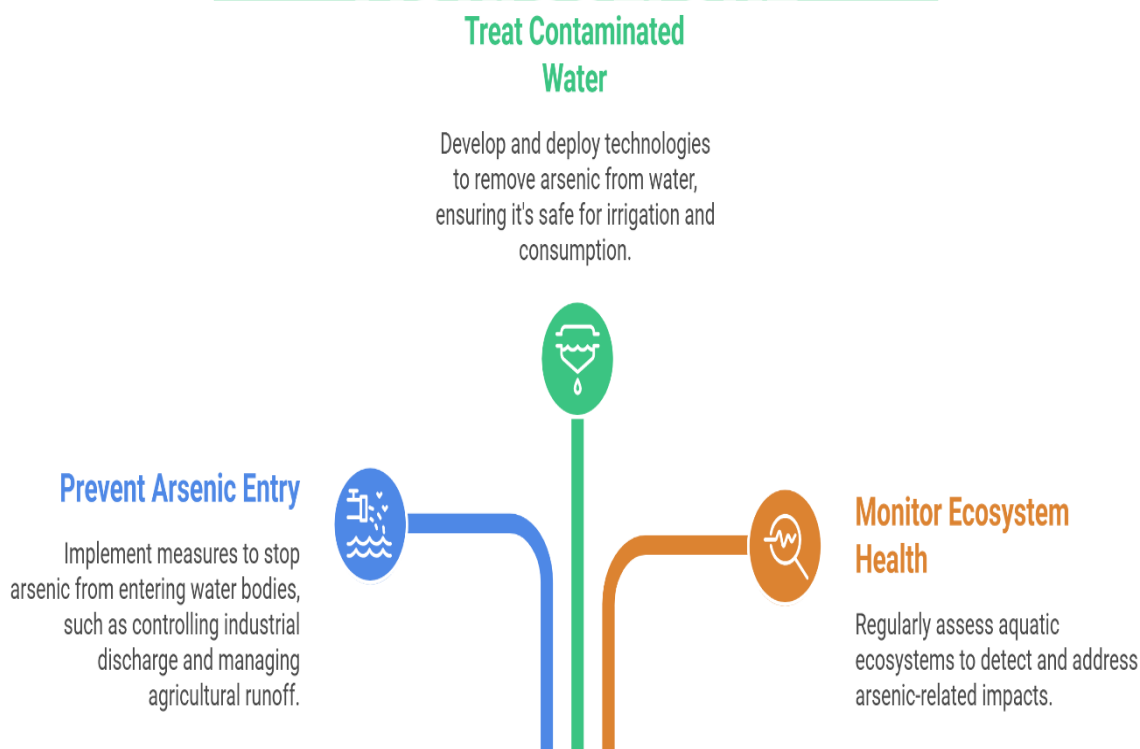


Fig. 2 Impacts on Aquatic ecosystems

Social and economic impacts

- Economic burden: For affected communities, treating and preventing drinking water from arsenic poisoning can be costly, especially in places with limited resources. Adopting efficient water treatment technology can be costly.
- Access to safe water: Communities may find it difficult to obtain safe drinking water due to arsenic contamination, causing them to rely on tainted sources or require an extra cost for alternatives.
- Affected livelihoods: Farmers who depend on irrigation water tainted with arsenic may experience a decline in agricultural output, which could result in financial losses. The possible health effects on farmers may also exacerbate the socioeconomic challenges faced by affected communities (Mahamallik & Swain, 2023).

Monitoring of arsenic

Due to its high toxicity and widespread occurrence, arsenic monitoring and measurement have become extremely difficult. The limits of detection given by these monitoring methods are significantly lower than the WHO's arsenic recommendation. Calometric, spectrophotometric, electrochemical and coupling techniques are a few of the techniques used to track arsenic toxicity (Pawar et al., 2022).

Mitigation strategies of arsenic

Numerous action plans have been put forward to address the issue of arsenic-related water pollution. It can be broadly divided into two categories.

1. Removing arsenic from water to make it available with less or no arsenic,
2. Giving people access to an alternative, easily accessible and sustainable water source.

Table 1: Chemical & Biological Methods

Process	Active Agents	Pros / Cons	Key Performance Metrics	Ref.
Chem. Oxidation	H ₂ O ₂ , Cl ₂ , KMnO ₄	Fast & simple / Requires pH control	• 100%: KMnO₄ (pH 7.5–10.3, 1 min) • 86%: ClO₂ (pH 8–12)	[1]
Coagulation / Flocculation	Alum, Ferric chloride/sulphate	Easy operation / High sludge yield	• 90.9%: C₀ = 0.2 mg/L (pH 7, 24 min) • 99%: Ferric ion + coarse calcite	[2]
Advanced Oxidation (AOP)	UV/H ₂ O ₂ , Ozone, Fenton	High efficiency / Non-selective	• ~100%: pH 3–11 (1–10 mg/L, 30 min) • ~100%: As 30 mg/L (Photocatalyst, 10 h)	[1]
Phytoremediation	Phytoextraction, Phytofiltration	Eco-friendly / Time-consuming	• Uptake: 7.65 nmol/g (<i>S. polyrhiza</i>) • Absorbed: 1,000 µg/g (<i>P. vittata</i>)	[3]

[1] Mahamallik & Swain (2023) | [2] Nicomel et al. (2016) | [3] Pawar et al. (2022)

Table 2: Physical & Media Separation

Process	Active Agents	Pros / Cons	Key Performance Metrics	Ref.
Adsorption	Activated C/Alumina, Zeolite, ZVI	Low cost & O&M / Phase transfer only	• Capacity: 4.2 ± 0.3 mg/g (pH 3, iron-coated cork)	[2]
Ion Exchange	Natural & synthetic resins	High selectivity / High cost; exhausts	• 99%: 25 mg/L (Cellulose anion exchanger) • Capacity: 53.33 mg/g (pH 3, Ferrix A33E)	[3]
Membrane Filtration	Nanofiltration (NF), RO, ED	Top tier purity / Membrane fouling	• 93–99%: As(V) at 100–382 µg/L via NF • pH reliance: As(V) efficient > pH 4; As(III) > pH 9.1	[4]

[2] Nicomel et al. (2016) | [3] Pawar et al. (2022) | [4] Pezeshki et al. (2023)

Conclusion

Due to intricate interactions between geogenic, anthropogenic and biogenic processes, arsenic contamination in aquatic ecosystems continues to be a persistent environmental and public health concern. Particularly in areas that rely on groundwater, the high mobility and toxicity of arsenic species, especially As (III) and As (V), pose serious risks to human health, ecological degradation and socioeconomic burdens. Sensitive detection and speciation, which are crucial for risk assessment and management, have been made possible by advancements in monitoring techniques, such as spectrophotometric, electrochemical and hyphenated methods. Under controlled conditions, a variety of mitigation techniques, including chemical oxidation, coagulation-flocculation, adsorption, ion exchange, membrane technologies and phytoremediation, have shown high removal efficiencies; however, their practical applicability varies depending on cost, operational complexity and environmental sustainability.

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Water Balance Method for Estimation of Crop Water Requirement



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Abstract

Efficient management of irrigation water is essential for sustainable crop production and conservation of water resources. The water balance method is one of the most scientific approaches used to estimate crop water requirement under varying climatic and soil conditions. This method is based on the balance between incoming water, outgoing water and the change in soil moisture storage within the crop root zone. By accounting for all components of water movement, the method helps determine the actual amount of water required by crops during their growth period. This article explains the concept, governing equation, major components, procedure, advantages, limitations and agricultural applications of the water balance method.

Keywords: Water balance method, crop water requirement, climate, crop production

1. Introduction

Agriculture consumes a major share of available freshwater resources. Increasing pressure on water resources due to population growth, climate variability, and expanding irrigation demands has made efficient water management a necessity. Accurate estimation of crop water requirement plays a vital role in improving irrigation scheduling and water use efficiency.

Among different techniques used for estimating crop water requirement, the water balance method is considered highly reliable because it evaluates the movement of water within the soil–plant–atmosphere system. The method determines how much water enters the root zone, how much leaves the system and how much remains stored in the soil.

2. Concept of Water Balance

The water balance method follows the principle of conservation of mass. According to this principle, the total amount of water entering a system minus the water leaving the system is equal to the change in water stored within the system.

For agricultural fields, the crop root zone is treated as the control volume. Water may enter the root zone through rainfall, irrigation, and upward movement from groundwater, while it may leave through evapotranspiration, runoff and deep percolation.

The balance among these components provides the basis for estimating crop water requirement.

3. Water Balance Equation

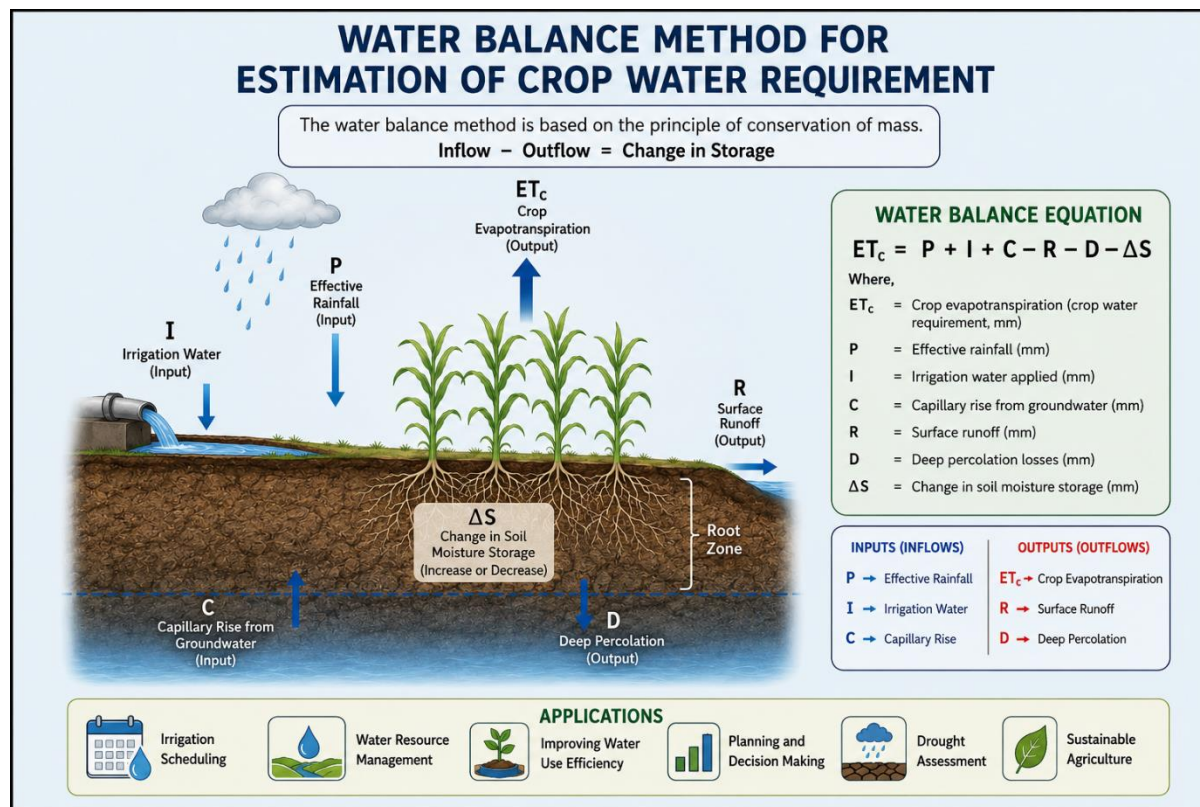
The equation of water balance for crop water requirement is:

$$ET_c = P + I + C - R - D - \Delta S$$

Where:

- ET_c = Crop evapotranspiration or crop water requirement (mm)
- P = Effective rainfall or precipitation (mm)
- I = Irrigation water applied (mm)
- C = Capillary rise from groundwater (mm)
- R = Surface runoff (mm)
- D = Deep percolation losses (mm)
- ΔS = Change in soil moisture storage (mm)

The equation indicates that crop water use can be estimated by measuring all other components affecting soil water balance.



4. Parameters of Water Balance Method

4.1 Rainfall

Rainfall is a natural source of water for crops. However, not all rainfall contributes to crop growth. The portion stored within the root zone and available for crop use is known as effective rainfall.

4.2 Irrigation Water

Irrigation water refers to the quantity of water supplied artificially to the field to meet crop demand when rainfall is insufficient.

4.3 Capillary Rise

In areas with shallow groundwater tables, water may move upward into the root zone through capillary action. This contribution can reduce irrigation requirement.

4.4 Crop Evapotranspiration

Crop evapotranspiration represents the combined loss of water through:

- Evaporation from soil surface
- Transpiration from crop plants

It is the major component of crop water requirement.

4.5 Surface Runoff

Excess rainfall or irrigation water that flows out of the field without entering the soil is called runoff.

4.6 Deep Percolation

Water moving downward below the effective root zone is termed deep percolation loss. This water becomes unavailable for crop uptake.

4.7 Change in Soil Moisture Storage

Soil moisture storage may increase or decrease depending on water availability and crop use. It is determined by measuring soil moisture content at the beginning and end of the study period.

5. Procedure for Estimating Crop Water Requirement

The following steps are generally followed in the water balance approach:

Step 1: Selection of Root Zone Depth

The effective root zone depth of the crop is identified based on crop type and growth stage.

Step 2: Measurement of Soil Moisture

Soil moisture content is measured periodically using suitable methods such as:

- Gravimetric method
- Tensiometers
- Neutron moisture meter
- Soil moisture sensors

Step 3: Recording Water Inputs

Data related to rainfall and irrigation water applied are collected during the crop period.

Step 4: Estimation of Water Losses

Runoff and deep percolation losses are estimated based on soil properties, irrigation practices, and rainfall intensity.

Step 5: Application of Water Balance Equation

All measured values are substituted into the water balance equation to calculate crop water requirement.

6. Example

Assume the following data for a crop field during a growth period:

- Irrigation water applied = 120 mm
- Effective rainfall = 40 mm
- Capillary rise = 10 mm
- Runoff = 15 mm
- Deep percolation = 20 mm
- Increase in soil moisture storage = 5 mm

Using the water balance equation:

$$ET_c = 120 + 40 + 10 - 15 - 20 - 5$$

$$ET_c = 130 \text{ mm}$$

Thus, the crop water requirement during the period is 130 mm.

7. Advantages of Water Balance Method

1. Provides realistic estimation of crop water use.
2. Suitable for field as well as research studies.
3. Helps improve irrigation scheduling.
4. Assists in efficient utilization of water resources.
5. Useful under different soil and climatic conditions.
6. Supports scientific water management practices.

8. Limitations of Water Balance Method

1. Requires continuous field observations and measurements.
2. Estimation of runoff and deep percolation may be difficult.
3. Errors in measurement can affect final results.
4. Time-consuming for large-scale studies.

9. Applications in Agriculture

The water balance method is widely applied in:

- Irrigation planning
- Crop water requirement estimation
- Watershed management
- Evaluation of irrigation efficiency
- Hydrological studies

- Precision farming
- Drought monitoring

10. Conclusion

The water balance method is an effective and scientifically sound approach for determining crop water requirement. By accounting for all inflow, outflow, and storage components within the crop root zone, the method provides a clear understanding of water movement in agricultural fields. Accurate estimation of crop water requirement through this method helps improve irrigation efficiency, conserve water resources, and increase agricultural productivity. Despite requiring detailed field measurements, the method remains one of the most dependable tools for agricultural water management.

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Climate-Smart Breeding Approaches for Developing Climate-Resilient Vegetable Crops



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Abstract

The growth, development, yield, and quality of vegetable crops are all greatly impacted by climate change, which is becoming one of the biggest challenges to world agricultural output. Abiotic stressors in vegetable production systems have been exacerbated by rising temperatures, erratic rainfall patterns, drought, salt, waterlogging, increased atmospheric CO₂ concentrations, and frequent heat waves. Due to their extreme sensitivity to environmental changes throughout crucial growth and reproductive periods, vegetable crops are especially sensitive. While drought and salinity affect water relations, nutrient intake, and metabolic processes, heat stress can affect pollen viability, flower initiation, and fruit set. Waterlogging decreases plant survival and output by further restricting root respiration. In order to guarantee food and nutritional security in the face of shifting climatic conditions, it is now crucial to produce climate-resilient vegetable cultivars. Vegetable crops' ability to withstand stress is being greatly enhanced by conventional breeding methods in conjunction with contemporary molecular and genomic technology. Marker-assisted selection (MAS), genomic selection (GS), genome-wide association studies (GWAS), quantitative trait loci (QTL) mapping, and next-generation sequencing (NGS) are examples of climate-smart breeding techniques that have expedited the identification and integration of desired stress-resilient traits. Furthermore, sophisticated phenotyping instruments such as thermal imaging, fluorescence imaging, visible imaging, and imaging spectroscopy allow for accurate assessment of plant reactions to stress. By adjusting temperature, photoperiod, and controlled environmental conditions, speed breeding methods further reduce breeding cycles and speed up varietal development. Vegetable crop development has been transformed by genome editing technologies including CRISPR/Cas9, TALENs, zinc finger nucleases (ZFNs), and mega nucleases, which precisely modify genes linked to drought, salinity, heat, and cold tolerance. Stress tolerance and quality features have been successfully improved in a number of vegetable crops, including tomato, potato, lettuce, cucumber, pumpkin, carrot, and others. The effects of climate change on vegetable crops, critical target features for stress resistance, and current developments in climate-smart breeding techniques for the creation of climate-resilient vegetable cultivars appropriate for sustainable agriculture are all highlighted in this study.

Key words: Climate resilient; MAS; GWAS; QTL.

Introduction

- Changes in weather patterns that result in more frequent and severe weather occurrences are among the most obvious consequences of climate change. The frequency and severity of heatwaves, droughts, severe rainfall, hurricanes, and wildfires are increasing. Climate change also directly affects human livelihoods and health. Rising temperatures can worsen the transmission of infectious diseases and cause heat-related disorders. Furthermore, food and water security may be threatened by altered weather patterns and an increase in the frequency of extreme weather events, especially in already vulnerable areas. Climate change has a substantial economic influence on tourism, agriculture, and fishing. It may also result in widespread migration and displacement.
- Since the world's vegetable crop is seriously threatened by the growing frequency and intensity of heatwaves caused by climate change, developing climate-resilient vegetable cultivars is an essential goal for food security. Global temperatures have increased due to greenhouse gas emissions, which has led to longer and more intense heat waves that change plant physiology, reduce yields, and deteriorate crop quality. Many traditional vegetable varieties, such as lettuce, tomatoes, and peppers, are particularly susceptible to intense heat and exhibit stress-related symptoms such reduced fruit set, poor root development, and flower abortion.

For instance, temperatures above 35°C may cause tomatoes' pollen to become sterile, which drastically lowers productivity. Similarly, leafy greens like spinach and lettuce become unsellable when they bolt (flower too soon) due to heat stress.

Targeted traits climate resilient breeding

CO₂ (Carbon dioxide)

- Carbon dioxide has a major role in the production of carbohydrates in crops, which are essential for crop growth and yield. When CO₂ levels rise, vegetable crop productivity will likely increase. However, losses from weeds, plant diseases, other abiotic stresses, and phytophagous insects could balance any production improvements, either entirely or in part. The possibility of temperature and water supply variations as CO₂ concentration increases complicates accurate projections for vegetable production at high CO₂ concentrations.

Heat waves

- Vegetable crops' growth and development are expected to be impacted by temperature occurrences that fall outside of their usual growth ranges, ultimately affecting their prospective yields and quality. However, the age and growth stage of the plants also affect how various species and types respond to extreme temperatures. It is commonly believed that temperatures above 35°C prevent seeds from germinating and seedlings from emerging, disrupt typical photosynthetic activities, and increase respiration at night, which lowers the quantity of biomass generated for plant growth and yield.
- Additionally, high temperatures prevent edible organs such the leafy head, bulb, tuber, fleshy stem, fleshy root, and curd from changing. Additionally, they disrupt regular reproductive processes, which lowers the quantity of fruit and seed set on annual crops like cucurbitous, leguminous, and solanaceous vegetables as well as the amount of cruciferous vegetable flowering. High temperatures inhibit the development of floral buds in vegetable crops by causing flower abortion. High temperatures can also reduce the postharvest quality of vegetable products.

Waterlogging stress

- Waterlogging can damage vegetable crops because it lowers the soil's oxygen content and gas exchange rates, which restricts root respiration. Plant age, the duration of the waterlogging period, ambient temperature, the condition of the floodwater, and site characteristics all have a significant impact on how sensitive or tolerant vegetable species, genotypes, and rootstocks are to waterlogging.
- High temperatures and moisture cause herbaceous vegetables to quickly wilt and die. The majority of vegetables cultivated globally are vulnerable to waterlogging, which can result in significant declines in yield, especially those with shallow root systems.
- The genetic diversity of this attribute is really low. Combining all tolerance genes into a single genotype could significantly increase waterlogging tolerance because the various genes may link to distinct mechanisms of resistance to waterlogging. The primary factor influencing the inheritance of waterlogging tolerance is additive gene action.

Salt stress

- Particularly in arid and semi-arid areas, salt stress is an important abiotic element that limits agricultural yield by hindering plant growth. Salinity has negative impacts on vegetables, which range from sensitive to somewhat resistant. These consequences include disturbances in seed germination, growth, flowering, and fruit development. Because increased salt concentrations in the root zone demand more energy for plants to absorb water, salinity inhibits the uptake of water from the soil. Nutritional imbalances result from sodium salts in particular interfering with the absorption of vital nutrients such as potassium, phosphorus, and nitrogen.
- Salt stress significantly lowers the number of nitrogen-fixing nodules in peas. Although a significant reduction in N-fixation occurred under saline circumstances, it has been reported that salt-induced reduction in N₂-fixation was not caused by a change in the expression of the nif H gene, an essential encoding component of nitrogenase reductase. However, as is the case in other species, the enzymes involved in assimilate import for N fixing may be downregulated, and numerous additional genes are likely impacted.

Salt stress has been shown to raise the total phenolic content in peas, and phenolics are essential as reactive oxygen species (ROS) scavengers in salty environments.

Drought

- Plants can sustain productivity with less water thanks to breeding for increased water-use efficiency, which makes them more drought-resistant. Enhancing drought tolerance requires traits including deeper root systems, stomatal control, and osmotic adjustment.
- Crops with deep, wide root systems are better able to withstand extended dry spells because they can get water from deeper soil layers. Drought resilience depends on choosing root characteristics that improve water intake.

Smart breeding

- The utilisation of molecular markers and NGS data is crucial in vegetable crop breeding in the twenty-first century because to the availability of reference genomes and novel genomic methods including GBS, BSA-seq, GWAS, and GS. Our knowledge of the genetics of many vegetable crops has already advanced tremendously as a result of the recent use of contemporary technologies, which has also greatly increased the effectiveness and precision of breeding programs. For instance, sophisticated DNA technology have accelerated the discovery and application of genetic markers and candidate genes linked to significant horticultural traits, resulting in more successful and efficient breeding techniques.
- While some vegetable crops, such as chicory, spinach, and eggplant, lag behind in the availability and application of new technologies for breeding, MAS is already standard practice for many traits in both public and private breeding programs, particularly disease resistance and fruit quality characteristics.
- It is anticipated that marker-assisted selection (MAS) will become increasingly prevalent for various traits and other vegetable crops in the near future. The simplicity of developing and applying markers, along with the declining costs of marker genotyping, positions MAS as a leading option for numerous traits across most breeding programs.
- The use of MAS for the majority of complex quantitative traits is currently hindered by a number of factors, including inaccurate QTL identification due to phenotyping difficulties and the large size of QTL, in contrast to simple qualitative traits for which the application of markers has been rather straightforward. Intervals, a lack of QTL validation, a lack of trustworthy, closely-linked markers, QTLs from wild species that are distantly related, QTL population specificity, and linkage drag. For instance, documented QTLs for many quantitative traits and in the majority of vegetable crops frequently span wide genomic intervals that contain genes with unfavourable phenotypic effects, making it impossible to exploit them effectively in breeding programs.
- The adoption of MAS for many crucial agricultural features has been severely hampered by these problems, which are obviously not unique to vegetable crops but also exist in the majority of other crops.
- It is crucial to fine-map and delineate QTLs to tiny intervals, validate QTLs and their associated markers across breeding populations, and find dependable and repeatable closely-linked markers prior to the successful application of QTLs in widespread marker-assisted breeding. It is anticipated that the application of MAS will quickly and gradually expand beyond simple Mendelian qualitative features as QTLs are well described and validated.

Imaging Techniques	Growing environment	Applications
Visible imaging	Field	Imaging canopy cover and canopy colour information can be used for green indices; the use of 3D stereo reconstruction from multiple cameras or viewpoints allows the estimation of canopy architecture parameters.
Fluorescence imaging	Field	Photosynthesis status, indirect measurement of biotic or abiotic stress.
Thermal imaging	Field	Stomatal conductance; water stress induced by biotic or abiotic factors.
Imaging spectroscopy	Field	Biochemical composition of the leaf or canopy concentration; water content; indirect measurement of biotic or abiotic stress; canopy architecture.

The applications of imaging techniques for plant phenotyping under different growing environments

Speed breeding

- A method that shortens the breeding cycle and allows for rapid generation advancement in glasshouses or poly houses by prolonging photoperiod and controlling growing variables like temperature, spacing, soil medium, etc. Accelerated breeding includes speed breeding. It essentially shortens the crop cycle and speeds up the traditional breeding process. In this approach, photoperiod and the glass house's atmosphere are crucial. To put it another way, it shortens the time needed for crossing and inbreeding. A new variety cannot be developed or raised only through fast breeding. Additionally, this procedure cannot cause a seed to germinate; therefore, various seed treatments, such as cold treatment, are required.
- Numerous species, including wheat, barley, canola, chickpeas, garden peas, cauliflower, tomatoes, carrots, etc., can undergo speed breeding. Agronomic crops were the first. However, it is currently feasible for horticulture crops (331 Recent Advances in Agricultural Sciences and Technology). Many crops with lengthy crop cycles are found in horticulture. Research is being done on cauliflower, tomatoes, and carrots. For all kinds of crops, speed breeding procedures are a crucial idea. Be day-neutral, short-day, and long-day plants. The tomato plant is day-neutral. Some findings from this crop include the use of the tomato simulation model "TOMSIM" to forecast tomato genotype performance under continuous light. A hypothetical continuous light-tolerant tomato genotype has been discovered to produce between 22 and 26% more fruits when lighted for 24 hours per day (CL) as opposed to 18 hours per day during the day. It is possible to boost yield by up to 20% by introducing the tolerance into contemporary tomato F hybrid lines. In essence, tomato yield can be increased by constant light. Using double haploidy in cauliflower (*Brassica oleracea* var. *Botrytis* L.) to boost crops is another example of speed breeding. Similarly, this method can be used to develop numerous crops, including better carrot cultivars.

Set up of Speed Breeding

Temperature

- Each agricultural plant should be exposed to the ideal temperature. A high temperature should be maintained throughout the photoperiod, whereas a drop in temperature during the dark hours can aid in stress recovery.
- Since temperature has a significant and greater influence on the rate of plant development, raising the temperature can speed up the generation time. On the other hand, high temperatures can also cause stress.

Light

- The best light for fast breeding is one that focuses on the blue, red, and far-red range 6 and covers the Photosynthetically Active Radiation (PAR), or 400–700 nm.
- Light Emitting Diodes (LEDs) or a combination of LEDs and halogen lamps can be used to achieve this spectrum. It is also advised to have a photosynthetic photon flux density (PPFD) of around 450–500 $\mu\text{mol}/\text{m}^2/\text{s}$ at the height of the plant canopy. Depending on the needs of the crop, this can be slightly reduced or increased.

Photoperiodic regime

- The ideal photoperiodic regime for fast breeding is 22 hours of light and 2 hours of darkness throughout a 24-hour diurnal cycle. Another option, such as constant light with brief periods of darkness, is believed to enhance plant health.

Crop	Photoperiod	Temperature	Humidity (%)	Field condition (Days)	Speed breeding (Days)
<i>B. rapa</i>	22h	22/17C (light/dark)	70	171	98
<i>B. oleracea</i>	22h	20/15C (light/dark)	70	112	91
<i>B. napus</i>	22h	20/15C (light/dark)	70	109	91
Pea	22h	20/17C (light/dark)	70	84	51
Amaranthus	16h	35/30C (light/dark)	70	180	60

Humidity

- Generally maintained between 60% and 70% for optimal plant health.

Genome editing

- Food and nutritional security are severely hampered by the expanding population, climate change, and finite natural resources. Although they are crucial for attaining food security, vegetable crops are subject to both biotic and abiotic stressors. It is crucial to improve vegetable varieties' ability to withstand environmental stress, particularly when they have several resistance traits. Traditional breeding techniques are useful, but they are frequently slow and necessitate lengthy breeding cycles to add desired features. Crop improvement can be achieved through the precise, effective, and focused alterations that genome editing offers. Mega nucleases (MegaN), zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the CRISPR-Cas9 system are examples of technologies that allow for targeted changes to enhance quality attributes, stress tolerance, and disease and pest resistance in a variety of vegetable crops.
- Single nucleotide alterations without introducing foreign DNA or causing double strand breaks (DSBs). Furthermore, many genes and epigenetic features can be simultaneously modified in vegetable crops by multiplex and epigenome editing. The enhancement of lycopene content and parthenocarp in tomatoes, starch quality, enzymatic browning and glycoalkaloid reduction in potatoes, browning resistance in brinjal, increased anthocyanin content in carrots, gynocious and parthenocarp in cucumbers, herbicide tolerance in watermelon, salt tolerance in pumpkin, and more are notable uses of genome editing. With a focus on recent developments and their promise to improve crops, this study summarises the evolution, mechanisms, and uses of genome editing in a variety of vegetables.

Stress Tolerance	Plant Species	Target Gene	Method of Delivery
Drought tolerance	<i>Solanum lycopersicum</i>	SINPR1	Agrobacterium-Mediated
Drought tolerance	<i>Solanum lycopersicum</i>	SIMAPK3	Agrobacterium-Mediated
Drought tolerance	<i>Solanum lycopersicum</i>	SILBD40	Agrobacterium-Mediated
Drought tolerance	<i>Solanum lycopersicum</i>	SIARF4	Agrobacterium-Mediated
Salt tolerance	<i>Solanum tuberosum</i>	StCoilin	PEG-mediated
Salt tolerance	<i>Solanum lycopersicum</i>	S1HyPRP1	PEG-mediated
Heat tolerance	<i>Lactuca sativa</i>	LsNCED4	Agrobacterium-Mediated
Heat tolerance	<i>Solanum lycopersicum</i>	SICPK28	Agrobacterium-Mediated
Heat tolerance	<i>Solanum lycopersicum</i>	SIMAPK3	Agrobacterium-Mediated
Cold tolerance	<i>Solanum lycopersicum</i>	SICBF1	Agrobacterium-Mediated

Conclusion

Climate change is an ongoing process that has been noticeable in the agricultural sector in recent years, with a lasting impact on crop yield. Because vegetable crops have many different growing seasons and harsh weather has a significant impact on agricultural yields and output, they are especially vulnerable to the effects of climate change. Knowing how temperature variations impact vegetable crops is the first step in developing practical adaptation strategies to lessen the adverse consequences of climate change. However, more focus should be given to developing heat- and drought-resistant crops, where crop physiology and design may be genetically altered to adapt to warmer environmental conditions, in addition to developing such technologies that fully utilise and mitigate climate change.

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Soil organic matter: The hidden key stone of soil health, climate resilience and microbial networks



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Abstract

Soil organic matter (SOM) is a critical determinant of soil functioning, agricultural productivity, and climate resilience. Despite constituting a small fraction of mineral soils, SOM regulates essential physical, chemical, and biological processes, including nutrient cycling, aggregate formation, water retention, and microbial activity. Contemporary understanding conceptualizes SOM as a dynamic continuum comprising particulate organic matter (POM), mineral-associated organic matter (MAOM), dissolved organic compounds, microbial biomass, and necromass. Among these fractions, MAOM and microbial necromass represent the primary long-term carbon reservoirs due to their strong organo-mineral associations and physico-chemical protection. SOM also serves as a major terrestrial carbon sink, storing more carbon than the atmosphere and vegetation combined, thereby playing a pivotal role in climate change mitigation. However, intensive cultivation has accelerated SOM depletion and weakened soil resilience. Enhancing soil organic carbon requires integrative strategies such as organic amendments, residue retention, green manuring, cover cropping, conservation tillage, agroforestry, balanced nutrient management, and soil–water conservation measures. Strengthening SOM is therefore fundamental for sustainable soil management, improved agricultural productivity, and long-term ecosystem stability.

Key words: Mineral associated organic matter[MAOM], carbon sequestration, microbial necromass, soil aggregation, resilience

Soil organic matter (SOM) forms the fundamental basis of soil fertility, biological activity, and biogeochemical cycling. It is defined as the heterogeneous mixture of plant and animal residues at various stages of decomposition, microbial biomass, and humified compounds intimately associated with mineral particles. Although SOM typically constitutes only 1–5% of the mass of mineral soils, it controls a disproportionate range of physical, chemical, and biological processes that determine soil health and ecosystem functioning (Brady & Weil, 2016). Soil organic matter also acts as a sink for sequestration of carbon dioxide. This helps in the stabilization of global temperatures amid rising concerns of global warming. It also harbours a varied diversity of microbes – “The Mother entity of the soil” many of them being still unknown to the World and thus serves as a COMPLETE FOOD for plants enhancing soil fertility.

Composition and functional pools of soil organic matter (SOM)

The major sources of SOM include fallen leaves, twigs, tree stalks, roots of trees, shrubs, harvested residues, animal excreta, dead organisms, etc. Soil organic matter (SOM) is a heterogeneous matrix comprising particulate organic matter (POM), mineral-associated organic matter (MAOM), dissolved organic matter (DOM), microbial biomass, necromass, and humified fractions. Modern SOM science increasingly emphasizes that SOM is not a static humus pool, but a continuum of compounds undergoing constant biochemical transformation (Lehmann & Kleber, 2019).

POM represents relatively undecomposed plant residues and is highly sensitive to management practices such as tillage, residue return, and cropping intensity. MAOM, by contrast, forms through adsorption of microbially processed organic molecules to silt-and clay- sized minerals, and is now recognized as the dominant long-term carbon sink in most soils (Cot Rufo et al., 2023).

What is MAOM?

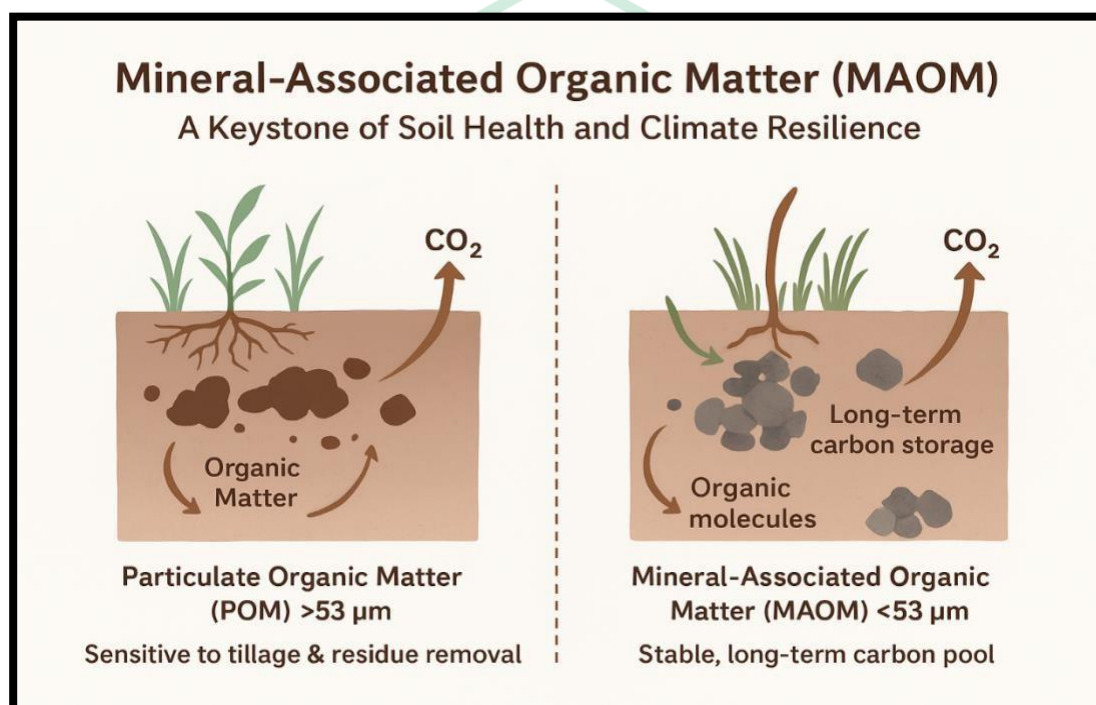
- Stable fraction of soil organic carbon (SOC)
- Organic matter tightly bound to clay, silt, and metaloxides
- Long residence time: decades to centuries

How is MAOM formed?

- Plant residues and root exudates → decomposed by soil microbes
- Microbial biomass grows and dies → microbial necromass
- Necromass binds to mineral surfaces → MAOM

Why is MAOM important?

- Main driver of long-term SOC storage
- Resistant to rapid decomposition
- Enhances soil fertility and nutrient retention
- Contributes to climate change mitigation by sequestering CO₂



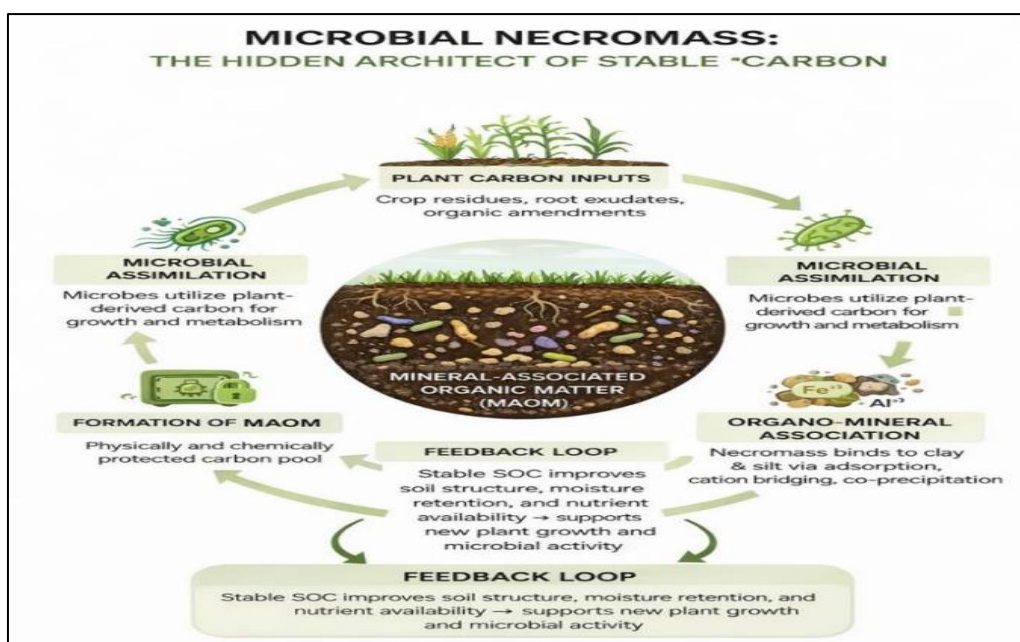
Microbial necromass: The hidden architect of stable soil carbon

Microbial necromass comprising the dead microbial cells and their biochemical residues such as amino sugars, peptides, lipids, and cell-wall polymers has emerged as a central component of long-term soil organic carbon (SOC) stabilization. Contrary to the earlier belief that plant residues are the primary precursors of stable SOM, contemporary research demonstrates that microbial-derived carbon contributes disproportionately to mineral-associated organic matter (MAOM). Following microbial turn over, necromass compounds undergo physico-chemical protection through adsorption to clay and silt surfaces, occlusion within soil aggregates, and co-precipitation with polyvalent metal ions such as Fe³⁺ and Al³⁺. These stabilization mechanisms significantly reduce microbial accessibility and enzymatic degradation, enabling microbial necromass to persist in soils for decades to centuries. As a result, microbial necromass is now recognized as the principal building block of stable SOM and a critical driver of long-term carbon sequestration, particularly under conservation-oriented management systems. Thus, soil microorganisms not only regulate short-term nutrient cycling but also function

as the unseen engineers of climate- resilient soils by converting labile plant carbon into persistent mineral-associated carbon pools.

Table 1: Functional advantages of soil organic carbon (SOC) –Processes and Evidence

Soil Function	SOC- Driven Mechanism	Scientifically observed effects/facts
Aggregate formation	Polysaccharides, microbial exudates, and fungal hyphae act as binding agents	SOC increases mean weight diameter (MWD) of aggregates by 20–50%; stable aggregates reduce erosion and SOC mineralization
Bulk density regulation	Organic matter lowers soil particle packing density	Each 1% increase in SOC can reduce bulk density by $\sim 0.05\text{--}0.15 \text{ Mg m}^{-3}$, improving root penetration
Water holding capacity	SOC increases micro porosity and hydrophilic functional groups	1% SOC increase enhances available water capacity by $\sim 1.5\text{--}2.5 \text{ mm}$ per 10 cm soil depth
Infiltration	Improved aggregation and pore continuity	SOC-rich soils show 2–6 times higher infiltration rates than degraded soils
CEC	Carboxyl and phenolic functional groups provide negative charges	SOC contributes 20–70% of total CEC in tropical soils, exceeding clay contribution in many cases
Nutrient reservoir	SOC stores organically bound N, P, and S	$\sim 95\%$ of soil N and 20–80% of soil P are organically bound and released through mineralization
Nutrient use efficiency	Synchronization of nutrient release with crop demand	Higher SOC improves fertilizer N recovery efficiency by 10–25%
Microbial biomass	SOC supplies energy substrates for microbes	Microbial biomass carbon (MBC) constitutes $\sim 1\text{--}5\%$ of total SOC and regulates nutrient cycling
Carbon stabilization (MAOM)	Microbial necromass sorbs to clay and Fe–Al oxides	MAOM accounts for 50–80% of total SOC in fine-textured soils
SOC residence time	Mineral association and aggregate occlusion	MAOM residence time ranges from decades to centuries; POM turns over in months to years
Green house gas regulation	SOC improves aeration, moisture balance, and nutrient synchrony	Improves SOC, reduces N_2O emissions by improving N use efficiency and Lowers CO_2 flux per unit yield
Thermal buffering	High SOC moderates soil temperature fluctuations	SOC- rich soils show $2\text{--}4^\circ\text{C}$ lower diurnal temperature variation in root zone
Erosion resistance	Stable aggregates resist detachment	SOC- rich soils reduce sediment loss by up to 50–70%
Climate resilience	SOC improves water, nutrient, and structural buffering	SOC- rich soils maintain yield stability under drought and extreme rainfall events
Long-term sustainability	Formation of stable SOC pools (MAOM)	Sustained SOC prevents land degradation and supports climate-smart agriculture



Strategies for Enhancing Soil Organic Carbon:

Increasing Biomass-Derived Carbon Inputs

- Green Manuring
- Crop rotation & agroforestry

Promoting root mediated carbon deposition

- Mycorrhizal hyphal growth and decay

Enhancing microbial carbon use efficiency

- Balanced application of nitrogen, phosphorus and potassium

Minimizing SOC losses through reduced disturbance

- Conservation agriculture
- Reduced tillage

Building resilient agro-ecosystems therefore requires management strategies that enhance not only carbon inputs, but also the biological and physico-chemical pathways that stabilize carbon over the long term. Strengthening SOM is thus not merely a soil management objective; it is a cornerstone of sustainable agriculture and climate-smart ecosystem. Thus, **“Take care of the soil, the soil will take care of the plant”**.

“Managing soils for stable organic carbon is not an option any more, it is the foundation of productive, resilient, and climate-smart agriculture.”

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Silent Signals beneath the Water: Understanding Fish Behaviour in Changing Environments



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Abstract

Fish behavior serves as an important biological indicator of environmental health and aquatic ecosystem stability. Environmental factors such as water quality, temperature, dissolved oxygen, pollutants, and toxic substances significantly influence fish physiology and behavioural activities. Alterations in swimming, feeding, schooling, migration, and reproductive behaviour often indicate ecological stress and environmental imbalance. Behavioural responses are widely used in aquatic toxicology and environmental monitoring because they provide rapid and sensitive indicators of pollution. This chapter highlights the relationship between fish behaviour and environmental changes, the impact of pollutants on aquatic organisms, and the importance of behavioral studies in ecosystem conservation and sustainable environmental management.

Keywords: Fish behavior, Aquatic ecosystem, Environmental stress, Bioindicators, Aquatic toxicology, Water pollution

1. Introduction

Water is one of the most essential natural resources supporting life on Earth. Aquatic ecosystems such as rivers, ponds, lakes, reservoirs, wetlands, and oceans provide habitat for a wide diversity of organisms. Among aquatic organisms, fishes play an important role in maintaining ecological balance and supporting fisheries, biodiversity, and food security. Fish behaviour is closely connected with environmental conditions. Any change in water quality or habitat directly influences fish physiology, metabolism, and behavioural activities. Fish exhibit various behavioural responses including swimming, feeding, schooling, migration, predator avoidance, and reproduction, all of which are essential for their survival. In recent decades, increasing industrialization, urbanization, agricultural runoff, and environmental pollution have significantly affected aquatic ecosystems. Toxic substances entering water bodies can disturb normal fish behaviour and may ultimately threaten aquatic biodiversity. Therefore, behavioural studies in fishes are considered important tools for understanding environmental stress and ecosystem health.

2. Fish Behaviour and Its Importance

Behaviour refers to the response of an organism to internal and external environmental stimuli. In fishes, behavior helps them adapt to changing environmental conditions and ensures survival in aquatic habitats.

Fish behavior can be categorized into several types:

2.1 Swimming Behaviour

Swimming behavior reflects the general health and physiological condition of fishes. Healthy fishes exhibit smooth, coordinated, and active swimming patterns. Environmental stress may cause erratic swimming, hyperactivity, or loss of balance.

2.2 Feeding Behaviour

Feeding activity is highly sensitive to water quality and environmental disturbances. Pollutants and toxic substances may reduce appetite and feeding efficiency.

2.3 Schooling Behaviour

Many fish species swim in groups called schools. Schooling behavior provides protection from predators and improves feeding efficiency. Disturbance in schooling patterns may indicate environmental stress.

2.4 Reproductive Behaviour

Environmental factors such as temperature, photoperiod, and water quality regulate fish reproductive activities. Pollution can adversely affect breeding behavior and reproductive success.

3. Environmental Factors Influencing Fish Behaviour

Several physical, chemical, and biological factors influence fish behaviour.

3.1 Temperature

Temperature controls fish metabolism, respiration, growth, and reproduction. Sudden temperature fluctuations may induce stress and alter behavioral responses.

3.2 Dissolved Oxygen

Oxygen is essential for fish survival. Low dissolved oxygen levels force fishes to come near the water surface and increase opercular movement.

3.3 Water Pollution

Industrial discharge, agricultural chemicals, sewage, pesticides, heavy metals, and plastic waste are major sources of aquatic pollution. These pollutants can interfere with nervous coordination and physiological processes in fishes.

3.4 pH and Salinity

Changes in pH and salinity affect osmoregulation and physiological balance, leading to behavioral and metabolic disturbances.

3.5 Anthropogenic Activities

Anthropogenic activities refer to human-induced actions that significantly affect aquatic ecosystems and fish behavior. Rapid industrialization, urbanization, deforestation, agricultural expansion, mining, dam construction, sewage disposal, and excessive use of pesticides and fertilizers have resulted in severe degradation of freshwater habitats.

Industrial effluents and domestic wastewater introduce toxic chemicals, heavy metals, and organic pollutants into water bodies, altering water quality and disturbing fish physiology and behaviour. Agricultural runoff containing fertilizers and pesticides often causes eutrophication and oxygen depletion, leading to stress responses in fishes.

Overfishing, habitat destruction, plastic pollution, and climate change further contribute to ecological imbalance in aquatic ecosystems. These anthropogenic disturbances may induce abnormal behavioural responses such as erratic swimming, reduced feeding activity, altered migration patterns, impaired reproduction, and increased stress in fishes.

Understanding the impact of anthropogenic activities on fish behaviour is essential for environmental conservation, sustainable resource management, and protection of aquatic biodiversity.

4. Behavioural Responses as Indicators of Environmental Stress

Fish behavioral responses are considered among the earliest and most sensitive indicators of environmental stress and aquatic toxicity. Behavioural alterations generally appear before visible anatomical or physiological damage becomes evident, making behavioral studies highly valuable in aquatic toxicology and environmental monitoring. Even exposure to low concentrations of pollutants can significantly affect the nervous system, metabolism, respiration, and endocrine activities of fishes, resulting in noticeable changes in normal behavioral patterns.

Environmental stressors such as industrial effluents, pesticides, heavy metals, sewage discharge, agricultural runoff, nanoparticles, and other toxic contaminants interfere with the normal physiological functioning of fishes. Since behavior is directly regulated by the nervous and hormonal systems, fishes rapidly respond to environmental disturbances through modifications in swimming activity, feeding behavior, schooling patterns, respiration, and reproductive activities.

One of the most common stress responses observed in fishes is erratic swimming behavior. Under toxic conditions, fishes often exhibit irregular and uncontrolled swimming movements, sudden jerks, rapid darting, or circular swimming patterns. These abnormal movements indicate neurological disturbances and loss of muscular coordination caused by toxic substances.

Hyperactivity is another important behavioral response observed during the initial stages of stress exposure. Fishes may display excessive swimming activity, increased opercular movement, and frequent movement near the water surface. Hyperactivity generally occurs as an immediate response to irritation or toxic exposure and may represent an attempt to escape from unfavorable environmental conditions.

Pollutant exposure also significantly affects feeding behavior. Stressed fishes often show reduced appetite, irregular feeding patterns, or complete cessation of feeding activity. This reduction in feeding behavior may lead to poor growth, weakened immunity, and decreased survival under prolonged exposure conditions.

Another commonly observed behavioral abnormality is surfacing behavior, in which fishes frequently come near the water surface for oxygen intake. This behavior is generally associated with reduced dissolved oxygen levels, respiratory distress, or damage to gill tissues caused by pollutants. Increased surfacing activity indicates physiological stress and impaired respiratory efficiency.

Under severe toxic stress, fishes may exhibit loss of equilibrium and lethargy. Affected fishes often become weak, inactive, and unable to maintain normal body balance. They may remain motionless near the bottom or corners of aquaria and show reduced response to external stimuli. Such symptoms indicate advanced physiological disturbances and metabolic imbalance.

Environmental stress also affects schooling behavior, which is essential for protection, feeding, and social interaction in many fish species. Pollutant exposure may disturb coordinated group movement and increase isolation or abnormal aggregation among fishes. Alteration in schooling behavior reflects impairment of sensory perception and nervous coordination.

Behavioural responses provide rapid and reliable information regarding aquatic pollution and ecosystem health. Since these responses occur earlier than many physiological and histological changes, behavioral studies are widely used in environmental risk assessment and eco-toxicological investigations. Continuous monitoring of fish behavior can therefore serve as an effective tool for detecting environmental disturbances and protecting aquatic biodiversity.

5. Fish as Bioindicators

Fishes are widely recognized as effective bioindicators of aquatic ecosystem health because they are highly sensitive to environmental changes and pollutants. Their physiological and behavioral responses provide valuable information regarding the quality and stability of aquatic environments. Since fishes occupy different trophic levels and interact continuously with their surroundings through respiration, feeding, and reproduction, they readily respond to variations in water quality and environmental stress.

Aquatic pollutants such as pesticides, heavy metals, industrial effluents, sewage discharge, pharmaceuticals, plastics, and nanoparticles can significantly alter fish physiology and behaviour. Changes in behavioural patterns often occur rapidly after exposure to contaminants, making fishes reliable organisms for environmental monitoring and eco-toxicological studies.

Several fish species including zebrafish (*Danio rerio*), carp (*Cyprinus carpio*), tilapia (*Oreochromis* sp.), and *Puntius* species are commonly used as experimental models in aquatic toxicology research. These species are preferred because of their sensitivity to pollutants, ease of maintenance under laboratory conditions, rapid adaptation, and well-understood behavioral responses.

Fish behavioral studies help scientists evaluate multiple environmental parameters and ecological disturbances. One of the primary applications is the assessment of water quality. Alterations in fish behavior such as abnormal swimming, reduced feeding, or increased surfacing activity often indicate deterioration in water quality caused by contamination or oxygen depletion.

Behavioural analysis also assists in determining pollution levels in aquatic ecosystems. Exposure to toxic substances may disrupt nervous coordination, metabolism, respiration, and endocrine functions in fishes. Monitoring behavioral abnormalities provides early evidence of environmental contamination before severe ecological damage occurs.

Another important application is the evaluation of chemical toxicity. Behavioural studies help identify the toxic effects of pesticides, heavy metals, industrial chemicals, pharmaceuticals, and emerging pollutants on aquatic organisms. Since behavioral responses appear rapidly, they are considered highly sensitive endpoints in toxicity assessment.

Fish behavior additionally reflects ecological disturbances such as habitat destruction, climate change, thermal stress, eutrophication, and anthropogenic activities. Disturbances in migration, schooling, feeding, and reproductive behaviour may indicate disruption of ecological balance within aquatic ecosystems.

Behavioural studies also contribute to understanding environmental sustainability by helping researchers and policymakers assess the long-term impact of human activities on aquatic biodiversity and ecosystem functioning. Monitoring behavioral responses supports the development of sustainable conservation strategies and pollution control measures.

Behavioural monitoring is considered a rapid, reliable, economical, and non-invasive method for assessing aquatic ecosystem health. Unlike complex biochemical or molecular analyses, behavioral observations can often be performed with minimal equipment and provide immediate information regarding environmental stress. Therefore, fish behavioral studies have become an important component of modern aquatic toxicology, environmental monitoring, biodiversity conservation, and ecological risk assessment.

6. Impact of Emerging Pollutants

Modern industrial and technological developments have introduced new pollutants into aquatic ecosystems. Emerging contaminants such as nanoparticles, pharmaceuticals, pesticides, and microplastics pose serious threats to aquatic organisms. Nanoparticles possess unique physicochemical properties due to their extremely small size and high surface reactivity. Exposure to nanoparticles may alter fish behaviour, chromatophore activity, respiration, and physiological processes. Continuous exposure to emerging pollutants may affect fish growth, immunity, reproduction, and survival, thereby influencing aquatic biodiversity and ecosystem stability.

7. Role of Behavioural Studies in Conservation

Behavioural studies play a significant role in aquatic conservation and environmental management because they provide valuable information regarding the health and stability of aquatic ecosystems. Fishes respond rapidly to environmental changes, and even minor disturbances in water quality or habitat conditions can alter their normal behavioural patterns. Therefore, continuous monitoring of fish behaviour helps researchers identify ecological disturbances at an early stage before severe physiological damage or large-scale biodiversity loss occurs.

Environmental degradation caused by pollution, habitat destruction, climate change, industrialization, and unsustainable human activities has become a major threat to aquatic ecosystems worldwide. Behavioural alterations in fishes such as abnormal swimming, reduced feeding, loss of equilibrium, disturbed schooling behaviour, and altered reproductive activities often indicate ecological stress and declining environmental quality. Early detection of these behavioural changes allows scientists and environmental agencies to implement corrective measures and minimize further ecological damage.

One of the most important conservation strategies is the reduction of water pollution. Industrial discharge, domestic sewage, pesticides, fertilizers, heavy metals, plastics, and toxic chemicals contaminate freshwater ecosystems and negatively affect aquatic organisms. Controlling the release of pollutants into water bodies is essential for maintaining healthy aquatic environments.

The adoption of sustainable agricultural practices is also crucial for aquatic conservation. Excessive use of chemical fertilizers and pesticides leads to agricultural runoff, eutrophication, and contamination of rivers, lakes, and ponds. Environment-friendly farming methods, organic agriculture, and controlled use of agrochemicals can significantly reduce environmental stress on aquatic ecosystems.

Proper waste disposal and management help prevent accumulation of harmful substances in aquatic habitats. Untreated solid waste and sewage disposal into water bodies increase organic pollution and reduce water quality. Efficient waste management systems are therefore necessary for protecting aquatic biodiversity.

Another important conservation measure is industrial effluent treatment. Industries often release untreated chemical wastes and toxic effluents into nearby rivers and lakes, causing severe ecological damage. Installation of proper wastewater treatment plants and strict environmental regulations can reduce aquatic pollution and improve ecosystem health.

The protection of natural water bodies and aquatic habitats is equally important for sustaining fish diversity and ecological balance. Wetlands, rivers, ponds, lakes, and mangrove ecosystems serve as breeding and feeding grounds for numerous aquatic species. Habitat destruction through urbanization, mining, deforestation, and dam construction disrupts aquatic biodiversity and ecosystem functioning.

Public awareness and environmental education play an essential role in aquatic conservation. Educating communities about the importance of clean water, pollution control, biodiversity conservation, and sustainable

resource utilization encourages environmentally responsible behaviour and community participation in conservation programs.

Conservation of aquatic ecosystems is essential for maintaining biodiversity, ecological balance, fisheries productivity, and long-term environmental sustainability. Healthy aquatic environments support not only fishes and aquatic organisms but also human livelihoods, agriculture, and overall ecosystem functioning.

Therefore, behavioural studies serve as valuable scientific tools for environmental monitoring, conservation planning, and sustainable management of aquatic resources.

8. Future Scope

Future research on fish behavior and environmental stress can contribute significantly to aquatic conservation, environmental monitoring, and sustainable ecosystem management. Advanced behavioral studies combined with modern technologies such as artificial intelligence, biosensors, image analysis, and molecular tools may improve the accuracy of aquatic toxicity assessment and environmental risk evaluation.

Emerging pollutants including nanoparticles, microplastics, pharmaceuticals, pesticides, and industrial chemicals require detailed investigation regarding their long-term effects on fish physiology and behavior. Behavioural biomarkers may serve as effective early warning indicators for detecting aquatic contamination and ecological disturbances.

Climate change and increasing anthropogenic activities are continuously altering freshwater ecosystems. Therefore, future studies should focus on understanding the combined effects of temperature fluctuations, oxygen depletion, habitat degradation, and pollution on fish behavioral responses and biodiversity.

There is also a growing need to develop eco-friendly and sustainable environmental management strategies for protecting aquatic ecosystems. Public participation, environmental education, and scientific awareness programs can play an important role in promoting aquatic conservation and reducing environmental degradation. Further interdisciplinary research integrating zoology, environmental science, toxicology, biotechnology, and ecology will help in developing innovative approaches for monitoring aquatic ecosystem health and conserving biodiversity for future generations.

9. Conclusion

Fish behavior reflects the overall condition of aquatic ecosystems and serves as a sensitive indicator of environmental health. Environmental changes and pollution significantly influence fish physiology and behavioral activities. Behavioural responses such as altered swimming, feeding disturbances, and abnormal schooling patterns provide valuable information regarding aquatic toxicity and ecological imbalance.

Understanding fish behavior is essential for aquatic toxicology, environmental monitoring, biodiversity conservation, and sustainable ecosystem management. Protecting aquatic environments from pollution and ecological degradation is necessary for preserving aquatic biodiversity and ensuring environmental sustainability. Fish silently communicate the condition of their environment through their behavior. Careful observation and scientific understanding of these silent signals can guide society toward a healthier and more sustainable future.

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Organic Intensification: New Dimensions in Sustainable Crop Management



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Abstract

Organic intensification has emerged as an innovative and sustainable approach for enhancing agricultural productivity while conserving natural resources and environmental quality. It integrates ecological principles, biological nutrient cycling and modern scientific technologies to achieve higher crop productivity with reduced dependence on synthetic agrochemicals. Practices such as integrated nutrient management, crop diversification, biofertilizer application, conservation agriculture and carbon farming play a significant role in improving soil health, nutrient-use efficiency and climate resilience. Recent advancements in precision agriculture, artificial intelligence, nano-biofertilizers and plant biostimulants have further expanded the scope of organic intensification in modern crop management. Studies indicate that organically intensified systems improve soil organic carbon, microbial activity, water-use efficiency and long-term sustainability while reducing greenhouse gas emissions and environmental pollution. Despite challenges such as limited availability of organic inputs and transitional yield instability, organic intensification offers a promising pathway toward resilient, regenerative and climate-smart agriculture. Therefore, adoption of scientifically managed organic intensification practices can significantly contribute to sustainable food security and environmental conservation in the future.

Keywords: Organic intensification; Sustainable agriculture; Climate- Regenerative agriculture.

Introduction

Modern agriculture is currently facing the challenge of increasing food production while maintaining environmental sustainability and conserving natural resources. The excessive use of synthetic fertilizers, pesticides and intensive cultivation practices during the Green Revolution significantly enhanced crop productivity; however, it also caused soil degradation, nutrient imbalance, groundwater pollution and biodiversity loss. In this context, *organic intensification* has emerged as a promising approach for sustainable crop management.

Organic intensification refers to increasing agricultural productivity through ecological processes, biological nutrient cycling and efficient use of organic resources while minimizing dependence on synthetic agrochemicals. It combines traditional organic farming principles with modern scientific innovations to improve productivity, soil health and environmental quality simultaneously. According to the latest global organic agriculture statistics, more than 96 million hectares of land worldwide are under organic farming, indicating the growing importance of sustainable agricultural systems (Willer *et al.*, 2024).

Organic intensification is gaining importance under climate change scenarios because it improves soil resilience, resource-use efficiency and ecosystem stability. It is increasingly associated with concepts such as regenerative agriculture, carbon farming, climate-smart agriculture and precision organic farming.

Scientific Basis of Organic Intensification

Soil Health Improvement

Soil health is the foundation of sustainable agriculture. Organic intensification emphasizes the use of farmyard manure (FYM), vermicompost, green manures, crop residues and biofertilizers to enhance soil organic matter and microbial activity. Organic amendments improve soil structure, aggregation, water-holding capacity and nutrient availability.

Research has shown that organically managed soils possess 20–30% higher microbial biomass and greater soil organic carbon compared to conventionally managed systems (Krause *et al.*, 2024). Increased soil organic carbon enhances nutrient retention, reduces soil erosion and improves crop resilience under drought conditions.

Biological Nutrient Cycling

Organic intensification promotes efficient nutrient recycling through biological processes. Leguminous crops contribute significant amounts of biologically fixed nitrogen, while biofertilizers such as *Rhizobium*, *Azotobacter*, phosphate-solubilizing bacteria (PSB) and mycorrhizae enhance nutrient availability and nutrient-use efficiency. Integrated application of organic manures and microbial inoculants has been reported to improve nitrogen-use efficiency by 25–35% compared with sole chemical fertilization (Zheng *et al.*, 2024). Such practices reduce nutrient losses through leaching and volatilization while maintaining long-term soil fertility.

Emerging Dimensions of Organic Intensification

Precision Organic Farming

The integration of digital technologies into organic agriculture has opened new dimensions in sustainable crop management. Precision farming tools such as remote sensing, drones, GIS, IoT sensors and artificial intelligence (AI) help monitor crop growth, nutrient status and soil moisture variability in real time.

AI-based systems can optimize irrigation scheduling, nutrient application and pest management while reducing resource wastage and environmental pollution (Wang *et al.*, 2024). This technological integration is transforming traditional organic agriculture into a more knowledge-intensive and efficient farming system.

Carbon Farming and Regenerative Agriculture

Carbon farming is an emerging component of organic intensification that focuses on increasing soil carbon sequestration through conservation tillage, cover cropping, residue recycling and agroforestry. These practices improve soil fertility while mitigating greenhouse gas emissions.

Studies have indicated that conservation-based organic systems significantly enhance ecosystem resilience and climate adaptation capacity (Ellis and Paustian, 2024). Organic farming systems also reduce nitrous oxide emissions due to lower synthetic nitrogen fertilizer use.

Nano-Bio Inputs and Biostimulants

Recent advancements in nanotechnology and biological inputs are further strengthening organic intensification. Nano-biofertilizers improve nutrient delivery efficiency and reduce nutrient losses through controlled nutrient release mechanisms. Similarly, plant biostimulants such as seaweed extracts, humic substances and microbial consortia enhance root growth, nutrient uptake and abiotic stress tolerance.

Application of biostimulants has shown yield improvement of nearly 10–25% in several crops under stress conditions. These technologies provide environmentally safe alternatives to conventional agrochemicals.

Impact on Crop Productivity and Sustainability

One of the major criticisms of organic farming has been reduced productivity; however, recent scientific evidence suggests that properly managed organic intensification systems can achieve competitive yields while improving environmental sustainability.

Integrated nutrient management involving vermicompost, FYM and biofertilizers has shown substantial improvement in grain yield, biological yield and nutrient uptake in cereal crops. Organic residue management also improves water-use efficiency by 15–20%, especially in arid and semi-arid regions.

Organic intensification improves agricultural sustainability through:

- Enhanced soil fertility and microbial activity
- Better water conservation
- Reduced chemical pollution
- Improved biodiversity
- Increased climate resilience
- Lower greenhouse gas emissions

Krause *et al.* (2024) reported that organic cropping systems effectively balance agricultural productivity with environmental sustainability, making them highly suitable for future climate-resilient agriculture.

Challenges and Future Prospects

Despite its advantages, organic intensification faces several challenges including limited availability of quality organic inputs, higher labor requirements, certification constraints and lack of scientific awareness among farmers. Yield reduction during the transition period from conventional to organic farming also discourages adoption in some regions.

Future research should focus on:

- Development of efficient biofertilizers and nano-inputs
- AI-based precision organic farming systems
- Region-specific organic nutrient management models
- Climate-resilient organic cropping systems
- Digital advisory and decision-support tools

Integration of ecological principles with advanced technologies such as artificial intelligence, remote sensing and nanotechnology will play a major role in strengthening sustainable agriculture in the coming decades.

Conclusion

Organic intensification represents a transformative approach toward sustainable crop management by integrating ecological processes with modern scientific innovations. It improves soil health, enhances nutrient-use efficiency, conserves natural resources and reduces environmental degradation while maintaining crop productivity. Emerging technologies such as precision farming, carbon farming, nano-biofertilizers and biostimulants are expanding the scope and efficiency of organic agriculture.

In the era of climate change and resource scarcity, organic intensification offers a practical pathway for achieving sustainable agricultural development, food security and environmental conservation simultaneously. Therefore, adoption of scientifically managed organic intensification practices can significantly contribute toward resilient and regenerative agricultural systems for the future.

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“Role of Startups in Transforming Indian Agriculture”



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Introduction

Agriculture is the backbone of the Indian economy and plays a vital role in ensuring food security, employment generation and rural development. A large proportion of India's population still depends directly or indirectly on agriculture for their livelihood. Despite its importance, the agricultural sector faces several challenges such as low productivity, fragmented landholdings, inadequate market access, post-harvest losses, lack of modern technology and fluctuating market prices. These issues often reduce farmers' income and limit the growth of the sector.

In recent years, agricultural startups have emerged as a powerful force in transforming Indian agriculture. The integration of technology, innovation and entrepreneurship into agriculture has opened new opportunities for farmers and agribusinesses. Agri-startups are introducing modern solutions such as digital platforms, precision farming, smart irrigation systems, supply chain management, online marketplaces and financial services. These innovations are helping farmers improve productivity, reduce costs and gain better access to markets. India has witnessed rapid growth in the startup ecosystem, including the agricultural sector. Government initiatives such as Startup India, Digital India and various agricultural development schemes have encouraged young entrepreneurs to enter agribusiness. Today, agri-startups are playing a significant role in modernizing agriculture and making it more sustainable, profitable and technology-driven.



Fig. 1: Technology-driven agriculture is transforming traditional farming practices in India

Emergence of Agri-Startups in India

The rise of agri-startups in India is closely linked to the increasing adoption of digital technologies and the growing interest of youth in entrepreneurship. Traditional agricultural practices are gradually being replaced by data-driven and technology-oriented approaches. Young entrepreneurs are identifying the problems faced by farmers and developing innovative business models to address them.

India has become one of the fastest-growing hubs for agri-startups. The availability of smartphones, internet connectivity, digital payment systems, and government support has accelerated the growth of agricultural enterprises. Agri-startups are working in various fields such as farm input delivery, precision agriculture, food processing, supply chain management, organic farming, agricultural finance and market intelligence.

These startups are bridging the gap between farmers and markets by providing real-time information, better pricing mechanisms and direct market access. They are also creating employment opportunities in rural areas and promoting inclusive agricultural growth.

Major Roles of Startups in Transforming Agriculture

1. Technological Advancement in Farming

Agri-startups are introducing modern technologies that help farmers improve productivity and efficiency. Technologies such as drones, artificial intelligence, remote sensing and Internet of Things (IoT) are being used for crop monitoring, soil testing, weather forecasting and pest management. Precision farming techniques enable farmers to use water, fertilizers and pesticides more efficiently, thereby reducing production costs and environmental damage.

Smart irrigation systems and mobile-based advisory services are also helping farmers make informed decisions regarding crop management. These innovations increase agricultural productivity and support sustainable farming practices.

2. Improving Market Access

One of the major problems faced by farmers is the lack of direct access to markets. Middlemen often reduce farmers' profit margins. Agri-startups are solving this issue through digital marketplaces and online trading platforms that connect farmers directly with buyers, retailers and consumers.

Startups such as Ninjacart and DeHaat have developed efficient supply chain systems that help farmers sell their produce at fair prices. These platforms reduce marketing costs, minimize wastage and ensure timely delivery of products.

3. Providing Quality Farm Inputs

Many startups provide high-quality seeds, fertilizers, pesticides and agricultural machinery directly to farmers through online and offline platforms. This ensures timely availability of farm inputs at reasonable prices. Some startups also offer customized advisory services related to crop selection, nutrient management and disease control.

Companies like AgroStar are helping farmers access agricultural inputs and expert guidance through digital applications. Such services improve crop productivity and enhance farmers' income.

4. Financial Inclusion and Credit Support

Lack of access to institutional credit remains a major challenge for small and marginal farmers. Agri-startups are collaborating with banks and financial institutions to provide easier access to loans, crop insurance and digital payment solutions. Fintech innovations are helping farmers receive financial assistance with minimal paperwork and faster processing.

Digital platforms also help farmers maintain records of transactions and improve financial transparency. This contributes to the overall development of rural economies.

5. Reducing Post-Harvest Losses

India faces significant post-harvest losses due to poor storage, transportation, and supply chain infrastructure. Agri-startups are addressing these issues through cold storage facilities, warehouse management, logistics services and efficient transportation systems.

Modern supply chain management reduces wastage and helps maintain product quality. As a result, farmers receive better prices and consumers get fresh agricultural products.

6. Promoting Sustainable Agriculture

Sustainability has become an important aspect of modern agriculture. Many startups are promoting organic farming, climate-smart agriculture and eco-friendly farming practices. They encourage efficient use of natural resources and reduce the environmental impact of agriculture.

Startups working in renewable energy, bio-fertilizers and water conservation are contributing towards sustainable agricultural development. These initiatives support long-term food security and environmental protection.

Successful Agri-Startups in India

India has several successful agri-startups that are transforming the agricultural sector through innovation and technology.

- DeHaat provides end-to-end agricultural services including farm inputs, advisory services and market linkages.

- Ninjacart has revolutionized the agricultural supply chain by connecting farmers directly with retailers.
- AgroStar offers digital solutions for farm advisory and input delivery.
- BigHaat supports farmers through online agricultural products and expert guidance.

These startups demonstrate how innovation and entrepreneurship can solve agricultural problems and improve rural livelihoods.



Fig. 2: AgriTech platforms connecting farmers directly with markets and retailers

Transforming Agriculture: Key Statistics on the Impact of Agri-Startups in India:

Agri-startups are playing a crucial role in transforming Indian agriculture by introducing digital technologies, improving productivity, strengthening supply chains and increasing farmers' access to markets. The following updated statistics highlight the rapid growth and impact of the AgriTech ecosystem in India:

1. Rapid Growth of Agri-Startups:

India has emerged as one of the world's fastest-growing AgriTech ecosystems, with more than 7,000 Agri startups operating across areas such as precision farming, digital marketplaces, supply chain management, farm advisory and agricultural finance by 2025.

2. Economic Contribution and Farmer Income:

The AgriTech sector has the potential to increase farmers' incomes by 25–35% through improved productivity, reduced input costs, better market access, and lower post-harvest losses. Experts estimate that the sector could contribute nearly \$100 billion to the Indian agricultural economy in the coming years.

3. Increase in Investments:

India's AgriTech sector has attracted approximately \$2.5–2.6 billion in investments since FY2022, reflecting strong investor confidence in agricultural innovation and digital transformation. Venture capital funding continues to support emerging agribusiness solutions and rural entrepreneurship.

4. Impact on Agricultural Productivity:

Technologies such as artificial intelligence, drones, IoT sensors and precision farming tools are helping farmers improve crop management and resource efficiency. Studies indicate that precision agriculture technologies can enhance crop yields by up to 25–30% while promoting sustainable farming practices.

5. Digital Transformation of Agriculture:

Rapid smartphone penetration, internet connectivity and digital platforms have accelerated the adoption of AgriTech solutions across rural India. The COVID-19 pandemic further boosted the use of online marketplaces, digital supply chains and e-commerce platforms for agricultural products.

6. Government Support and Policy Initiatives:

Government initiatives such as Startup India, Digital Agriculture Mission, Agri Infrastructure Fund and the promotion of over 10,000 Farmer Producer Organizations (FPOs) are strengthening the AgriTech ecosystem and improving farmers' access to technology, markets, and financial services.

7. Employment Generation:

The expansion of AgriTech startups is creating significant employment opportunities in rural and semi-urban areas. The startup ecosystem in India has generated millions of direct and indirect jobs, with agribusiness and agritech contributing substantially to rural employment and entrepreneurship development.

8. Future Market Potential:

India's AgriTech market is expected to grow rapidly and may reach nearly \$24–28 billion by 2030, driven by increasing digital adoption, climate-smart agriculture, precision farming and rising demand for efficient food supply systems.

These statistics clearly demonstrate that AgriTech startups are transforming Indian agriculture by improving productivity, enhancing farmers' incomes, encouraging sustainable practices and modernizing the agricultural economy through innovation and technology.

Challenges Faced by Agri-Startups

While Agri-startups hold immense potential, they also face significant challenges in scaling their impact. Some of these hurdles include:

- **Farmer Awareness:** Many farmers are unfamiliar with new technologies, making it essential for startups to invest in education and training to demonstrate the benefits of these solutions.
- **Infrastructure Gaps:** Connectivity, especially in remote rural areas, is often limited, which can hinder the adoption of digital platforms.
- **Regulatory Roadblocks:** Agri-startups must navigate complex regulations and policies in the agricultural sector, which can slow down innovation and growth.
- **Financing and Funding:** While investor interest is growing, many startups still face difficulties in securing funding, particularly for scaling operations and reaching farmers at the grassroots level.

Government Support for Agri-Startups

The Government of India is actively promoting agricultural entrepreneurship through various schemes and initiatives. Programs such as Startup India, Atmanirbhar Bharat, Digital India and the Agri Infrastructure Fund provide financial support, incubation facilities, training and policy assistance to startups.

Institutions like ICAR and MANAGE are also encouraging innovation and agribusiness development through training and incubation programs.

Government support has created a favorable environment for the growth of agri-startups in India.

Future Prospects

The future of agri-startups in India appears highly promising. Increasing digitalization, rising investment in agritech, and growing awareness among farmers are expected to accelerate agricultural transformation. Technologies such as artificial intelligence, blockchain, drone technology and data analytics will further revolutionize the sector.

Agri-startups have the potential to improve farmers' income, generate rural employment, strengthen food supply chains and promote sustainable agriculture. With continuous innovation and policy support, startups can play a major role in achieving agricultural growth and rural prosperity.

Conclusion

Startups are emerging as key drivers of change in Indian agriculture. By integrating technology, innovation, and entrepreneurship into farming systems, agri-startups are addressing many challenges faced by the agricultural sector. They are improving productivity, market access, financial inclusion, supply chain efficiency and sustainability.

The transformation brought by startups is helping Indian agriculture become more modern, efficient, and farmer-friendly. Although challenges still exist, supportive government policies and increasing technological adoption are creating new opportunities for agricultural entrepreneurship. In the coming years, agri-startups are expected to play an even greater role in strengthening the Indian agricultural economy and improving the livelihood of millions of farmers.

Carbon Footprint Reduction in Food Industries



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Introduction

The food industry is one of the most essential sectors in the world because it provides food for millions of people every day. From agricultural production to food processing, packaging, transportation, and storage, every stage of the food chain supports modern society. However, these activities also contribute significantly to greenhouse gas emissions and environmental pollution. A carbon footprint refers to the total amount of greenhouse gases released directly or indirectly through human activities.

In food industries, emissions mainly arise from the use of fossil fuels, electricity, transportation systems, refrigeration units, packaging materials, and food waste disposal. Today, reducing carbon footprint has become a major priority for food industries across the world. Industries are increasingly adopting sustainable technologies and eco-friendly practices not only to protect the environment but also to improve energy efficiency, reduce operational costs, and satisfy consumer demand for environmentally responsible products.

Major Sources of Carbon Emissions in Food Industries

Agricultural Activities

Agriculture is one of the major contributors to greenhouse gas emissions in the food sector. Excessive use of chemical fertilizers and pesticides releases harmful gases into the atmosphere. The use of tractors, irrigation pumps, and farm machinery also increases fuel consumption.

Livestock farming contributes methane emissions because animals such as cattle release methane gas during digestion. Deforestation for agricultural expansion further increases carbon dioxide levels by reducing the number of trees that absorb atmospheric carbon.

Food Processing Operations

Food processing industries consume large amounts of energy for heating, cooling, drying, pasteurization, freezing, and packaging operations. Many industries still depend on fossil fuels such as coal, diesel, and natural gas. Old and inefficient machinery increases electricity consumption and results in higher carbon emissions.

Transportation and Distribution

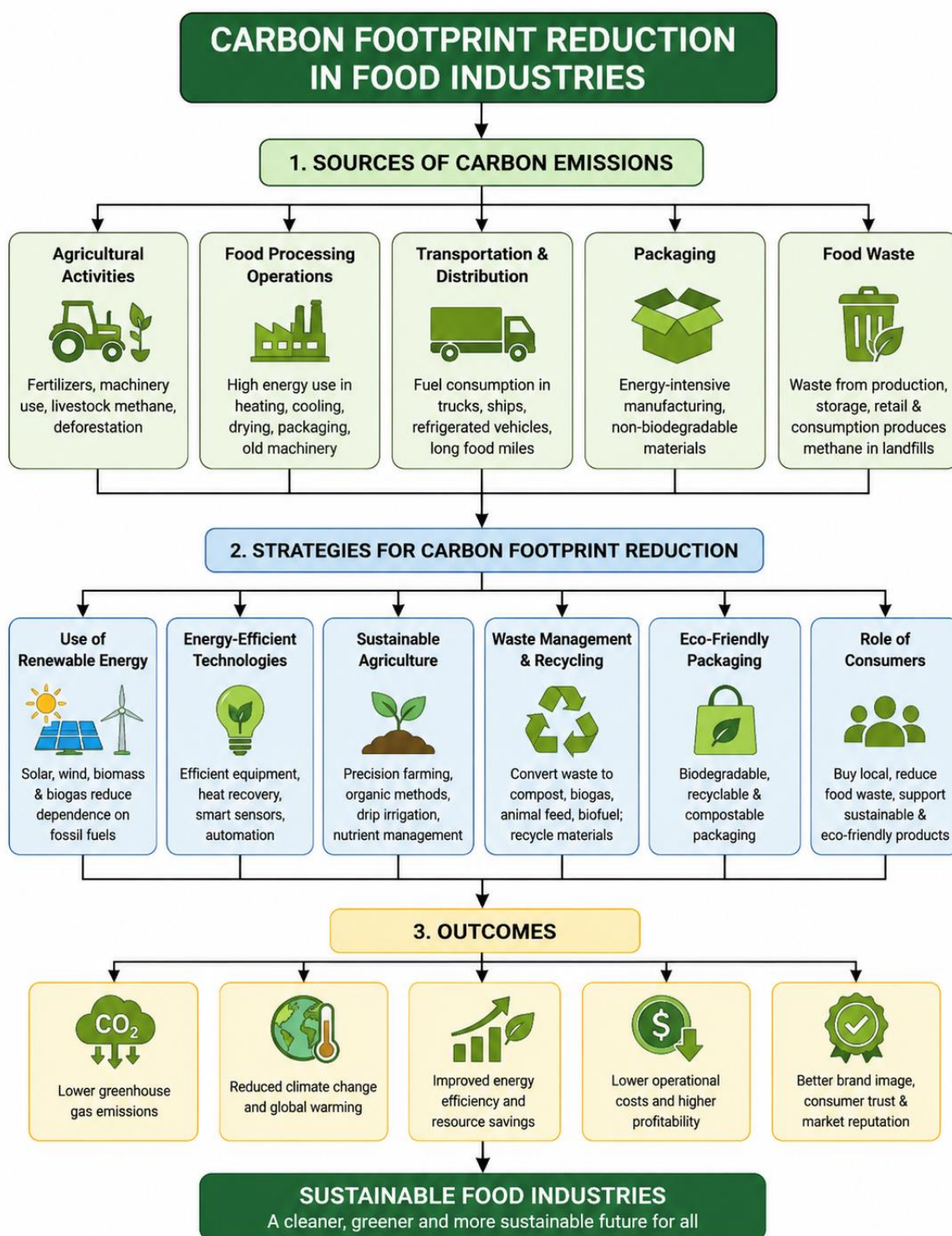
Transportation of raw materials and finished products requires large quantities of fuel. Food products are often transported over long distances through trucks, ships, and refrigerated vehicles. Global trade has significantly increased "food miles," meaning food travels long distances before reaching consumers.

Packaging and Food Waste

Packaging materials such as plastics and aluminum require energy-intensive manufacturing processes. Non-biodegradable packaging also creates environmental pollution. Food waste generated during production, storage, retailing, and consumption contributes to carbon emissions. When food waste decomposes in landfills, it produces methane gas.

Table 1: Major Sources of Carbon Emissions in Food Industries

Source	Main Activities	Environmental Impact
Agriculture	Fertilizer use, machinery operation, livestock farming	Methane and CO ₂ emissions
Food Processing	Heating, cooling, drying, refrigeration	High energy consumption
Transportation	Long-distance movement of food products	Fuel-related emissions
Packaging	Plastic and aluminum production	Resource depletion and pollution
Food Waste	Disposal in landfills	Methane generation



Importance of Reducing Carbon Footprint

Reducing carbon emissions in food industries is essential for environmental protection and sustainable development. Lower greenhouse gas emissions help reduce global warming, climate change, and air pollution. Sustainable food production also improves energy efficiency and reduces unnecessary use of water, fuel, and raw materials. Industries can lower operational costs through energy-saving technologies and waste reduction practices.

Consumers today are more environmentally conscious and prefer products made using sustainable methods. Companies adopting eco-friendly practices often gain better market reputation and consumer trust. Governments across the world are also introducing environmental regulations and encouraging industries to adopt cleaner technologies.

Strategies for Carbon Footprint Reduction

Use of Renewable Energy

Many food industries are shifting toward renewable energy sources such as solar energy, wind energy, biomass, and biogas. These energy sources reduce dependence on fossil fuels and lower greenhouse gas emissions. Solar panels can provide electricity to processing units, while biogas plants can convert organic waste into useful energy.

Energy-Efficient Technologies

Modern food industries are adopting energy-efficient equipment and automated systems to reduce electricity consumption. Technologies such as efficient refrigeration systems, heat recovery systems, smart sensors, and advanced processing equipment improve energy efficiency and reduce emissions.

Sustainable Agricultural Practices

Sustainable farming methods such as precision agriculture, organic farming, drip irrigation, integrated nutrient management, and conservation agriculture help reduce greenhouse gas emissions. Precision agriculture uses sensors and digital technologies to optimize fertilizer and water application, reducing resource wastage.

Waste Management and Recycling

Food industries are increasingly adopting waste management and recycling practices. Food waste can be converted into compost, animal feed, biofuel, or biogas. Recycling packaging materials and reusing water in processing operations further reduce environmental impact.

Eco-Friendly Packaging

Many companies are replacing conventional plastic packaging with biodegradable, recyclable, and compostable materials. Reducing unnecessary packaging and encouraging recycling systems can significantly reduce pollution and carbon emissions.

Table 2: Sustainable Practices for Carbon Footprint Reduction

Sustainable Practice	Method Used	Benefits
Renewable Energy	Solar, wind, biomass, biogas	Reduces fossil fuel dependence
Energy Efficiency	Smart machinery and heat recovery	Saves energy and cost
Sustainable Farming	Precision agriculture and organic farming	Reduces resource wastage
Waste Recycling	Composting and biogas production	Minimizes landfill waste
Eco-Friendly Packaging	Biodegradable and recyclable materials	Reduces pollution

Challenges Faced by Food Industries

One major challenge is the high initial investment required for renewable energy systems, advanced machinery, and sustainable infrastructure. Small and medium-scale industries may find it difficult to afford these technologies. Another challenge is the lack of technical knowledge and skilled workers needed to manage modern sustainable systems. Managing emissions across complex supply chains is also difficult because food products pass through multiple stages before reaching consumers. Consumer behaviour can also create challenges. High demand for processed foods, imported products, and excessive packaging increases the carbon footprint of food systems.

Table 3: Challenges and Possible Solutions

Challenges	Impact	Possible Solutions
High investment cost	Delays adoption of green technologies	Government subsidies and incentives
Lack of technical skills	Inefficient management systems	Training and awareness programs
Complex supply chains	Difficult emission monitoring	Digital tracking and coordination
Consumer demand for processed foods	Increased packaging and transport emissions	Consumer awareness campaigns

Conclusion

Carbon footprint reduction has become essential for achieving sustainable food production and environmental protection. Food industries contribute significantly to greenhouse gas emissions through farming, processing, transportation, packaging, and waste generation. The adoption of renewable energy, energy-efficient technologies, sustainable farming practices, eco-friendly packaging, and effective waste management can greatly reduce carbon emissions in the food sector. Reducing carbon footprints not only protects the environment but also improves economic efficiency and supports long-term sustainability. With the combined efforts of industries, governments, and consumers, the food sector can move toward a cleaner, greener, and more sustainable future.



TRANSFORMING SUSTAINABLE AQUACULTURE BY APPLYING CIRCULARITY PRINCIPLES



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Abstract

Aquaculture has emerged as one of the fastest-growing food production sectors in the world, contributing significantly to global food security, nutrition, and economic development. However, rapid intensification of aquaculture practices has also generated environmental concerns such as water pollution, excessive resource consumption, habitat degradation, and waste accumulation. In recent years, the concept of circular economy has gained attention as an innovative framework for transforming aquaculture into a more sustainable and resource-efficient system. Circularity principles focus on minimizing waste, reusing resources, recycling nutrients, and creating regenerative production cycles that reduce environmental impacts while improving productivity. By integrating waste-to-resource strategies, renewable energy systems, integrated multi-trophic aquaculture, and sustainable feed alternatives, aquaculture can transition from a linear production model to a circular and resilient system. This context examines the importance of applying circularity principles in sustainable aquaculture, discusses key strategies and benefits, and highlights the challenges and future prospects of implementing circular aquaculture practices for long-term environmental and economic sustainability.

Keywords: Sustainable aquaculture, Circular economy, Resource efficiency, Waste management, Integrated farming

Introduction

Aquaculture plays a vital role in meeting the growing global demand for fish and seafood products. As capture fisheries face declining productivity due to overfishing, climate change, and marine ecosystem degradation, aquaculture has become an essential source of protein and livelihood for millions of people worldwide. According to global food and agriculture reports, aquaculture contributes more than half of the fish consumed globally, making it one of the most important food production sectors in the modern economy. Despite its significant contribution, conventional aquaculture practices often follow a linear production model characterized by intensive input use, high waste generation, and environmental degradation. Excess feed, fish excreta, chemical residues, and untreated wastewater can negatively affect aquatic ecosystems and surrounding communities. These challenges have raised concerns regarding the long-term sustainability of aquaculture systems. The concept of circular economy has emerged as a transformative approach to address these sustainability concerns. Circularity principles emphasize reducing waste, extending resource use, recovering nutrients, and designing regenerative production systems that mimic natural ecological cycles. In aquaculture, circularity promotes the efficient use of water, energy, feed, and biological resources while minimizing environmental pollution. The application of circular economy strategies in aquaculture has the potential to improve economic profitability, environmental sustainability, and social resilience simultaneously. Circular aquaculture systems not only reduce resource dependency but also create opportunities for innovation, employment, and ecosystem restoration. Therefore, transforming aquaculture through circularity principles is increasingly recognized as a critical pathway toward sustainable food systems and blue economy development.

Circular Economy and Sustainable Aquaculture

The circular economy is an economic model that seeks to replace the traditional “take-make-dispose” approach with systems that maintain the value of resources for as long as possible. In aquaculture, this model encourages producers to recover nutrients, recycle waste materials, and optimize resource utilization across the production

cycle. Sustainable aquaculture under circularity principles focuses on balancing environmental protection, economic efficiency, and social responsibility. Instead of viewing aquaculture waste as a disposal problem, circular systems consider waste as a valuable input for other productive activities. One important aspect of circular aquaculture is nutrient recycling. Fish farming generates significant quantities of organic waste in the form of uneaten feed and metabolic by-products. In conventional systems, these wastes are often released into water bodies, causing eutrophication and water quality deterioration. Circular aquaculture systems aim to capture and reuse these nutrients through biological and technological processes. For example, nutrient-rich wastewater from fish ponds can be used for irrigation and fertilization in agriculture, thereby reducing dependence on synthetic fertilizers. Similarly, sludge from aquaculture operations can be converted into biogas or compost, creating additional economic value while reducing environmental pollution. Another important circularity strategy is the efficient use of water resources. Water scarcity and contamination are major concerns in aquaculture-intensive regions. Recirculating aquaculture systems (RAS) represent an innovative approach that allows water to be filtered, treated, and reused within the production system. These systems significantly reduce water consumption and minimize the discharge of pollutants into natural ecosystems. Although RAS technology requires high initial investment and technical expertise, it offers long-term sustainability benefits by improving water efficiency and biosecurity.

Integrated Multi-Trophic Aquaculture and Resource Optimization

Integrated Multi-Trophic Aquaculture (IMTA) is one of the most promising applications of circularity principles in aquaculture. IMTA involves cultivating species from different trophic levels within the same system so that waste generated by one species becomes a nutrient source for another. For instance, fish waste rich in nitrogen and phosphorus can support the growth of seaweed and shellfish, which absorb excess nutrients and improve water quality. This integrated approach mimics natural ecosystems and enhances ecological balance within aquaculture operations. The implementation of IMTA provides several environmental and economic advantages. By recycling nutrients internally, IMTA reduces pollution and improves resource efficiency. Seaweeds cultivated in IMTA systems can be harvested for food, pharmaceuticals, cosmetics, and biofuel production, thereby generating additional income streams for farmers. Shellfish such as mussels and oysters help filter water and maintain ecosystem health while also serving as valuable commercial products. The diversification of species within IMTA systems reduces economic risks associated with disease outbreaks or market fluctuations affecting a single species. Resource optimization also extends to aquaculture feed production. Conventional aquaculture depends heavily on fishmeal and fish oil derived from wild fish stocks, contributing to pressure on marine ecosystems. Circular aquaculture promotes the use of alternative and sustainable feed ingredients such as insect meal, algae, agricultural by-products, and food waste-derived proteins. Black soldier fly larvae, for example, can convert organic food waste into high-protein feed suitable for aquaculture species. This approach reduces dependence on finite marine resources and supports waste valorization within the food production system. Renewable energy integration further strengthens circular aquaculture systems. Aquaculture operations often require significant amounts of electricity for aeration, pumping, and water treatment. Solar panels, wind turbines, and biogas systems can provide clean energy for aquaculture farms while reducing greenhouse gas emissions and operational costs. In some integrated systems, biogas generated from aquaculture sludge can be used to power farm operations, creating a self-sustaining energy cycle.

Environmental and Socioeconomic Benefits

Applying circularity principles in aquaculture offers numerous environmental benefits. One of the most important advantages is pollution reduction. By recycling nutrients and minimizing waste discharge, circular aquaculture helps prevent eutrophication, oxygen depletion, and biodiversity loss in aquatic ecosystems. Improved waste management practices also reduce the accumulation of harmful substances in sediments and surrounding water bodies. Furthermore, sustainable feed alternatives and renewable energy adoption contribute to lower carbon emissions and reduced ecological footprints. Socially, circular aquaculture contributes to rural development, employment generation, and food security. Sustainable aquaculture practices can create jobs in waste management, renewable energy, biotechnology, and integrated farming sectors. Increased production efficiency and environmental sustainability help ensure the availability of nutritious seafood for growing populations.

Moreover, circular aquaculture aligns with global sustainable development goals related to responsible consumption, climate action, poverty reduction, and ecosystem conservation.

Challenges and Future Prospects

Despite its significant benefits, the transition toward circular aquaculture faces several challenges. High initial investment costs for advanced technologies such as recirculating systems, waste treatment facilities, and renewable energy infrastructure can limit adoption, particularly among small-scale farmers. Technical complexity and lack of knowledge regarding circular practices also present barriers to implementation. In many regions, inadequate policy support, limited access to financing, and weak regulatory frameworks hinder the development of sustainable aquaculture systems. The integration of circular economy principles into aquaculture has the potential to revolutionize the sector by creating regenerative systems that balance ecological sustainability with economic development. Future aquaculture systems are likely to become more interconnected with agriculture, renewable energy, and waste management sectors, forming integrated bioeconomic networks that maximize resource efficiency and minimize environmental impacts.

Conclusion

The transformation of aquaculture through circularity principles represents a crucial step toward achieving sustainable food production and environmental conservation. Conventional aquaculture systems have contributed significantly to food security and economic growth, but their linear production models have also generated serious environmental challenges. Circular aquaculture offers an innovative and sustainable alternative by promoting waste reduction, nutrient recycling, resource efficiency, and ecosystem integration. Practices such as Integrated Multi-Trophic Aquaculture, recirculating aquaculture systems, sustainable feed production, and renewable energy integration demonstrate the potential of circular economy strategies to improve environmental performance and economic resilience. Ultimately, applying circularity principles in aquaculture is essential for ensuring long-term food security, protecting aquatic ecosystems, and building a sustainable future for coming generations.

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LIVELIHOOD OF INDIAN FISHERMEN



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Abstract

The fishing community in India plays a significant role in the nation's economy by contributing to food security, employment generation, export earnings, and rural development. Millions of fishermen across coastal and inland regions depend directly or indirectly on fisheries and aquaculture for their livelihood. Despite the importance of the fisheries sector, a large section of Indian fishermen continues to face economic hardship due to poverty, indebtedness, low income, inadequate infrastructure, seasonal unemployment, environmental degradation, and market exploitation. Traditional fishermen often struggle with limited access to modern technology, financial support, healthcare, education, and social security benefits. Climate change, declining fish stocks, coastal pollution, and industrial fishing activities have further affected their economic stability. Government schemes and cooperative societies have attempted to improve the living conditions of fishermen through subsidies, welfare programs, housing support, and infrastructure development. However, socioeconomic inequalities and regional disparities still persist among fishing communities. This context examines the economic status of Indian fishermen, the challenges affecting their livelihoods, government initiatives for welfare and development, and the future prospects for improving the socioeconomic conditions of fishing communities in India.

Keywords: Indian fishermen, Fisheries economy, Coastal livelihood, Poverty, Socioeconomic development

Introduction

India possesses a vast coastline of more than 7,500 kilometers along with extensive inland water resources including rivers, lakes, reservoirs, ponds, and wetlands. These aquatic resources support one of the largest fisheries sectors in the world. Fisheries and aquaculture contribute significantly to the Indian economy by providing employment, nutritional security, and export revenue. Millions of people in coastal and inland regions depend on fishing-related activities such as fish catching, fish farming, processing, transportation, and marketing for their livelihood. Fishing communities form an important social and economic group in states such as Tamil Nadu, Kerala, Andhra Pradesh, West Bengal, Odisha, Maharashtra, Gujarat, Assam, and Karnataka. The economic status of fishermen in India varies depending on factors such as region, fishing methods, ownership of fishing equipment, access to markets, and government support. While some mechanized and commercial fishing operators earn substantial profits, small-scale and traditional fishermen remain economically vulnerable. Understanding the economic condition of Indian fishermen is essential for developing effective policies aimed at poverty reduction, sustainable fisheries management, and social welfare improvement.

Fisheries Sector and Employment in India

The fisheries sector is one of the fastest-growing segments of Indian agriculture and allied industries. India is among the leading fish-producing countries in the world and ranks high in aquaculture production. The sector contributes significantly to the national Gross Domestic Product and foreign exchange earnings through seafood exports. Fisheries also play an important role in providing affordable protein-rich food to millions of people. Fishing is also a seasonal occupation influenced by monsoon conditions, fishing bans, and fish migration patterns. During non-fishing periods, many fishermen face unemployment and financial difficulties. Some engage in temporary labor work or migration to supplement household income. Therefore, the economic condition of fishermen is closely linked to environmental and seasonal factors.

Poverty and Financial Challenges

Poverty remains one of the major problems affecting Indian fishermen. Many fishing families live below the poverty line and lack access to basic amenities such as proper housing, sanitation, clean drinking water, healthcare, and education. Small-scale fishermen often depend on daily fish catches for survival, making their

income highly uncertain and unstable. The rising cost of fuel, maintenance, and fishing gear has also increased operational expenses in recent years. Mechanized fishing requires substantial investment in engines, diesel, storage facilities, and navigation systems. Small fishermen with limited capital struggle to compete with large commercial fishing operators equipped with advanced technologies. Natural disasters such as cyclones, tsunamis, floods, and storms frequently damage fishing boats, nets, and coastal infrastructure, leading to severe economic losses. Climate change and environmental degradation have further reduced fish availability in many coastal and inland regions. Declining fish stocks caused by overfishing and pollution directly affect fishermen's income and livelihood security.

Social and Living Conditions of Fishermen

The economic status of fishermen is closely connected to their social and living conditions. Many fishing villages in India suffer from inadequate infrastructure and poor public services. Housing conditions in several coastal communities remain weak due to poverty and exposure to environmental hazards such as cyclones and coastal erosion. Despite these difficulties, fishing communities possess strong cultural traditions, social cooperation, and indigenous ecological knowledge. Community solidarity and cooperative activities help fishermen survive during economic hardships and natural disasters. Traditional knowledge regarding tides, weather patterns, and fish behavior continues to remain valuable in fisheries management.

Government Initiatives and Welfare Programs

The Government of India has introduced several schemes and welfare programs to improve the economic condition of fishermen. Fisheries development policies focus on increasing fish production, improving infrastructure, promoting aquaculture, and supporting fishermen's welfare. Financial assistance programs provide subsidies for boat construction, fishing equipment, engines, cold storage facilities, and fish farming activities. Fishermen welfare programs also include insurance schemes, housing assistance, savings-cum-relief schemes, and accident compensation programs. Seasonal fishing ban relief measures provide financial support to fishermen during non-fishing periods imposed for marine conservation purposes. Cooperative societies help fishermen access credit facilities, marketing support, and collective bargaining opportunities. Infrastructure development projects such as fishing harbors, landing centers, cold storage units, transportation facilities, and fish markets improve the efficiency and profitability of fishing activities. Training programs and skill development initiatives also encourage fishermen to adopt modern technologies and sustainable fishing practices. Although government programs have improved fisheries development in several regions, implementation challenges and unequal distribution of benefits continue to affect many small-scale fishermen. Greater policy attention is required to ensure inclusive growth and social justice within fishing communities.

Future Prospects and Sustainable Development

The future economic development of Indian fishermen depends on sustainable fisheries management, technological advancement, and social welfare improvement. Sustainable fishing practices are essential for conserving marine and freshwater resources while ensuring long-term livelihood security for fishing communities. Controlling overfishing, reducing pollution, protecting coastal ecosystems, and promoting responsible aquaculture are important measures for maintaining fish productivity. Modern technologies such as GPS navigation, fish finders, weather forecasting systems, and cold chain infrastructure can improve fishing efficiency and reduce economic risks. Expanding aquaculture and inland fisheries also offers opportunities for income diversification and rural employment generation. The fisheries sector possesses immense potential for contributing to India's economic growth and food security. However, ensuring equitable development requires focused efforts to improve the living conditions, financial stability, and social welfare of fishing communities across the country.

Conclusion

The economic status of Indian fishermen reflects both the importance and the vulnerability of the fisheries sector in India. Fishing communities contribute significantly to employment, nutrition, exports, and rural development, yet many fishermen continue to face poverty, indebtedness, environmental risks, and social inequality. Small-scale and traditional fishermen are particularly affected by unstable income, declining fish stocks, market exploitation, and inadequate infrastructure. Government welfare schemes and fisheries development programs

have provided support through subsidies, insurance, infrastructure, and aquaculture promotion. However, continued efforts are needed to ensure sustainable fisheries management, social protection, financial inclusion, and educational advancement for fishing communities. Improving the economic condition of fishermen requires integrated policies that balance environmental conservation with livelihood security. By promoting sustainable fishing practices, modern technology adoption, infrastructure development, and social welfare initiatives, India can strengthen the fisheries sector while improving the quality of life of millions of fishermen and their families. Protecting the economic well-being of fishermen is essential for achieving inclusive development and ensuring the long-term sustainability of India's aquatic resources.

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SEA TURTLES THROUGH HISTORY



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Abstract

Sea turtles are among the oldest living marine reptiles on Earth, with a history that dates back more than 100 million years. These ancient creatures evolved during the age of dinosaurs and survived major geological and climatic changes that led to the extinction of many species. Sea turtles have played an important ecological, cultural, and economic role in marine ecosystems and human societies across the world. Historically, they were abundant in oceans and coastal regions, providing food, oil, shells, and cultural symbolism for many civilizations. However, overexploitation, habitat destruction, pollution, climate change, and accidental capture in fishing activities have caused significant declines in sea turtle populations globally. Conservation efforts during the twentieth and twenty-first centuries have increased awareness regarding the importance of protecting these endangered marine animals. International agreements, marine protected areas, scientific research, and community-based conservation programs have contributed to sea turtle recovery in several regions. This context examines the global history of sea turtles, including their evolution, cultural significance, ecological role, threats, conservation efforts, and future prospects for their survival in changing marine environments.

Keywords: Sea turtles, Marine reptiles, Ocean conservation, Endangered species, Marine biodiversity

Introduction

Sea turtles are ancient marine reptiles that have inhabited the world's oceans for millions of years. They belong to the order Testudines and are specially adapted for life in marine environments. Unlike freshwater turtles and tortoises, sea turtles spend almost their entire lives in the ocean, except when females come ashore to lay eggs on sandy beaches. Their streamlined bodies, paddle-like flippers, and strong swimming abilities allow them to migrate across vast ocean distances. Today, seven species of sea turtles are recognized globally: the green turtle, loggerhead turtle, leatherback turtle, hawksbill turtle, olive ridley turtle, Kemp's ridley turtle, and flatback turtle. Sea turtles have survived dramatic environmental changes throughout Earth's history, including continental drift, ice ages, volcanic events, and mass extinctions. Fossil evidence indicates that the ancestors of modern sea turtles evolved over 100 million years ago during the Cretaceous period. Their survival across geological eras demonstrates remarkable evolutionary adaptation and resilience. Historically, sea turtles were widely distributed across tropical, subtropical, and temperate oceans and were deeply connected to the cultures and livelihoods of coastal communities around the world.

Evolution and Ancient History of Sea Turtles

The evolutionary history of sea turtles dates back to the age of dinosaurs. Scientists believe that early turtle ancestors first appeared around 220 million years ago during the Triassic period. However, true marine turtles evolved later during the Cretaceous period approximately 100 to 120 million years ago. Fossil records reveal that ancient sea turtles already possessed flippers and streamlined bodies suitable for marine life. One of the earliest known marine turtles was Archelon, a giant sea turtle that lived during the Late Cretaceous period. It could grow over four meters in length and is considered one of the largest turtles ever discovered. Ancient sea turtles inhabited warm prehistoric seas and coexisted with marine reptiles such as mosasaurs and plesiosaurs. Their ability to adapt to marine environments allowed them to survive environmental changes that caused the extinction of dinosaurs around 66 million years ago. Over millions of years, sea turtles evolved specialized features for ocean survival. Their lungs adapted for efficient oxygen storage, allowing long dives underwater. Strong flippers enabled long-distance migration, while salt glands near their eyes helped remove excess salt from seawater. Sea turtles also developed remarkable navigational abilities using Earth's magnetic field to return to nesting beaches across generations.

Cultural and Historical Importance

Sea turtles have held cultural, spiritual, and economic significance in many human societies throughout history. Coastal civilizations in Asia, Africa, the Americas, and Pacific islands viewed sea turtles as symbols of longevity, wisdom, fertility, and protection. Ancient myths and legends often associated turtles with creation stories and ocean spirits.

In many indigenous communities, sea turtles were an important source of food, oil, and materials. Turtle meat and eggs were consumed as traditional food, while shells were used for ornaments, jewelry, tools, and ceremonial objects. Hawksbill turtle shells, known as tortoiseshell, became particularly valuable in international trade due to their attractive patterns and durability. Turtle products were widely traded across Europe, Asia, and the Americas for centuries.

Ecological Role of Sea Turtles

Sea turtles play a crucial role in maintaining the health and balance of marine ecosystems. Different turtle species contribute to ocean ecology through their feeding behaviors and migratory activities. Green turtles, for example, feed mainly on seagrasses and help maintain healthy seagrass beds by preventing excessive growth. Healthy seagrass ecosystems support fish populations, stabilize sediments, and improve water quality. Hawksbill turtles feed primarily on sponges within coral reef ecosystems. By controlling sponge populations, they help maintain coral diversity and reef health. Leatherback turtles consume large quantities of jellyfish, helping regulate jellyfish populations and maintain ecological balance within open ocean ecosystems.

Threats to Sea Turtles in Modern Times

Although sea turtles survived natural environmental changes for millions of years, human activities have become the greatest threat to their survival. One of the major threats is habitat destruction caused by coastal development, tourism infrastructure, artificial lighting, and beach erosion. Nesting beaches are increasingly disturbed by urbanization and human activities, reducing suitable nesting habitats for female turtles. Pollution is another serious problem affecting sea turtles globally. Plastic waste in oceans is often mistaken for food by turtles, leading to digestive blockages, starvation, and death. Chemical pollution, oil spills, and marine debris also harm turtle health and marine ecosystems. Ghost fishing nets and abandoned fishing gear can entangle turtles, causing injuries and drowning. Accidental capture in fishing operations, known as bycatch, is one of the leading causes of sea turtle mortality. Turtles are frequently trapped in trawl nets, longlines, and gillnets during commercial fishing activities. Although turtle excluder devices and fishing regulations have reduced some impacts, bycatch remains a significant threat worldwide.

Global Conservation Efforts

International conservation efforts for sea turtles increased significantly during the twentieth century as awareness about their endangered status grew. Governments, scientists, conservation organizations, and local communities have worked together to protect sea turtle habitats and reduce human impacts. Scientific research has improved understanding of sea turtle migration, genetics, reproduction, and population dynamics. Satellite tracking technologies help monitor migration routes and identify critical habitats for protection. Conservation organizations also promote sustainable fishing practices and the use of turtle excluder devices to reduce bycatch mortality. Several sea turtle populations have shown signs of recovery due to long-term conservation efforts. However, continued protection and international cooperation remain necessary because sea turtles migrate across national boundaries and depend on healthy global marine ecosystems.

Conclusion

Sea turtles are ancient marine reptiles with a remarkable evolutionary history spanning more than 100 million years. They survived major geological and climatic changes and became ecologically important components of marine ecosystems worldwide. Throughout history, sea turtles have held cultural, spiritual, and economic significance for many human societies while contributing to ocean health through their ecological functions. Despite their resilience, modern sea turtles face severe threats from habitat destruction, pollution, climate change, illegal exploitation, and fishing-related mortality. Human activities have caused significant population declines, placing several species at risk of extinction. However, global conservation efforts involving scientific research, legal protection, community participation, and international cooperation have improved awareness and

contributed to recovery in some regions. Protecting sea turtles is essential not only for conserving marine biodiversity but also for maintaining healthy ocean ecosystems. Sustainable coastal management, pollution reduction, responsible fishing practices, and climate action are necessary to ensure the survival of sea turtles for future generations. The global history of sea turtles serves as a reminder of the interconnected relationship between humans and marine life and the importance of preserving Earth's natural heritage.

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Peri-Urban Aquaculture: Navigating Sustainable Food Systems at the City's Edge



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Abstract

Rapid urbanization and population growth have increased the demand for nutritious food and sustainable resource management in urban areas. Peri-urban aquaculture, practiced in transitional zones surrounding cities, plays an important role in enhancing urban food security by supplying fresh and affordable fish rich in protein, essential fatty acids, and micronutrients. Its proximity to urban markets reduces transportation costs and post-harvest losses while improving livelihood opportunities for peri-urban communities. Peri-urban aquaculture also promotes efficient resource utilization through recycling of wastewater, organic waste, and nutrient-rich effluents in systems such as aquaponics, biofloc, and recirculating aquaculture systems. These approaches support climate-resilient and sustainable food production by reducing water consumption, minimizing environmental pollution, and improving adaptability to climate change and urban resource scarcity. Despite challenges including land conversion, pollution, and limited institutional support, peri-urban aquaculture has significant potential to contribute to sustainable urban development and resilient food systems.

Introduction

Rapid urbanization is one of the defining global trends of the twenty-first century. The expansion of cities has created transitional landscapes known as peri-urban areas, where rural and urban activities coexist under dynamic socio-economic and environmental changes (Mondal & Banerjee, 2021). These regions are characterized by mixed land use, rapid population growth, increasing competition for natural resources, and strong dependence on nearby urban markets for food supply and economic activities (Bunting & Little, 2003).

In India, peri-urbanisation around metropolitan cities has emerged as a prominent phenomenon over the last few decades. Peri-urban spaces develop around expanding cities as a result of rapid urbanization and urban sprawl (Shaw, 2005). These transitional zones exhibit a coexistence of rural and urban characteristics and are highly dynamic in nature, undergoing continuous changes in land use patterns, demographic composition, and social systems (Narain, Anand, & Banerjee, 2013). According to Schenk (2005), peri-urban regions continuously “expand and shrink geographically, eating their way into the countryside, while they are swallowed by the expanding urban core area,” making them true “regions of change.” Consequently, areas that are peri-urban today may become part of the urban core tomorrow, while having been predominantly rural in the recent past.

The increasing concentration of human populations in urban centers has substantially increased the demand for affordable and nutritious animal protein. Fish is widely recognized as an excellent source of high-quality protein, essential amino acids, vitamins, and omega-3 fatty acids important for human nutrition (FAO, 2022). However, global capture fisheries have reached biological limits due to overexploitation and environmental degradation, resulting in aquaculture emerging as the fastest-growing food production sector worldwide (FAO, 2022; Edwards, 2015).

What is Peri-Urban Aquaculture?

The term “peri-urban” refers to the transitional spaces situated between urban centers and rural countryside, formed through the gradual urbanization of previously rural areas. These regions are often described as urban fringes, hinterlands, or city outskirts and display a hybrid combination of both rural and urban characteristics (Aijaz, 2019). Peri-urban areas generally overlap rural and urban administrative jurisdictions and are inhabited by native populations engaged in agriculture and allied sectors, along with migrant populations involved in non-farm occupations.

Peri-urban aquaculture refers to the farming of aquatic organisms in water bodies located within or around these expanding urban fringes (Datta, 2015). Such systems are strategically important because their proximity to

urban consumers reduces transportation costs, minimizes post-harvest losses, and improves access to large and profitable markets compared with remote rural aquaculture systems (Bunting & Little, 2003).

Traditionally, peri-urban aquaculture depended largely on extensive pond-based systems. However, increasing urban pressure, scarcity of land and water resources, and rising demand for fish have encouraged the adoption of intensive and water-efficient production technologies in these areas (Leage et al., 2025). India represents a significant example of this transformation due to its rapid urban growth, increasing fish consumption, and expanding commercial aquaculture sector that is progressively adapting to urban resource limitations.

Evolution of Traditional Peri-Urban Farming Systems

Early peri-urban food production systems developed primarily to supply highly perishable food products to nearby urban populations. Before the development of modern cold chains and rapid transportation, agricultural production needed to remain geographically close to urban markets (Orsini, 2013).

Traditional peri-urban agriculture was dominated by market gardening systems where vegetables, herbs, and horticultural crops were cultivated in open fields. Organic manures, livestock wastes, and composted urban organic residues were commonly utilized to maintain soil fertility (Steenbergen, 2010). Similarly, early peri-urban aquaculture consisted mainly of extensive earthen ponds that relied on natural productivity for fish growth. These systems depended on low stocking densities and nutrient inputs such as rice bran, cow dung, and agricultural by-products to stimulate plankton production (Tidwell, 2012).

One of the most historically significant traditional models involves wastewater-fed fish farming. The East Kolkata Wetlands in India represent one of the world's largest sewage-fed aquaculture systems, where municipal wastewater is recycled through shallow fish ponds locally known as *bheries* (Bunting et al., 2010). In these systems, nutrients in the wastewater stimulate natural algal productivity that supports fish growth while simultaneously contributing to biological wastewater treatment (Edwards, 2003).

Traditional systems also included backyard livestock rearing, wetland harvesting, and the utilization of urban organic wastes for agricultural production (Marshall & Randhawa, 2017). However, increasing urban expansion, wetland reclamation, and rising land values have gradually reduced the viability of these extensive systems.

Transition Toward Intensive Peri-Urban Aquaculture

Rapid urban growth has significantly altered peri-urban ecosystems and resource availability. Agricultural lands and wetlands surrounding cities are increasingly converted into residential, industrial, and commercial infrastructure, resulting in severe land scarcity and escalating land prices (Bunting & Little, 2003).

Simultaneously, industrial effluents, urban runoff, and untreated sewage have degraded many natural water bodies historically used for traditional aquaculture (Omitoyin & Adebayo, 2012). Water scarcity has also intensified due to competition among domestic, industrial, and agricultural sectors. These environmental and economic pressures have driven a paradigm shift toward intensive aquaculture systems capable of producing larger quantities of fish within limited spaces, emphasizing water recycling, nutrient recovery, controlled environments, and biosecurity (McClintock, 2010).

Modern Peri-Urban Aquaculture Technologies

1. Biofloc Technology (BFT)

Biofloc Technology is an intensive system that promotes the growth of heterotrophic microbial communities through the manipulation of the carbon-to-nitrogen ratio within the culture water (Avnimelech, 2012). These microbial flocs assimilate toxic nitrogenous wastes (such as ammonia) and convert them into microbial biomass consumed by the cultured fish. BFT systems significantly reduce water exchange requirements while supporting high stocking densities, making them highly suitable for land- and water-scarce peri-urban environments (Avnimelech, 2012).

2. Recirculating Aquaculture Systems (RAS)

RAS are highly controlled environments that continuously recycle culture water through advanced mechanical and biological filtration units (Badiola et al., 2012). By utilizing drum filters, biofilters, and ultraviolet sterilizers, RAS maintains optimal water quality with minimal consumption. This technology allows for exceptionally high stocking densities and year-round production while minimizing environmental discharge (Badiola et al., 2012).

3. Aquaponics

Aquaponics combines recirculating aquaculture with hydroponic plant cultivation. Fish waste nutrients are utilized for plant growth, and as the plants absorb these dissolved nutrients, they bio-filter the water before it recirculates back to the fish tanks (Rakocy, 2012)). This integrated system supports the simultaneous, high-density production of fish and vegetables using minimal land and water resources (Somerville et al., 2014).

4. Flow-Through Systems (FTS) and Tank-Based Culture

To combat land scarcity and secure harvests against theft, modern peri-urban farmers overwhelmingly prefer above-ground concrete, fiberglass, or tarpaulin tanks over earthen ponds, as they improve biosecurity and facilitate waste removal (Tidwell, 2012; Miller & Atanda, 2011). In specific geographical fringes—such as the sub-Himalayan belts adjacent to fast-flowing mountain streams—Flow-Through Systems (FTS) channel continuous fresh water through concrete raceway tanks to flush out waste naturally, allowing for high-density cold-water farming (Datta, 2015).

Commercial Peri-Urban Aquaculture Systems in India

India demonstrates a highly diverse commercial landscape adapting to regional constraints:

- **Ecological Wastewater Models:** The East Kolkata Wetlands continue to operate globally as a premier ecological model. Approximately 12,500 hectares of wetlands surrounding Kolkata biologically treat municipal sewage through fish ponds and agricultural fields, producing highly affordable protein (Bunting et al., 2010).
- **High-Tech RAS:** Indoor RAS farms, such as *Smart Green Aquaculture* in Hyderabad, have been established to produce premium cold-water species (like rainbow trout) under climate-controlled conditions, bypassing traditional supply chains entirely (Leage et al., 2025).
- **Biofloc and IoT Startups:** Commercial biofloc systems have expanded rapidly around cities like Chennai, Vijayawada, and Kochi. Pan-India startups frequently utilize tarpaulin-lined tanks equipped with Internet of Things (IoT) sensors to support high-density catfish and tilapia culture with limited water resources (Kaur et al., 2020).
- **Commercial Aquaponics:** Enterprises like *Madhavi Farms* (Bengaluru) and *Urba Grow* (Kolkata) have emerged to meet urban demands for pesticide-free vegetables and fresh fish. Integrated production allows these rooftop and peri-urban operations to target premium urban supermarkets directly (Somerville et al., 2014).

Environmental and Economic Significance

Peri-urban aquaculture contributes significantly to urban food security by bridging the metabolic rift between city consumption and rural production (McClintock, 2010). Supplying fresh fish directly to nearby consumers drastically reduces transportation distances, minimizing the carbon footprint, post-harvest losses, and reliance on cold-chain logistics (Bunting & Little, 2003).

Periurban aquaculture in and around the cities create jobs and can improve the environment, reduce waste and provide quality food. Previously the risk of contamination from waste water posed dangers. But safe ways of producing fish and growing water vegetables around the cities are now available. There is a concern that climate change could increase food insecurity. From this point of view, periurban aquaculture represents a new dimension in fish production. Aquaculture offers opportunities to increase food production that may also help to increase income, food security and the livelihood of millions of poor residents. Periurban aquaculture systems are located on the periphery of the cities (Datta, 2015).

Environmentally, intensive systems like BFT and RAS improve water-use efficiency and reduce harmful discharge compared with conventional open ponds (Avnimelech, 2012; Badiola et al., 2012). Furthermore, wastewater-fed systems provide critical ecological services by recycling municipal effluents and organic nutrients into productive, consumable biomass, actively championing the circular economy (Bunting et al., 2010). Economically, the sector generates robust employment opportunities across hatchery production, feed supply, processing, and retail marketing.

Challenges and Constraints

Peri-urban aquaculture in India has received comparatively limited attention in research and policy discourse despite its growing importance in urban food systems and livelihood generation (Nivedita & Ankita, 2024). Existing studies have largely focused on broader issues such as governance, pollution, wastewater management, metropolitan expansion, and sustainability, while the specific challenges faced by peri-urban aquaculture farmers remain inadequately addressed. Studies by Narain (2010), the United Nations Environment Programme (2014), Hussain and Hanisch (2014), Bhatt et al. (2016), Marshall and Randhawa (2017), and Aijaz (2019) have highlighted concerns related to water scarcity, climate vulnerability, food security, governance, and adaptation in peri-urban regions, but the aquaculture dimension continues to be underrepresented.

One of the most critical constraints affecting peri-urban aquaculture is land tenure insecurity. Rapid urban expansion and infrastructure development continuously convert agricultural and wetland areas into residential and commercial spaces, leading to the displacement of farming and fishing communities (Bunting & Little, 2003). Increasing urbanization exerts immense pressure on land and water resources, gradually encroaching upon floodplains and wetlands that traditionally supported aquaculture activities. The disappearance of these wetlands has serious ecological and socio-economic consequences, particularly for economically vulnerable populations dependent on such systems for their livelihoods (Datta, 2015).

Water pollution represents another major challenge in peri-urban aquaculture systems. Discharge of industrial effluents, domestic sewage, and untreated wastewater into culture waters adversely affects fish health, productivity, and food safety. In poorly managed wastewater-fed aquaculture systems, there is a significant risk of accumulation of heavy metals and pathogenic microorganisms in fish tissues, posing serious public health concerns (Omitoyin & Adebayo, 2012).

In addition, adoption of modern intensive aquaculture technologies such as Recirculating Aquaculture Systems (RAS) and aquaponics is often constrained by high initial investment costs, dependence on uninterrupted electricity supply, and the requirement for advanced technical expertise. Small-scale farmers frequently face limited access to institutional credit, training facilities, and extension services, which restricts the wider adoption of these technologies and reduces their capacity to improve productivity and sustainability (Miller & Atanda, 2011; Badiola et al., 2012).

Future Scope

The future expansion of peri-urban aquaculture depends on resource-efficient, climate-resilient technologies. The integration of automated feeding technologies, renewable energy, and precision IoT-based monitoring systems is expected to drastically improve sustainability. Crucially, urban planning policies must officially protect peri-urban agricultural lands and wetlands. Massive institutional investments in decentralized wastewater treatment infrastructure, micro-finance, and farmer training will be essential to secure this sector as a permanent component of the urban food system.

Conclusion

Peri-urban aquaculture has evolved from traditional, land-heavy extensive pond systems and raw wastewater-fed fisheries into technologically advanced production systems capable of sustaining rapidly expanding urban populations. Increasing land scarcity, water limitations, and environmental degradation have accelerated the necessary adoption of intensive models such as Biofloc Technology, Recirculating Aquaculture Systems, aquaponics, and above-ground tank culture. By optimizing resource utilization, nutrient recycling, and highly localized food production, peri-urban aquaculture stands as an indispensable cornerstone for achieving global urban food security and climate-resilient aquaculture.

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Revolutionizing Rice Production: The Role of CRISPR-Cas9 in Agricultural Resilience



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The increasingly difficult issue of feeding the world's constantly escalating population has increased the appeal for high agricultural productivity. Rice, as an essential crop upon which more than 50% of the global population relies for sustenance. The world's food security is largely dependent on rice's agricultural performance. Crop plant development has long benefitted from both conventional breeding techniques and Green Revolution discoveries. However, a complete reliance on the available and naturally occurring genetic material and the extremely slow process of evolution are start to obstruct these conventional methods. In light of growing environmental concerns and decreasing land for agriculture, researchers have taken into consideration the developments in current biotechnology. In the field of biotechnology, genome editing, particularly through the ground-breaking CRISPR-Cas9 technology, has proven to be highly efficient. Through this method, it becomes possible to develop desirable traits within rice, which is why it becomes a highly resilient crop that is capable of adapting itself to the ever fluctuating climate around the globe.

In view of being the second largest producer of rice in the world, India can be seen as a key centre for these changes in agriculture, mainly in view of the fact that there exists a significant gap in rice production in India. The current average rice production rate in India ranges from 2.7 to 3.0 tons per hectare. However, compared to its biological capacity, the yield per hectare can range from 6 to 8 tons. It should be noted that the unfavourable impact of biotic and abiotic stresses is one of the reasons for farmers cannot accomplish maximum production. The fatal damage to agriculture is brought about by biotic stressors, such as a wide array of persistent pests and dangerous diseases, beside abiotic stressors, which involve long drought periods, high soil salinity, and temperature changes. Despite this, losses in highly-productive regions such as Punjab still reach 15% to 30% per year. Countrywide, the mentioned stressors can decrease the potential harvest by 30% to 50%. Therefore, there is an enormous opportunity in the use of accurate and targeted genome editing in order to eliminate some of the significant flaws and ensure the nation's food security.

There have been significant expansions in the area of plant genetics with regard to the way that CRISPR-Cas9 systems work. In fact, they were first discovered to function perfectly as bacteria defence mechanisms against invasive viruses. This technology allows for alteration of the genetic information in a highly precise manner and even multiplex, which means that numerous genes can be edited at the same time. In particular, a guide RNA molecule guides the Cas9 enzyme functioning like molecular scissors to its target site in plant DNA. Double strand breaks are introduced at specific sites on the DNA molecule using the Cas9 protein after the target has been identified. The natural repairing system of the plant cell, repair the DNA break once it is made in this precise way. It is possible for scientists to influence the effect of this natural repairing system to produce gene knockout or gene insertion and deletion. Important agricultural traits like environmental stress resistance, herbicide tolerance, or crop yield and plant structure can now be altered without introducing foreign DNA material through this process.

One such gene is known as the *Gn1a* gene; it is also scientifically named as *OsCKX2*. This gene is one of the most important yield related genes and has been successfully manipulated using CRISPR technology in a bid to improve crop yields. The *Gn1a* gene regulates the degradation of cytokinin hormones, which are a vital group of growth hormones found in rice. The degradation of these hormones can be paused through the application of CRISPR technology, and therefore, a build-up of cytokinin hormones occurs locally within the meristem tissue (Li et al., 2016 ; Tabassum et al., 2021). In a direct comparison with wild-type plants and mutant varieties

generated by this technique, exhibit extraordinarily important improvements in terms of the total number of flowers development per panicle. The maximum potential yield that could be achieved biologically is thus increased, producing more grains right away.

There have been tremendous success stories regarding the correction of plant architecture. The term plant architecture affects the productivity of the plant more than simply increasing its yield. Scientists and agriculturists have paid attention to the *DEP1* gene since it plays an important role in the construction of the panicle of rice. One particular type of this gene generates a dense and upright panicle. Similarly, the *IPA1* gene, which is an excellent controller for the Plant Architecture has been extensively modified and restrict the naturally occurring cell division process of the transcripts of the *IPA1* gene, scientists introduce mutations in the *IPA1* gene, leading to continuous and prolonged expression of the gene. The phenotype that is produced through such genetic modifications becomes extremely robust, possessing much stronger and bigger tillers capable of bearing more heavy grains on each panicle without falling down (Li et al., 2016 ; Tabassum et al., 2021).

In addition to the above, each individual rice kernel is an excellent choice for CRISPR manipulation due to its physical properties and ultimate weight being significant parameters contributing to agricultural yield and value. Specifically, some regions of the *GS3* gene act as regulators in influencing the ultimate weight and length of the developing grain. Geneticists have successfully modified the plants to produce significantly larger grain and increased grain weight via loss of function mutations within these specific regulator domains in the mutant lines. Most importantly, the plants were healthy due to these specific modifications having been done without compromising other agronomically important traits (Li et al., 2016 ; Tabassum et al., 2021).

Competition from weed is yet another important challenge facing farmers today, which eventually gave rise to the development of herbicide tolerant rice through genome modification. The rice was intelligently developed by introducing specific alterations to the *ALS* gene sequence of the plant. Genetic engineers successfully conferred high tolerance to broad spectrum herbicides, such as pyroxsulam and flucarbazone, to the rice plants by creating mutants. Incredibly, these genetically modified lines were able to show that they can resist herbicide treatments at concentrations up to 32 times the normal level of application (Zhang et al., 2021). These plants constitute an incredible improvement because they have not only maintained their high yields but have also remained fully fertile, making them perfect for weed control systems.

Through the extremely precise technology of CRISPR, biotic and abiotic challenges have been solved using the latest techniques in rice plants. Through the removal of the promoter for the regulatory function of *Xa13*, researchers have been able to developed the bacterial blight resistant rice mutants without damaging any pollen formation or making the plant infertile (Li et al., 2019). In a similar way, the disease called Rice Tungro Disease has been combated through the editing of some YVV amino acid sites in the *eIF4G* gene to avoid the virus taking control. Researchers created a drought and salt tolerant mutants by targeting *OsDST* gene, which has increased osmotic resistance because of its ability to regulate stomatal closure to retain water and maintain ROS levels in the cells (Kumar et al., 2020).

Recently, this state-of-the-art biotechnology resulted in an important milestone in Indian agriculture. The dawn of the new age of predictive crop cultivation came on May 4, 2025, when the Indian Council of Agricultural Research (ICAR) officially announced the development of India's first genome-edited rice varieties. Scientists at ICAR-IIRR, based in Hyderabad, developed the first one of such cultivars called DRR Dhan 100 (Kamala), which is a genome-edited version of the well-known and widely cultivated Samba Mahsuri variety. The approach to enhance the overall number of grains on each panicle was achieved through the use of CRISPR-Cas technology to specifically target and modify the *CKX2* (*Cytokinin Oxidase 2*) gene. After rigorous countrywide field trials, the results were indeed amazing, with the Kamala outperforming the base-line Samba Mahsuri variety by a staggering 19%. It was clear from the outstanding yield performance, averaging 53.7 quintals per hectare and reaching up to a high of 88.96 quintals per hectare in some perfect plots (ICAR Press note, 2025).

Moreover, scientists from the Institute of Agricultural Research and Education of ICAR - IARI, have developed yet another revolutionary species of Pusa DST Rice1. Pusa DST Rice1 was bred to be an advanced form of the already popular fine-grain rice known as MTU1010. The DST (Drought and Salt Tolerance) gene of this variety was accurately manipulated with the help of CRISPR-Cas technology. In addition, Pusa DST Rice 1

was able to preserve the excellent characteristic trait of its parent MTU1010, that of fine grains, under rigorous trials in fields across India. However, most importantly, under extreme stress situations, it was able to yield 10 to 30% higher compared to its wild type. This is because it has tremendous adaptation ability due to the fact that physiologically, it can be grown in both Rabi and Kharif seasons. In difficult and stressing inland areas of Andhra Pradesh, Telangana, Karnataka, Tamil Nadu, Puducherry, Kerala, Odisha, Jharkhand, Bihar, Uttar Pradesh, West Bengal, Chhattisgarh, Maharashtra, and Madhya Pradesh, it has performed exceptionally well (ICAR Press note, 2025).

In conclusion, one of the greatest scientific advancements of the twenty-first century lies in the use of CRISPR-Cas9 technology for the purpose of advancing agricultural technology and offering a more efficient method of overcoming the disadvantages of traditional breeding processes. The redesigning of staple crops through the precise targeting of the pathways responsible for the production of crops, their architecture, their ability to withstand diseases, and environmental conditions is done through the use of CRISPR-Cas9 technology and is undoubtedly essential in meeting the demands of the growing population and an increasingly warming climate. The success of the genome-editing technology can be seen from its introduction through the development of the first genome edited crops in India, the DRR Dhan 100 and Pusa DST Rice 1. Looking ahead to the future, it is not only the financial potential that farmers working under tough environmental conditions will benefit from the application of precise genome editing, but also it will act as the foundation of food security for generations to come.

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The Role of Agriculture in Rural Development, Poverty alleviation and Prosperity Enhancement



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Abstract

Agriculture in rural areas serves not only as a source of sustenance but also as a vital economic activity that supports livelihoods and entrepreneurship. The main objective of this paper is to present perspectives on the role of agriculture in rural development and its contribution toward poverty alleviation and rural prosperity enhancement. This paper discusses rural development through various dimensions such as income generation, employment generation, social empowerment, and food security. It further examines the crucial relationship between agriculture and rural development while highlighting the opportunities and possibilities for sustainable rural progress.

Keywords: Rural Development, Poverty Alleviation, Rural Prosperity, Food Security, Employment Generation, Social Empowerment.

Introduction

Rural development has been an important issue throughout the history of countries across the world. Although millions of rural people have escaped poverty as a result of rural development in many countries, a large majority of rural people continue to suffer from persistent poverty. Furthermore, the progress of the rural areas and rural development is closely linked with agriculture and allied activities. For effective rural development, the policy makers of the country mainly focus and recognize the importance and vital role of agriculture in the rural development, and take certain measures to frame a mandate and objectives for proceedings and planning of the programmes which ultimately improve the living conditions of rural areas of the country.

Rural: Rural refers to regions, where the people are primarily engaged in primary occupations such as agriculture and related activities, working closely with natural resources. According to Srivastava (1961). Rural communities are generally sparsely populated and are located away from the direct influence of major towns and cities. These areas usually possess an agricultural character, and the lifestyle of the rural people differs from that of the urban populations due to limited access to services and infrastructure. Rural societies are often identified by features such as low population density, reduced social and spatial mobility, and a comparatively slower rate of social change.

Development: Refers to the process of the growth, progress and transformation. It is gradual in nature and occurs through different stages over time. Development involves continuous improvement in economic, social, and institutional conditions, leading to overall advancement in the quality of life.

Rural Development (RD) refers to a continuous process aimed at improving the quality of life and overall well-being of people living in the rural areas. It focuses on enhancing economic opportunities, social conditions and

cultural aspects of rural communities through collective efforts. According to Agarwal (1989), rural development involves planned strategies intended to uplift the economic and social status of disadvantaged rural populations. The United Nations describes rural development as a process in which people, along with government institutions, work together to improve the economic, social, and cultural conditions of rural communities and integrate them into the nation's development. It also promotes the transformation of traditional rural lifestyles into more progressive and sustainable ways of living. To understand rural development more clearly it is very important to examine the fundamental and basic elements of the Rural Development, which are given below,

The Basic Elements of Rural Development:

Whatever the geographic location, culture, and historic stage of development of a society, there are at least three basic elements which are considered to constitute the 'True' meaning of the rural development. They are as follows (Todaro 1977)

Basic Necessities of Life: People have certain basic needs, without which it would be impossible or very difficult for them to survive. The fundamental requirements for survival include food, proper clothing, housing, elementary education, healthcare, services, and security of life and property. When one or more of these necessities are lacking critically in a short supply, such a condition may be described as 'Absolute Underdevelopment'.

Self-Respect: Every person and every individual of the nation seek some sort of self-respect, dignity, and honour. Absence or denial of self-respect indicates 'Lack of Development'.

Freedom: In this context, freedom refers to political and ideological freedom, economic freedom, and social freedom and freedom from servitude. As long as a society is bound by the servitude of men to nature, ignorance, other men, institutions and dogmatic beliefs, it cannot claim to have achieved the goal of 'Development', Servitude in any form reflects a state of Underdevelopment.

The Characters of the Rural Sector

1. Excessive Dependence on Nature
2. Preponderance of Small Uneconomic Land and Livestock Holdings
3. Low Capital Labour Ratio
4. Low Factor Productivity
5. Long Gestation and low rate of turnover
6. High incidence of poverty and Unemployment
7. Preponderance of Illiterate and Unskilled Workforce
8. Lack of basic Infrastructure

'Poverty, Poverty alleviation and Poverty reduction; Prosperity enhancement'

Poverty: The basic definition of poverty is the inability of an individual to possess sufficient resources to satisfy his or her basic needs. The definition and range of basic needs depend on the place and time, or even the source of the definition. Nevertheless, poverty is a complex issue that extends beyond mere financial aspects. In this sense, poverty is also examined in non-monetary terms from a multidimensional viewpoint considering education, health and/or living conditions. Some of the most commonly used non-monetary measures of poverty include the Human Development Index, the Multidimensional Poverty Index, and the Global Hunger Index.

Poverty alleviation and poverty reduction Poverty alleviation is any process that reduces income fluctuation between poor and non-poor scenarios (Adongo and Deen-S Warray 2006). This is different from **poverty reduction**, which aims to permanently move an individual or household from a poor to a non-poor scenario. Eliminating poverty is one of the main objectives in most of the international treaties and commitments. Eradicating extreme poverty and hunger is the first and the foremost of the seventeen Sustainable Development Goals. Traditionally poverty was defined in terms of income, however, there has been a change in the way poverty is understood today. It is widely accepted now that no single indicator can capture the multiple aspects that contribute to poverty. Today poverty is seen as a multidimensional phenomenon including lack of healthcare, education, employment, housing, opportunities, and choices, etc. Eradication of poverty is a herculean task and cannot be done by the government alone.

The most common way used to measure poverty is based on incomes. A person is considered poor if his or her income level falls below some minimum level necessary to meet basic needs. This minimum standard of

living is commonly referred to as the “poverty line.” The basic requirements needed to meet human needs differ across societies and over time.

Prosperity enhancement in rural development refers to the enhancement and improving of the economical, social and living conditions of the rural people through provision of better opportunities for financial independence, employment, infrastructure, health and education. Gunnar Myrdal viewed rural prosperity as the reduction of inequalities and the balanced growth of economic and social opportunities in rural communities.

Agriculture is a cornerstone of rural communities and serves as the primary economic source in numerous countries worldwide. Any sudden and significant changes affecting the agricultural sector could lead to severe effects on social and political stability in developing nations. Additionally, agriculture is crucial for rural development, particularly regarding land utilization, in nations where the sector holds less economic importance. In remote areas, farming may be essential for sustaining economic and social infrastructure. Policies for rural development should leverage agriculture's role by enhancing on-farm practices and promoting supportive services to ensure sustainability. The primary potential benefits of agriculture to rural development include job creation, support for related businesses, and environmental services.

As discussed, India is predominantly a rural-based country, the impact of development policies is often reflected in rural villages. Therefore, rural development can be assessed through the changes occurring within rural communities.

INCOME GENERATION

Agriculture is widely recognized as the backbone of India; now we should also have our view as it plays a central role in Indian income generation. India is characterized by diverse agroclimatic conditions and different soil types. The major part of the Indian agriculture sector accommodates small and medium farmers. One of the most direct ways in which agriculture can alleviate poverty is by increasing the income of smallholder farmers. Studies have shown that a 1% increase in agricultural productivity can lead to a 0.6-1.2% reduction in poverty. The sales of the vegetables, milk, and poultry products may add additional income to the farmer, leading to the generation of higher income standards. This increase in income improves the farmers' livelihoods and enhances their ability to invest in education, healthcare, and better farming techniques. As a result, this increase creates a positive cycle that can further boost agricultural productivity and foster sustainable development within rural communities.

SOCIAL EMPOWERMENT

Agriculture can also contribute to the poverty alleviation by promoting the social empowerment particularly among indigenous and marginalized communities, including women and youth. Engaging in agriculture can provide these groups with a sense of identity, purpose, and agency, as well as opportunities for leadership and decision-making. Empowering women in agriculture through targeted interventions, such as land rights, training, and financial inclusion, can not only improve their productivity and incomes but also enhance their social status and bargaining power within households and communities. Similarly, engaging youth in agriculture can provide them with viable livelihood opportunities and reduce rural-urban migration. This is particularly important in countries with large youth populations, such as India, where nearly 60% of the population is under the age of 35. Providing youth with access to land, credit, training, and markets can help them establish sustainable livelihoods and reduce unemployment.

EMPLOYMENT GENERATION

Agriculture also provides employment to rural youth in developing countries. It is one of the largest unorganized sectors of the economy. Agriculture is one of the largest unorganised sectors in developing the economies, jobs extend far beyond traditional crop cultivation. The entire rural non-farm economy depends heavily on agricultural production and its ecosystem. Through dairy and livestock it engages millions in the milk production, poultry, and animal husbandry. Additionally, the horticulture and aquaculture sectors generate high value employment opportunities in fruit and vegetables cultivation as well as the fish farming. Farming is the corner stone for agro-based industries, which may create a chance of employment in production of the raw materials, value addition, supply chain thereby benefiting rural communities by improving income stability and living condition thriving for better conditions.

FOOD SECURITY

With respect to food, agriculture and rural development the main concerns are how can agriculture and rural development contribute to poverty eradication and how can poor households and individuals have access to the food they need. It is clear, however, that poverty and food insecurity, cannot be addressed from a purely sectoral viewpoint. Many researchers explain that agriculture is the primary source of food production and nutritional security in rural areas. Increased agricultural productivity ensures the availability of sufficient food grains, vegetables, milk, fruits, and livestock products for growing populations.

Food security can be understood through four major dimensions, which are food availability, food accessibility, food utilization, and food stability. Food availability refers to the adequate access of the food resources to the populations in rural areas, which is only possible through use of better production technology of the crops, Food accessibility refers to adopting the better income generation practices also lead to better purchasing power of an individual, Food utilization the agriculture also supports the supply of the safe and nutritious food to the individual which ultimately declines the rate of hidden hunger and malnutrition, Food stability the agriculture leads to the provision of the food all around the year, even during drought, floods and market fluctuations. Thus, agriculture plays a vital role in ensuring food security, improving nutrition, reducing poverty, and promoting sustainable rural development.

Conclusion

Agriculture plays a vital role in rural development by generating employment opportunities, increasing income levels, ensuring food security, and promoting social empowerment among rural communities. As the backbone of rural economies, agriculture contributes significantly toward poverty alleviation and prosperity enhancement. Sustainable agricultural development, along with effective rural development policies and institutional support, can improve the living conditions of rural populations and create long-term socio-economic stability. Therefore, strengthening the agricultural sector is essential for achieving inclusive growth, rural transformation, and sustainable development in developing countries like India.

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Petroleum-Based Plastics: A Silent Threat to Aquatic Ecosystems



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Abstract

Petroleum-based plastics are widely used due to their durability and low cost, but their improper disposal has created a major threat to aquatic ecosystems. Plastics enter water bodies through sewage, industrial discharge, urban runoff and fishing activities, where they degrade into microplastics and nanoplastics. These particles harm aquatic organisms through ingestion, entanglement and toxic chemical exposure, while also moving through food chains and raising concerns about food safety and human health. Plastic pollution further damages aquatic habitats, affects water quality and contributes to climate change. In India, increasing plastic waste and weak waste management intensify this issue despite policy measures. Addressing plastic pollution requires stronger regulations, improved waste management, public awareness and sustainable alternatives to protect aquatic ecosystems and environmental health.

Keywords: Petroleum-based plastics; Plastic pollution; Aquatic ecosystems; Microplastics; Nanoplastics; Waste management.

Introduction

Plastic has become an inseparable part of modern life. From water bottles and food packaging to fishing gear and medical equipment, plastics are everywhere. Their durability, lightweight nature and low production cost made them one of the greatest industrial inventions of the 20th century. Yet, beneath this convenience lies a growing environmental crisis. Petroleum-based plastics are silently polluting rivers, lakes, oceans and wetlands threatening aquatic biodiversity and human health alike (Tamayo-Belda *et al.*, 2023). Today, aquatic ecosystems across the globe are drowning in plastic waste. Every year, millions of tonnes of plastic enter water bodies through rivers, sewage systems, industrial discharge and coastal dumping. Unlike organic materials, plastics do not decompose naturally. Instead, they persist for decades, breaking into smaller fragments known as microplastics and nanoplastics, which spread throughout aquatic environments and enter food chains (Singh *et al.*, 2020).

What Is Petroleum-Based Plastics?

Petroleum-based plastics are synthetic polymers manufactured mainly from crude oil and natural gas. During production, petroleum is refined into chemical compounds called monomers, which are then linked together to form long polymer chains through polymerization. Common types include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET) (Kumari *et al.*, 2023). These plastics are widely used in packaging, household goods, construction materials, automotive parts and countless consumer products.

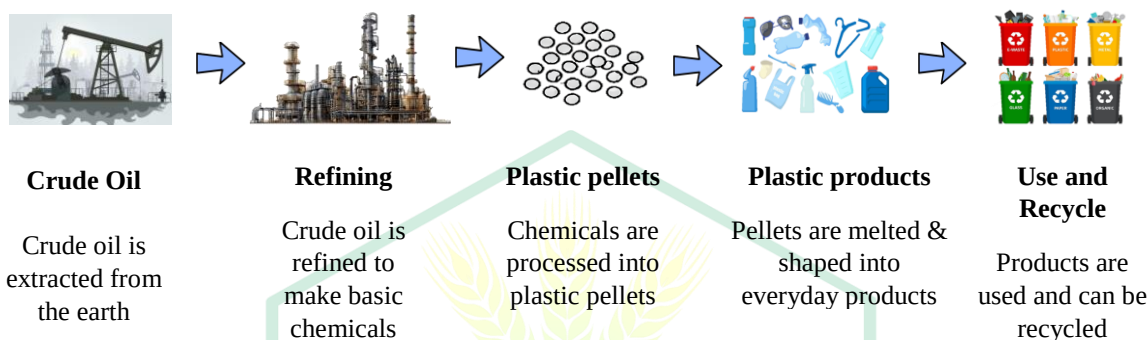
Their popularity stems from several useful properties:

- Lightweight and durable
- Resistant to water and chemicals
- Flexible and inexpensive
- Easy to manufacture in large quantities

Due to their reliance on non-renewable fossil resources and the effects of plastic trash accumulation on the environment, the widespread use of petroleum-based plastics has sparked concerns about sustainability. Their manufacture produces greenhouse emissions that contribute to climate change and uses a substantial quantity of

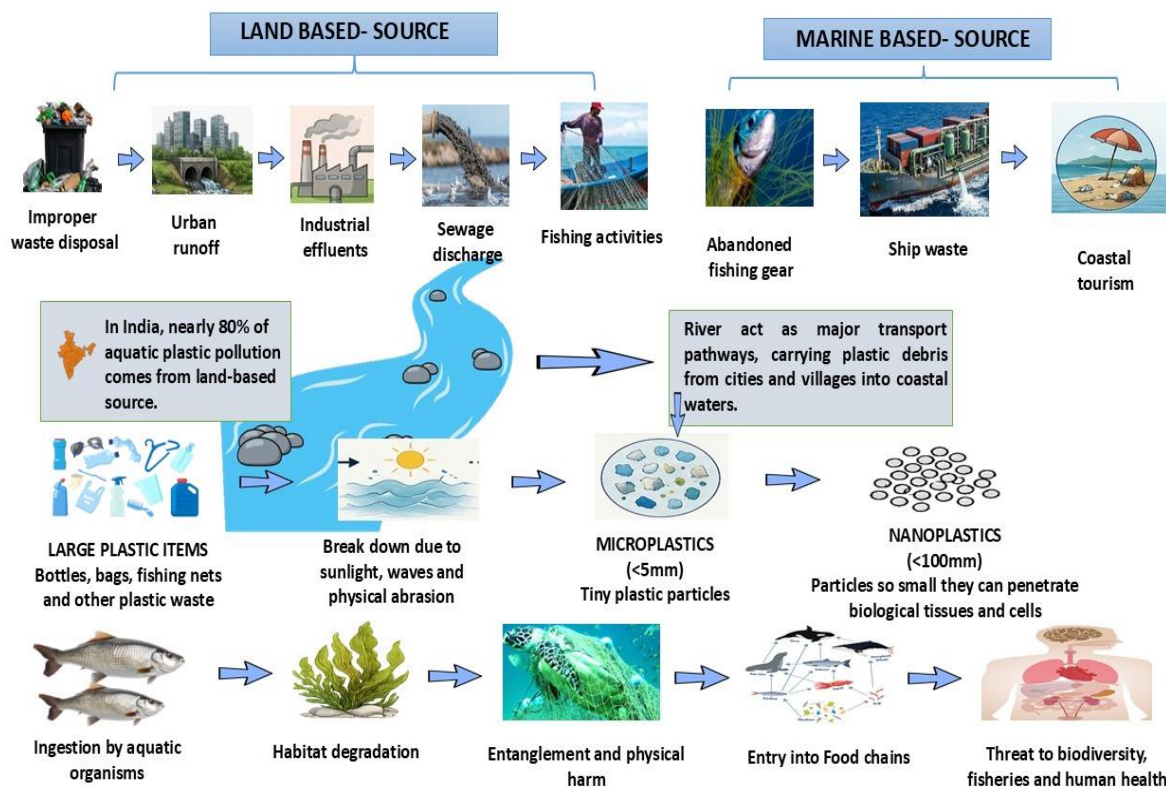
oil and gas (about 10% of U.S. oil and gas output is devoted to the creation of synthetic plastics). Furthermore, these polymers' resilience allows them to endure in ecosystems for decades or more without degrading organically. Research into bio-based substitutes that resemble petroleum-derived plastics but are made from renewable biomass is one way to solve these issues. However, because of their cost-effectiveness and well-established production infrastructure, petroleum-based plastics continue to dominate the market (Singh *et al.*, 2020). Developing ways to lessen petroleum-based plastics' environmental impact while preserving their practical advantages requires an understanding of their definition, kinds, production methods and important characteristics.

Petroleum Based Plastic



Pathways of Plastics into Aquatic Environments

Plastic pollution in aquatic systems mainly originates from human activities. Improper disposal of waste, urban runoff, industrial effluents, sewage discharge and fishing activities continuously introduce plastics into rivers and oceans. In India, nearly 80% of aquatic plastic pollution comes from land-based sources discharge (Amrutha *et al.*, 2020). Rivers act as major transport pathways, carrying plastic debris from cities and villages into coastal waters (Neelavannan *et al.*, 2023).



- The distribution and quantity of microplastics are influenced by the flow dynamics of rivers, which are important transporters of plastics from terrestrial to marine environments. The patterns of movement and deposition along Indian beaches and estuaries are influenced by seasonal fluctuations, particularly during the monsoon (Singh *et. al.*, 2024).
- Plastics are directly introduced into coastal waterways by marine-based sources such as shipping garbage and fishing gear (ghost nets). Polyethylene (PE) and polypropylene (PP) fragments, fibers, and foams have been shown to be the predominant polymers associated with these activities in studies conducted along India's southwest coast.
- All things considered, the routes by which plastics enter Indian aquatic habitats are intricate and varied, comprising inputs from both terrestrial and marine sources that are mediated by hydrological processes and human activity. Improved solid waste management regulations, riverine transportation monitoring and focused actions at pollution hotspots are all necessary to address this (Jeyasanta *et. al.*, 2023).

Research into bio-based substitutes that resemble petroleum-derived plastics but are made from renewable biomass is one way to solve these issues. However, because of their cost-effectiveness and well-established production infrastructure, petroleum-based plastics continue to dominate the market. Developing ways to lessen petroleum-based plastics' environmental impact while preserving their practical advantages requires an understanding of their definition, kinds, production methods and important characteristics.

Types of Plastic Pollution in Water

Plastic pollution in aquatic environments is a complex issue involving a spectrum of particle sizes and origins. The main types include macroplastics (>5 mm), microplastics (<5 mm) and the emerging concern of nanoplastics (typically <100 nm) (Alimi *et. al.*, 2018). Macroplastics are large, visible debris such as bottles and bags, while microplastics are smaller fragments resulting from the breakdown of larger plastics or manufactured at microscopic sizes. Nanoplastics represent an even smaller fraction, with unique environmental behaviours and risks. Microplastics are further classified as primary (intentionally produced small particles) or secondary (formed by fragmentation of larger plastics). The persistence of these plastics is driven by their resistance to degradation; environmental processes like UV radiation, mechanical abrasion, and biological activity gradually fragment macroplastics into micro and nanoplastics over time. Understanding these categories and their transformation pathways is crucial for assessing ecological risks and developing mitigation strategies.

Macroplastics

Macroplastics are large plastic debris such as bottles, bags, fishing nets and packaging materials. They are highly visible pollutants that can cause entanglement or ingestion hazards for aquatic life. Over time, macro plastics serve as the primary source material for secondary micro and nano plastics through environmental degradation processes.

Microplastics

Microplastics are defined as plastic particles less than 5 mm in diameter. They can be:

- **Primary microplastics:** Manufactured at small sizes for use in products like cosmetics (microbeads), industrial abrasives, or pre-production pellets ("nurdles").
- **Secondary microplastics:** Result from the fragmentation of larger plastics due to UV exposure, mechanical abrasion (waves/currents), or biological activity. Microplastic pollution is widespread in both marine and freshwater systems; common polymers include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET).

Nano plastics

Nanoplastics are typically defined as plastic particles smaller than 100 nm to 1 µm. Their detection is challenging due to their minute size but they are increasingly recognized as a significant risk because they can cross biological membranes more easily than larger particles. Nanoplastics originate from further breakdown of microplastics or direct release from certain products (Wang *et. al.*, 2024).

Persistence & Fragmentation Process

Plastics persist in aquatic environments due to their chemical stability. Fragmentation occurs via:

- **Photodegradation:** UV radiation breaks down polymer chains.

- Mechanical abrasion: Physical forces from waves/currents.
- Biological activity: Some organisms contribute to fragmentation. This process transforms macro into micro, then nano-sized plastics over time; smaller fragments have higher surface area to volume ratios which influence pollutant adsorption and ecological impact.

Impacts on Aquatic Organisms

Plastic pollution affects aquatic life physically, chemically and biologically.

Physical Effects

Aquatic species that ingest plastic typically develop gastrointestinal blockage, which reduces food absorption and causes hunger. Research carried out in Indian coastal waters and river systems like the Mahanadi have revealed the presence of microplastics in fish digestive tracts, suggesting widespread ingestion. Entanglement in larger plastic debris can cause illness or even death, even though ingesting impacts are the primary focus of Indian research since microplastics are more prevalent than macroplastics (Ganie *et. al.*, 2024).

Chemical Effects

Polychlorinated biphenyls (PCBs) and heavy metals, which adsorb onto microplastic surfaces found in sediments and biota along India's southwest coast, are transported by plastics. Additionally, plastic chemicals like phthalates and bisphenol A (BPA) seep into water bodies and interfere with aquatic creatures' endocrine systems. Although there are still few direct studies, BPA exposure has been connected to anomalies, changed behaviour, and decreased survival in aquatic creatures worldwide with concerns for Indian species (Khan *et. al.*, 2022). Through bioaccumulation, the presence of these substances along with microplastics raises the risk of toxicity.

Biological Effects

Exposure to microplastics affects growth, reproduction, immunity, and behaviour in aquatic organisms. Studies have shown altered swimming patterns, reduced feeding, developmental abnormalities, oxidative stress and increased mortality in fish and freshwater organisms exposed to plastic particles. (Roy *et. al.*, 2023).

Bioaccumulation and Food Chain Transfer

Microplastics, tiny plastic particles smaller than 5 mm, have emerged as a hidden threat to oceans and rivers, beginning at the very base of the aquatic food chain. These particles are often consumed by plankton, the microscopic organisms that form the foundation of aquatic ecosystems. When small fish feed on plankton, they unintentionally ingest microplastics, which gradually accumulate in their bodies. As larger predators consume these smaller fish, the microplastics move upward through the food chain in a process known as trophic transfer. This silent movement of plastic particles through aquatic ecosystems raises serious concerns about environmental health and potential risks to higher organisms, including humans.

Microplastics can carry toxic chemicals like heavy metals and pesticides, which may pose health risks when consumed by humans through seafood. Regular consumption of contaminated seafood could expose people to these pollutants, raising concerns especially for vulnerable groups such as pregnant women and children. The presence of microplastics in popular seafood highlights the importance of monitoring and managing plastic pollution to ensure seafood safety.

Environmental Impacts Beyond Organisms

Plastic pollution causes serious damage to aquatic environments beyond just harming individual organisms. It degrades vital habitats like coral reefs and mangroves, which serve as nurseries for many marine species and protect coastlines from erosion. The accumulation of plastics alters sediment properties, affecting how sediments hold nutrients and oxygen, which can disrupt the delicate balance needed for healthy ecosystems. Plastic debris also impacts water quality by releasing harmful chemicals and reducing oxygen levels, creating stressful conditions for aquatic life.

Moreover, the entire lifecycle of plastics from production to disposal contributes significantly to climate change through greenhouse gas emissions. Plastic manufacturing relies heavily on fossil fuels, and as plastics break down in the environment, they release gases like carbon dioxide and methane that worsen global warming. This creates a troubling feedback loop where climate change accelerates plastic pollution spread and plastic pollution in turn intensifies climate impacts. For example, warming oceans can increase plastic degradation rates and microplastic release.

Together, these environmental impacts threaten ecosystem services such as fisheries, coastal protection and carbon sequestration. Addressing plastic pollution requires urgent global action focused on reducing plastic use, improving waste management and developing sustainable alternatives. Protecting habitats like coral reefs and mangroves is especially critical to maintain biodiversity and resilience against climate change. Understanding these broad environmental effects highlights why tackling plastic pollution is essential not only for wildlife but also for the health of the planet.

In Scenario in India

India faces a significant challenge with plastic pollution due to its high plastic consumption and rapid waste generation, estimated at around 9.4 million tonnes per year as of 2019. Rivers like the Ganga are major contributors to this problem, carrying large amounts of mismanaged plastic waste into aquatic ecosystems. Modeling studies predict that without improved waste management, plastic pollution from the Ganga could reach between 550 and 750 kilotonnes annually by 2061, but enhanced waste management efforts could reduce this by over 80%. Coastal areas in India also suffer from plastic pollution hotspots, impacting marine biodiversity and local livelihoods (Anand *et. al.*, 2026).

The Indian government has taken steps to address these issues through policies such as the Plastic Waste Management Rules, which set guidelines for collection, segregation, and recycling of plastics. In 2022, India implemented a nationwide ban on single-use plastics to curb the most common sources of plastic litter. Despite these initiatives, challenges remain in enforcement and infrastructure development, especially in informal recycling sectors that handle a large portion of plastic waste but often lack formal support.

Efforts to improve public awareness and promote sustainable alternatives are crucial alongside regulatory measures. Strengthening waste management systems and expanding circular economy approaches can help reduce plastic leakage into rivers and oceans. Continued research and policy innovation will be key to balancing India's growing plastic use with environmental protection goals.

Conclusion

Petroleum-based plastics, long lauded for their simplicity and durability, have now become a severe danger to aquatic ecosystems across the world. Rapid urbanization, rising plastic usage, and fragile rivers and coasts provide India with a particularly significant issue. Large plastic debris obstructing streams and microscopic nanoplastics getting into food chains are examples of pollutants that disrupt aquatic life through chemical and physical effects, destroy ecosystems, and accelerate climate change. The seriousness of this issue is demonstrated by water bodies like the Arabian Sea and the Ganga River, where improperly managed plastic garbage endangers human health, fisheries, and wildlife.

Despite these obstacles, plastic pollution may be decreased by taking decisive action and sharing accountability. The 2022 ban on certain single-use plastics and India's Plastic Waste Management Rules are significant milestones, but more funding for sustainable alternatives, better recycling programs, and more enforcement are still required. Scientific research, circular economy principles, and public awareness may all help conservation initiatives. Society can save aquatic habitats and create a cleaner, healthier future for future generations by encouraging sustainable solutions and cutting back on plastic consumption.

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From decoration to detox: The pollution removing potential of indoor ornamental plants



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Abstract

Indoor air pollution has become a significant environmental and public health concern due to increased urbanization and the construction of energy-efficient but poorly ventilated buildings. The present study highlights the role of indoor ornamental plants as sustainable and eco-friendly biofilters for improving indoor air quality (IAQ). Common indoor pollutants such as carbon dioxide (CO₂), particulate matter (PM), volatile organic compounds (VOCs), formaldehyde, benzene, and nitrogen oxides adversely affect human health and contribute to sick building syndrome. Ornamental plants including *Epipremnum aureum*, *Chrysalidocarpus lutescens*, *Sansevieria trifasciata*, *Spathiphyllum wallisii*, *Dieffenbachia seguine*, *Hedera helix*, *Asplenium nidus*, and *Ficus elastica* etc. demonstrate significant pollutant removal efficiency through mechanisms such as stomatal uptake, cuticular adsorption, photosynthesis, and rhizospheric microbial degradation. These plants reduce indoor pollutant concentrations, enhance oxygen levels, and regulate humidity through transpiration. The study concludes that indoor ornamental plants provide a cost-effective, natural, and sustainable approach for mitigating indoor air pollution while improving human health and environmental quality.

Introduction

Plants are often referred to as the “lungs of cities” due to their ability to remove pollutants from the air and improve overall air quality. Research by Powe and Willis (2004) demonstrated that vegetation contributes to public health by lowering mortality rates and reducing hospital visits, as plants act as natural air purifiers that help minimize air pollution. In recent years, the global energy crisis has encouraged the construction of tightly sealed, energy-efficient buildings designed to conserve heat and reduce energy consumption. However, while these structures are effective in saving energy, ventilation systems are sometimes neglected. Poor ventilation limits air circulation within indoor spaces. Consequently, harmful pollutants and contaminants may accumulate to unsafe levels indoors. This reduced air exchange can lead to serious health problems for occupants over time.

According to WHO Around 2.1 billion people worldwide (around a quarter of the global population) cook using open fires or inefficient stoves fuel led by kerosene, biomass (wood, animal dung and crop waste) and coal, which generates harmful household air pollution. At current rates, only 78% of the global population is expected to have access to clean cooking by 2030. This shortfall would leave nearly 1.8 billion people still without clean cooking solutions. Household air pollution was responsible for an estimated 2.9 million deaths per year in 2021, including over 309 000 deaths of children under the age of 5. Around 95 million disability-adjusted life years (DALYs) were attributable to household air pollution exposure in 2021.

Poor indoor air quality (IAQ) is strongly associated with sick building syndrome, a condition characterized by symptoms such as respiratory problems, severe headaches, irritation of the eyes and skin, allergic reactions, fatigue, and even metabolic disorders. In severe cases, prolonged exposure to polluted indoor environments may lead to life-threatening outcomes. Beyond its health impacts, indoor air pollution also decreases work efficiency and overall productivity. It further increases medical expenses, thereby creating an additional economic burden on individuals and society.

In recent years, the energy crisis has encouraged the construction of air-tight and well- insulated buildings that require less energy for heating. However, while focusing on saving energy, proper ventilation systems are

often neglected. As a result, limited air exchange allows harmful pollutants to build up inside closed spaces, sometimes reaching toxic levels and causing serious health problems. Since people today spend about 85–90% of their time indoors in places like homes, schools, and offices, maintaining good indoor air quality has become very important for protecting health.

Indoor Air Pollutants

Poor indoor air quality (IAQ) is strongly linked to sick building syndrome, a condition characterized by symptoms such as breathing difficulties, intense headaches, eye and skin irritation, allergies, fatigue, and metabolic disturbances. In extreme situations, prolonged exposure to poor IAQ may even result in fatal outcomes.

In addition to carbon dioxide (CO₂), indoor environments contain several other harmful pollutants, are particulate matter (PM), volatile organic compounds (VOCs) and carbon monoxide (CO). The American Society of Heating, Refrigeration, and Air-Conditioning Engineers standard (ASHRAE Standard 62.1) recommends that the maximum acceptable CO₂ concentration for comfort should not exceed 700 ppm. Volatile organic compounds such as formaldehyde, benzene, nitrous oxide, trichloroethylene, fluorine, ammonia, radon, aldehydes, and various hydrocarbons. Continuous exposure to these chemicals can result in serious health problems including multiple chemical sensitivity, sick building syndrome, allergies, asthma, headaches, stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD), and lung cancer. These pollutants are known to cause both respiratory and cardiovascular disorders, as well as cancers of the bladder and lungs. Particulate matter (PM) are also hazardous as they can easily accumulate in the living cells and have high heavy metal content.

Maintaining clean indoor air is very important for human health and comfort. Most air purifiers cannot completely remove contaminants according to the standards set by the World Health Organization (WHO), and they are often costly. Some air purifiers may also release ozone, which can be harmful to people if it builds up to high levels. Therefore, there is a need to develop affordable and eco-friendly air purification methods. Indoor plants means the plants that can grow indoor i.e. their light, temperature and water requirements are low. They may be either flowering plants (Peace lily, Kalanchoe, Amaryllis, Hydrangeas, Poinsettia) or foliage plants (cactus, palm plants, fern and succulents) Growing ornamental plants indoors can be a simple, natural, and effective way to reduce air pollutants and improve indoor air quality.

Source of Indoor Air Pollution

Pollutant	Source	Health effect
❖ Biological Contaminants (bacteria, fungi, pollen and animal dander)	Production, Design, and Installation of asbestos-based products.	Lung cancer, malignant, mesothelioma, asbestosis and skin irritation
❖ Building materials (asbestos-containing product)	Human occupants, organic dust, stored materials, and air entering through ventilation and air-conditioning systems.	Allergies, asthma, hay fever, pneumonia, and sick building syndrome
❖ Tobacco smoking	From cigarettes, cigar or pipes. These produce some toxic chemicals and gases	Chronic respiratory symptoms; reduces the level of lung function in children; implicated as a cause of lung cancer in adults, tuberculosis, Heart diseases and general irritation of the eyes, throat, nose and lungs
❖ Heaters, insulation and moist materials. Air conditioning systems	Building materials and ventilating systems	Cause dampness and mould growth, leading to microbial contamination in buildings that may result in infections and allergic or hypersensitivity reactions.
❖ Chemical pollutants (benzene, formaldehyde, adhesives, cleaners, solvents, combustion by-products and emissions from floor or wall coverings).	Furniture and decorative materials such as artificial boards, solvents, paints, adhesives and synthetic fibers are major sources of indoor pollutants. Formaldehyde, a strong fungicide, is commonly used in hospitals and research laboratories	Formaldehyde exposure can lead to long-term breathing problems, colon cancer, and brain tumors. It may also cause leukemia, developmental problems, and memory and mental health issues in young people.

	for preserving biological samples.	
❖ Using diverse electronic products. Artificial lights	Ultrasound, radiation, electrical equipment, microwave, TV, electric blanket, telephone and other processes can produce electric radiation, noise, vibration which speeds up the electromagnetic field	Noise and vibration, fatigue, poor concentration, dizziness, headache with nausea, ringing in ears and pounding heart, eye problems (burning, dry, gritty eye)
❖ Particulate matter (PM 2.5–10) Ultrafine particles	Cigarette smoke, degradation of VOCs, cooking, heating systems and resuspension of house-settled dust. Ineffective house cleaning and improper ventilation	Lung and bladder cancer, heart diseases, nervous systems and respiratory illness
❖ SO ₂ , NO ₂ , NH ₃ (wood, smoke, gas stoves)	Atmospheric pollution starts when SO ₂ is released from burning coal and oil in factories, power plants, and vehicles. Heating systems that burn wood, oil, or natural gas also add pollutants to the air. Ammonia (NH ₃) mainly comes from agriculture, especially from animal waste and nitrogen fertilizers. NO ₂ is produced indoors by fuel- burning stoves that use wood, kerosene, natural gas, or propane.	High doses of NO ₂ exposure cause severe pulmonary oedema, diffuse lung tissue inflammatory injury
❖ Ozone	Most of the formation contributors are oxidant species, such as NO ₂ and non-methane volatile organic compounds	Particularly asthmatic symptoms and respiratory illnesses Depletion of the ozone layer, which protects humans from harmful ultraviolet radiation from the sun.
❖ VOCs (household products, gases)	Paints, paint strippers • Wood preservatives • Aerosol sprays, disinfectants, • Moth repellents, air fresheners, stored fuels, dry- cleaned clothing and • Pesticides	Irritation of the eyes, nose, and throat may occur, along with symptoms such as headaches, nausea, and impaired coordination. Prolonged exposure can result in damage to the liver, kidneys, and central nervous system, and may also trigger allergic skin reactions.

Entry of pollutants into the plants and mechanism of action

Photosynthesis is the main process through which plants reduce indoor carbon dioxide (CO₂) levels. Plants absorb CO₂ from the air and release oxygen (O₂) while producing organic compounds using sunlight and water. The rate of photosynthesis depends on factors such as light intensity, CO₂ concentration, and temperature. Higher CO₂ levels under strong light conditions increase photosynthesis and oxygen release. Studies conducted by NASA showed that indoor plants can effectively remove volatile organic compounds (VOCs) from the air. Plants purify air by absorbing pollutants through leaf stomata or by trapping them on leaf surfaces. These harmful substances are either broken down into non-toxic compounds, stored, or released after transformation. Transpiration, the evaporation of water from leaves, increases indoor humidity and improves comfort in enclosed spaces. Both

aboveground parts (leaves and stems) and roots contribute to indoor air purification. Pollutants enter mainly through stomata, while the leaf cuticle also absorbs certain chemicals.

Dust and smoke resistant plants should be compact branching and closely arranged leaves possess more dust-collecting ability. Broad leaves of simple elliptical and hairy structure collect a lot of dust. Plants having auricular hairs on the base of the leaf are well adopted in heavy dust areas. Leaves with shiny surface or waxy in nature collect the dust which is easily washed away by rainy water. Plant rich in proline content are tolerant to dust pollution. Conifers reduce up to 42% dust in temperate / urban area.

The uptake of pollutants depends on their chemical nature. Hydrophilic compounds like formaldehyde mainly enter through stomata, whereas hydrophobic compounds such as benzene easily pass through the cuticle. Roots also help remove pollutants by absorbing them and supporting microorganisms that degrade contaminants. Efficient pollutant removal requires active photosynthesis, as it drives transpiration and root activity. Inside plants, enzymes such as cytochrome P450 and dioxygenase help detoxify pollutants like benzene, toluene, ethylbenzene, and xylene (BTEX). These compounds are chemically transformed into simpler substances, eventually forming organic acids that enter normal plant metabolic pathways like the TCA cycle. Thus, plants not only absorb pollutants but also metabolize them into less harmful compounds, improving indoor air quality.

Most Commonly Used Ornamental Indoor Plants for Eliminating Air Pollutants

✚ Money Plant (*Epipremnum aureum*)

Epipremnum aureum is a stress-tolerant evergreen climber of the Araceae family. It efficiently removes indoor pollutants such as benzene, trichloroethylene, xylene, and formaldehyde, while enhancing oxygen levels. The plant can grow hydroponically and performs optimally at 300 lux, 22–27 °C, and 50–70% relative humidity.

Green walls with Golden Pothos show a CO₂ reduction rate of 1.74 ppm/min placed perpendicular to windows and allowed for maximum light exposure and can reduce formaldehyde (81–96%) and particulate matter (PM_{2.5}, PM₁₀, TSP) within 24 hours.



✚ Areca Palm (*Chrysalidocarpus lutescens*)



The Areca Palm (family Arecaceae) is a popular, low maintenance indoor plant that thrives in low light and is widely grown in tropical and subtropical regions. It is known for its strong air-purifying ability, removing pollutants such as acetone, CO₂, xylene, toluene, benzene, trichloroethylene, carbon monoxide, and formaldehyde released from paints, petroleum products, and furniture.

Pollutant removal occurs through stomatal absorption, cuticular adsorption. Studies report CO₂ reduction up to 88.5%, and overall pollutant reduction up to 95.7 % including significant decreases in TVOCs, CO₂, and CO.

✚ Snake Plant (*Sansevieria trifasciata*)

Snake plant is a widely grown indoor and outdoor ornamental plant that also possesses medicinal importance. It is highly effective in removing indoor air pollutants such as formaldehyde, benzene, nitrogen oxides, xylene, and trichloroethylene. Through Crassulacean Acid Metabolism (CAM) photosynthesis, it absorbs carbon dioxide and releases oxygen both during the day and at night, making it suitable for bedrooms and enclosed spaces. The plant grows well under conditions of about 24 °C temperature, 40% relative humidity, and 1500 lux light intensity.

Due to its high carbon dioxide absorption rate and greater photosynthetic and oxygen-releasing capacity compared to dracaena, snake plant is considered an excellent choice for improving indoor air quality, especially in colder climates.



✚ Peace lily (*Spathiphyllum wallisii*)

Peace lily (*Spathiphyllum wallisii*), a member of the Araceae family, is native to tropical regions of America and Southeast Asia. It is a popular indoor plant due to its tolerance to low light, attractive white flowers, and dark green foliage, making it suitable for modern indoor living walls. Peace lily helps improve indoor air quality by



releasing oxygen, reducing carbon dioxide levels, and removing airborne volatile organic compounds (VOCs) such as formaldehyde, benzene, and trichloroethylene.

Studies, including NASA research, show its high efficiency in pollutant removal. It grows best at 20–22 °C temperature, 60–70% relative humidity, and moderate light intensity. Research indicates that peace lilies can significantly lower CO₂ and reduce benzene levels by up to 93–94%, making them effective plants for indoor air purification.

✚ Dumb Cane (*Dieffenbachia seguine*)

Dieffenbachia seguine, commonly called dumb cane, belongs to the Araceae family and originates from tropical America, where it grows in shady, humid environments with 60–70% relative humidity. The name “dumb cane” refers to temporary speech loss caused by chewing its stem.

It is widely used as an indoor ornamental plant in homes and offices due to its attractive variegated leaves, adaptability to indoor conditions, and low maintenance needs. The plant grows best at 20–25°C with moderate humidity and light intensity around 20,000 lux. Studies show that dumb cane can reduce indoor CO₂ levels (about 216.5 ppm per hour), helping improve air quality and potentially lowering cooling energy demand and urban carbon emissions.



✚ English Ivy (*Hedera helix*)



English ivy (*Hedera helix*) is an evergreen climbing vine native to Europe and West Asia and widely grown as an ornamental indoor plant. It grows best in moist, shaded conditions and avoids direct sunlight. This plant is recognized as an effective indoor air purifier, especially for removing volatile organic compounds (VOCs) and formaldehyde (HCHO).

Optimal growth conditions include light intensity of about 1200 lux, temperature 22–26 °C, and 40–60% relative humidity. Studies show that potted *Hedera helix* can reduce formaldehyde levels by 81–96% within 24 hours and accelerate pollutant removal by nearly 70% compared to natural dissipation. It also helps lower indoor CO₂ levels and increase relative humidity, thereby improving overall indoor air quality.

✚ Bird Nest Fern (*Asplenium Nidus*)

Bird's Nest Fern (*Asplenium nidus*) is a tropical fern belonging to the Polypodiaceae family and is naturally found in the rainforests of Southeast Asia and Africa. It is one of the largest fern species, showing considerable morphological diversity. Studies (Su et al., 2015) indicate that this plant helps improve indoor air quality by reducing CO₂ and formaldehyde (HCHO) levels.

It can maintain photosynthesis under artificial light at night, allowing continuous removal of gaseous pollutants. Experimental results showed that a single pot could reduce CO₂ from 2000 ppm to about 800 ppm at an average rate of 1.984 ppm/h and lower HCHO from 2 ppm to 0.1ppm at approximately 0.003ppm/h, demonstrating its effectiveness as an indoor air-purifying plant.



✚ Rubber plant (*Ficus elastica*)



The rubber plant (*Ficus elastica*) is a popular indoor ornamental plant known for its air-purifying properties. It helps improve indoor air quality by absorbing airborne pollutants such as formaldehyde and other volatile organic compounds (VOCs) through its large, glossy leaves.

The plant also contributes to oxygen production and increases indoor humidity through transpiration, creating a healthier indoor environment. Due to its tolerance to low light and minimal maintenance requirements, the rubber plant is considered an effective and sustainable choice for indoor air purification.

Some other Ornamental plants removing air pollutants

Plants	Chemical Pollutant that can be removed
Spider Plant (<i>Chlorophytum comosum</i>)	Formaldehyde, Carbon Monoxide,
Chrysanthemum (<i>Dendranthema grandiflora</i>)	Benzene, Formaldehyde, Trichlorethylene
Madag Dragon Tree (<i>Dracaena marginata</i>)	Benzene, Formaldehyde, Trichlorethylene
Aloe vera (<i>Aloe barbadensis miller</i>)	CO ₂ , Formaldehyde
Weeping fig (<i>Ficus benjamina</i>)	Octane, Terpene, Formaldehyde and CO ₂
Song of India (<i>Dracaena reflexa</i>)	Xylene, Toluene, Trichloroethylene, and Formaldehyde
Dracaena (<i>Dracaena compacta</i>)	CO ₂ , Carbon monoxide, TVOCs
ZZ plant (<i>Zamioculcas zamiifolia</i>)	Ethylbenzene, Xylene
Asparagus fern (<i>Asparagus densiflorus</i>)	Ketones, Benzene
Wax plant (<i>Hoya carnosa</i>)	Toluene, Benzene
Purple heart (<i>Tradescantia pallida</i>)	Trichloroethylene (TCE), Benzene
Lucky bamboo (<i>Dracaena asanderiana</i>)	Benzene

Conclusion

Indoor air pollution has emerged as a major environmental and public health issue due to increasing urbanization, energy-efficient buildings, and poor ventilation systems. The present review highlights that ornamental indoor plants are not only decorative elements but also effective natural biofilters capable of improving indoor air quality. Plants such as *Epipremnum aureum*, *Chrysalidocarpus lutescens*, *Sansevieria trifasciata*, *Spathiphyllum wallisii*, *Dieffenbachia seguine*, *Hedera helix*, *Asplenium nidus*, and *Ficus elastica* have demonstrated significant potential in removing pollutants like CO₂, formaldehyde, benzene, and other volatile organic compounds. Through mechanisms such as stomatal uptake, cuticular adsorption, photosynthesis, transpiration, and rhizospheric microbial activity, these plants reduce pollutant concentrations while enhancing oxygen levels and humidity in indoor environments. Therefore, incorporating ornamental plants into homes, offices, and public buildings represents a sustainable, cost-effective, and eco-friendly strategy for mitigating indoor air pollution and promoting healthier living spaces.

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Sacred Forests of the Vedas - Ecological Harmony of Trees as Living Divinity



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Abstract

Forestry trees occupy a profound position in the Vedic and ancient Indian religious imagination, where they are not treated merely as biological resources but as sacred manifestations of life, divinity, healing and ecological balance. The Vedas, Aranyakas, Upanishads, Puranic traditions and living religious customs reveal that forests functioned as centres of knowledge, meditation, ritual practice and environmental ethics. Sacred trees such as Peepal, Banyan, Neem, Bilva, Sandalwood and Palash were deeply integrated into worship, yajna, medicine, life-cycle rituals and community traditions. These associations helped conserve important tree species through reverence, taboo, temple protection and sacred grove systems. Vedic hymns and ecological thought also express the idea that Earth, plants, water, fire, air and living beings are interdependent parts of a cosmic order. This worldview created an early cultural foundation for sustainable resource use, biodiversity protection and ethical human–nature relationships. In the present era of deforestation, biodiversity decline and climate change, the ancient Indian sacred understanding of trees offers valuable insight for modern forestry. It reminds us that tree conservation cannot depend only on scientific measurement and legal protection; it also requires cultural respect, spiritual responsibility and emotional connection. Therefore, integrating Vedic ecological wisdom with contemporary forestry can strengthen conservation, agroforestry, sacred grove restoration, urban greening and climate-resilient landscape management.

Keywords: Vedic ecology; Sacred trees; Traditional ecological knowledge; Biodiversity conservation.

Introduction

Forestry trees have never been viewed in Indian civilization merely as biological resources for timber, fuel, fodder or shade. In the Vedic and post-Vedic imagination, trees were living embodiments of divinity, cosmic order, fertility, healing and ecological balance. Long before the emergence of modern forestry, ancient Indian society developed a spiritual-ecological worldview in which forests, trees, rivers, mountains, animals and human beings were understood as interdependent parts of a sacred cosmic order (Amirthalingam, 2020; Sherma, 2021). The Vedas, Upanishads, Aranyakas, Puranas and traditional religious customs repeatedly reveal that trees were not only part of the natural landscape but also part of ritual life, medicine, worship, meditation, social ethics and environmental protection (Bhattacharya, 2014; Narayanan, 2001). The Sanskrit word “Vana” means forest, but it also carries a deeper cultural meaning: a place of life, learning, silence, tapas, divine presence and natural abundance. Ancient sages did not isolate spirituality from nature; they experienced spiritual truth within forests. Many Vedic hymns and philosophical reflections emerged from forest-based hermitages, where sages lived among trees, observed seasonal cycles, used medicinal plants, performed yajnas and developed a worldview rooted in harmony with nature (Rai & Rai, 2024; Sherma, 2021). Thus, forestry trees are deeply connected to the Vedic way of life, not only as useful plants but as sacred companions in the journey of human civilization.

Forests as the Cradle of Vedic Civilization

The early Vedic world was closely associated with natural landscapes. Forests provided food, fuelwood, sacred grass, medicinal herbs, flowers, fruits, resins, shade and materials for ritual implements. Beyond practical value, forests were centres of knowledge and spiritual discipline. Many philosophical texts are known as “Aranyakas,” meaning “forest texts,” because they were studied and contemplated in forest surroundings. These texts acted as

a bridge between ritualistic Vedic practices and the deeper philosophical vision of the Upanishads (Amirthalingam, 2020; Rai & Rai, 2024). Ancient gurukulas were often located in forest environments. Students learned not only grammar, philosophy, astronomy and ritual practice but also discipline, humility and respect for natural life. The forest functioned as a living classroom, where the rustling of leaves, seasonal flowering, fruiting cycles, animal movements, rainfall patterns and soil fertility became part of experiential learning. In this sense, Vedic education was ecological at its core (Narayanan, 2001; Sherma, 2021). The forest also symbolized withdrawal from excessive material attachment. The “Vanaprastha” stage, one of the four ashramas of life, encouraged individuals to move gradually from household responsibilities towards contemplation, simplicity and spiritual maturity. This stage did not represent abandonment of society but a movement towards wisdom, restraint and harmony with nature. Trees therefore became associated with reflection, detachment and higher consciousness (Bhattacharya, 2014; Sherma, 2021).

Trees in Vedic Hymns and Sacred Thought

The Vedas contain several hymns that honour nature as sacred. The Rigveda praises cosmic forces such as Agni, Vayu, Surya, Varuna, Indra, Ushas and Prithvi. Although many hymns are addressed to divine powers, they indirectly reveal a culture that saw nature as sacred, living and morally significant. The Atharvaveda, in particular, contains hymns on Earth, healing plants and herbs, presenting vegetation as a source of health, protection and vitality (Amirthalingam, 2020; Rai & Rai, 2024). A strong ecological sentiment in Vedic literature is the reverence for Earth as mother. This worldview places humans not above nature but within nature. If Earth is mother, then forests are her breathing organs, trees are her limbs, rivers are her veins and all living beings are her children. Such a sacred ecological imagination naturally discourages reckless exploitation and promotes restraint, gratitude and protection (Bora & Kumar, 2025; Sherma, 2021). Vedic hymns also refer to plants as possessing healing energy. Herbs are invoked to remove disease, strengthen life and restore balance. This reveals an early understanding of forest biodiversity as a source of health and resilience. Ancient people did not separate medicine from spirituality; the healing power of plants was seen as both biological and sacred. Even today, many sacred trees are also medicinal trees, showing continuity between Vedic healing traditions and ethnobotanical knowledge (Amirthalingam, 2020; Narayanan, 2001).

Peepal Tree: Symbol of Life, Breath and Divinity

Among sacred trees, Peepal or Ashvattha, botanically known as *Ficus religiosa*, holds a special place in Indian religious and ecological history. It is associated with divine presence, spiritual continuity and cosmic life. In Hindu tradition, it is linked with Lord Vishnu and Lord Krishna, while in Buddhist tradition it is associated with enlightenment. Such sacred associations gave the Peepal tree a protected status across many regions of India (Bhattacharya, 2014; Narayanan, 2001). Ecologically, Peepal is significant because it supports birds, insects and other organisms, provides shade and contributes to biodiversity within rural and urban landscapes. Religiously, people circumambulate the Peepal tree, offer water, light lamps and tie sacred threads around it. These customs may appear symbolic, but they created a powerful cultural protection mechanism. A sacred tree is rarely cut; therefore, religious reverence acted as an early form of community-based conservation (Amirthalingam, 2020; Bhattacharya, 2014). The Peepal tree also represents breath and life. Its leaves tremble even in gentle wind, creating an impression of living vibration. Ancient observers may have perceived this movement as a sign of pranic energy. Therefore, the tree became a living shrine, a bridge between visible nature and invisible divinity (Sherma, 2021).

Banyan Tree: The Tree of Immortality and Shelter

The Banyan tree, *Ficus benghalensis*, is another deeply revered tree in Indian tradition. Its aerial roots descend from branches and become pillar-like trunks, creating a living forest from a single tree. This unique growth pattern made the Banyan a symbol of immortality, continuity, shelter and cosmic expansion (Bhattacharya, 2014; Narayanan, 2001). In religious customs, the Banyan is associated with divine protection and long life. The Vat Savitri vrata, observed by married women in many parts of India, involves worship of the Banyan tree. The story of Savitri and Satyavan, where devotion conquers death, is symbolically linked with the Banyan's longevity and regenerative power. Thus, the tree becomes a ritual symbol of marital devotion, life continuity and spiritual strength (Amirthalingam, 2020; Narayanan, 2001). From a forestry perspective, the Banyan provides habitat for

many species. Birds feed on its figs, animals rest in its shade and village communities gather beneath its canopy. Traditionally, the Banyan tree was often the centre of village meetings, social discussions and community life. Its sacred status helped conserve microhabitats within human settlements and protected old-growth trees across generations (Bhattacharya, 2014; Bora & Kumar, 2025).

Neem: The Sacred Tree of Health and Protection

Neem, *Azadirachta indica*, is one of the most important sacred and medicinal trees of India. In ancient customs, Neem is associated with purification, disease prevention and protection from harmful influences. Neem leaves are used in festivals, rituals, household purification, seasonal health practices and traditional medicine (Amirthalingam, 2020; Narayanan, 2001). Neem's medicinal value is widely recognized due to its antimicrobial, insecticidal, anti-inflammatory and pesticidal properties. Traditional society understood its value through long observation and cultural integration. Neem leaves were hung at doorways, used in bathing water, applied in skin disorders and included in health-related rituals. The sacred status of Neem encouraged its planting near homes, temples and village boundaries (Bhattacharya, 2014; Bora & Kumar, 2025). In forestry and agroforestry, Neem is highly valuable because it is drought-tolerant, hardy and suitable for dryland conditions. It provides shade, fuelwood, biopesticide, medicine and ecological resilience. Ancient customs therefore preserved a species that modern science now recognizes as a multipurpose tree of high environmental and economic importance (Amirthalingam, 2020; Rai & Rai, 2024).

Bilva: The Tree of Lord Shiva

Bilva or Bael, *Aegle marmelos*, is one of the most sacred trees in Shaivite tradition. Its trifoliate leaves are offered to Lord Shiva and are believed to represent spiritual purity, cosmic balance and divine energy. The offering of Bilva leaves in worship reflects the symbolic union of plant life and sacred consciousness (Narayanan, 2001; Sherma, 2021). The tree is also medicinally important. Its fruit is traditionally used for digestive health, while its leaves, bark and roots have value in Ayurveda. The sacredness of Bilva helped conserve it around temples, hermitages and homesteads. This shows how religious practice functioned as a form of species conservation (Amirthalingam, 2020; Bhattacharya, 2014). Bilva worship also teaches a subtle ecological lesson: even a simple leaf, when offered with devotion, becomes spiritually meaningful. Such customs reduce excessive materialism in worship and cultivate emotional intimacy between humans and trees (Sherma, 2021).

Sandalwood: Fragrance, Purity and Ritual Grace

Sandalwood, *Santalum album*, is deeply associated with purity, cooling energy, sacred fragrance and ritual refinement. Sandal paste is used in temple worship, deity decoration, forehead marks, meditation and funeral rites. Its fragrance symbolizes spiritual elevation, calmness and sacred presence (Narayanan, 2001; Sherma, 2021). In ancient religious customs, fragrance had a sacred role. It purified the atmosphere, pleased the deity and prepared the mind for worship. Sandalwood became a material expression of purity and devotion. In forestry terms, sandalwood is a high-value tree species, but its overexploitation has created serious conservation concerns. Ancient reverence for sandalwood reminds modern society that economically valuable trees must be treated with restraint, responsibility and protection (Bhattacharya, 2014; Bora & Kumar, 2025). The use of sandalwood in rites from birth to death shows how trees accompany human beings throughout life. A tree grown silently in the forest becomes part of prayer, healing, meditation and final farewell. This continuity reveals the profound emotional and spiritual relationship between forestry species and human culture (Narayanan, 2001).

Sacred Groves and Community Conservation

Sacred groves are among the finest examples of traditional ecological conservation in India. These are patches of forest protected due to religious belief, ancestral worship, local deities or community customs. Such groves often contain old trees, medicinal plants, rare species, water sources and wildlife habitats. They functioned as community-conserved forests long before the emergence of modern protected-area systems (Bhattacharya, 2014; Amirthalingam, 2020). Sacred groves demonstrate that conservation becomes stronger when it is emotionally, culturally and spiritually rooted. A forest protected only by law may be violated, but a forest protected by faith becomes part of community identity. These groves also show that ancient Indian culture understood the importance of preserving certain forest patches from disturbance, thereby maintaining biodiversity, soil stability, water regulation and ecological memory (Bora & Kumar, 2025; Rai & Rai, 2024).

Trees in Life-Cycle Rituals

Trees and plant materials are present in almost every major Hindu life-cycle ritual. At birth, leaves, herbs and sacred water are used for purification. During marriage, mango leaves, banana stems, coconut, betel leaves and sacred wood symbolize fertility, prosperity and continuity. During housewarming ceremonies, leaves and plant materials are used to invite auspiciousness. During death rituals, wood, sesame, kusa grass and sacred plants form part of the final rites (Narayanan, 2001; Sherma, 2021). Mango leaves are used in toranas because they symbolize fertility and auspiciousness. Banana plants are placed at entrances during ceremonies because they represent abundance and continuity. Kusa grass, mentioned in Vedic ritual traditions, is associated with purity and spiritual discipline. These customs show that trees and plants are not passive decorations; they carry symbolic meaning and mark transitions in human life (Amirthalingam, 2020; Narayanan, 2001).

Yajna, Sacred Wood and Ecological Responsibility

In Vedic rituals, different types of wood were used for sacred fire depending on the purpose of the yajna. The selection of wood was not random; certain species were considered pure and ritually suitable. Firewood used in yajna represented transformation: the material tree became flame, smoke, fragrance and offering (Rai & Rai, 2024; Sherma, 2021). Modern interpretation must be careful. The ancient use of wood in yajna was governed by discipline, scale and sacred restraint. It was not an excuse for deforestation. Rather, ritualization of wood use created awareness that plant material should be taken respectfully. The idea of offering also implies responsibility: one cannot receive endlessly from forests without returning protection, planting and gratitude (Bora & Kumar, 2025; Narayanan, 2001). Thus, yajna can be understood as an ecological metaphor. Trees give oxygen, food, medicine, shade, flowers, fruits, soil stability and rainfall support. Human beings must give back through conservation, afforestation and ethical use.

Hymns as Ecological Ethics

The hymns of the Vedas are not environmental policy documents in the modern sense, but they contain the emotional and philosophical foundation of ecological ethics. They teach reverence for Earth, gratitude to natural forces, respect for medicinal plants and awareness of cosmic order. The concept of “Rta,” or universal order, is especially important. When humans violate natural balance, they disturb cosmic order; when they live with restraint and gratitude, they uphold it (Rai & Rai, 2024; Sherma, 2021). This idea is deeply relevant to forestry. Unsustainable cutting, biodiversity loss, soil erosion and climate change are modern forms of disturbing ecological order. Vedic wisdom reminds us that nature is not inert matter; it is a sacred system of relationships. A tree is not only biomass. It is shade, soil, bird habitat, medicine, memory, worship and future life (Bora & Kumar, 2025; Narayanan, 2001).

Ancient Customs as Traditional Conservation Systems

Many ancient religious customs protected trees indirectly. Sacred trees were not cut. Temple trees were maintained for generations. Groves dedicated to deities were preserved. Certain trees were planted during festivals. Women’s rituals around trees strengthened household-level conservation. Village deities were often associated with specific tree species, protecting them from destruction (Amirthalingam, 2020; Bhattacharya, 2014). These customs worked because they transformed conservation into culture. Instead of saying “do not cut this tree” only as a rule, tradition said “this tree is sacred.” That emotional transformation is powerful. Fear of punishment may protect a tree temporarily, but reverence can protect it for centuries. Modern forestry can learn from this cultural mechanism. Scientific management is essential, but science alone may not create emotional attachment. Cultural ecology can strengthen conservation by reconnecting people with the sacred value of trees (Bora & Kumar, 2025; Rai & Rai, 2024).

Relevance to Modern Forestry

Today, forestry faces serious challenges: deforestation, climate change, biodiversity loss, invasive species, soil degradation, water scarcity and decline of traditional knowledge. In this context, Vedic and ancient religious traditions offer not a replacement for modern science, but a moral foundation for ecological restoration and sustainable development (Bora & Kumar, 2025; Rai & Rai, 2024). Modern forestry measures carbon stock, growing stock, biomass, biodiversity and ecosystem services. Ancient tradition measured trees through reverence, utility, symbolism and sacred duty. When both approaches come together, forestry becomes more holistic. A

Peepal tree is not only a carbon sink; it is a cultural monument. A Neem tree is not only a biopesticide source; it is a household protector. A sacred grove is not only a biodiversity patch; it is a spiritual landscape (Amirthalingam, 2020; Bhattacharya, 2014). Therefore, integrating traditional ecological knowledge with scientific forestry can improve community participation. People protect what they emotionally value. Sacred tree traditions can support urban forestry, agroforestry, biodiversity conservation, medicinal plant gardens, temple forestry and climate-resilient landscapes (Bora & Kumar, 2025; Narayanan, 2001).

Conclusion

This ancient worldview carries an urgent message for the modern age. Contemporary forestry often measures trees through biomass, carbon stock, timber value and ecosystem services, but Vedic thought reminds us that a tree is also memory, medicine, culture, shelter, worship and life itself. Sacred groves, temple trees, ritual plantings and tree-based customs show that conservation becomes strongest when it is rooted in faith, emotion and community identity. At a time when forests are threatened by climate change, land degradation, biodiversity loss and human greed, ancient Indian ecological wisdom offers a timeless lesson: protecting trees is not only an environmental duty but a spiritual responsibility. A civilization that respects its trees protects its future; a society that destroys its forests weakens its own soul. The deepest hymn of the Vedas still lives in every forest that breathes, every sacred tree that shelters life and every human heart that learns to bow before nature.

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EDIBLE INSECTS – THE FUTURE OF SUSTAINABLE PROTEIN



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ABSTRACT

The growing population, expected to exceed 9 billion people by 2050, has increased the need for efficient and sustainable sources of food production. Although necessary, livestock farming is responsible for numerous environmental problems such as emissions of high levels of greenhouse gases, extensive usage of water and land resources, and the reduction of biodiversity. In this connection, edible insects may serve as an alternative protein source. This paper explores the potential of entomophagy in solving issues related to food insecurity on a global scale by discussing its importance historically, the nutritional properties of insects, their benefits from the environmental perspective, and some challenges to their consumption. Edible insects include crickets, mealworms, grasshoppers, and other species containing protein of high quality, essential amino acids, vitamins, and minerals which compete favourably with conventional protein sources. Moreover, insect cultivation is resource-friendly, produces less pollution, and uses organic waste materials, thus being more sustainable for the environment. However, some obstacles prevent the use of insects as a protein source because of cultural barriers, regulations, and food safety.

INTRODUCTION

With an estimated 9 billion people expected by 2050, the world's need for sustainable food products has become urgent. Livestock farming is necessary but entails many environmental problems that include excessive greenhouse gas emissions, high resource consumption, and loss of biodiversity. In the face of these issues, scientists and innovators have turned to finding alternative protein sources. Edible insects have come to represent one possible way forward. Having been part of the diets of millions of Asians, Africans, and Latinos for centuries, insects are known for their high-quality protein content and high levels of vitamins and minerals. The most nutritious of these species include crickets, mealworms, and grasshoppers whose nutritional value compares favourably with that of traditional meat products. In addition, raising insects does not require much space or water and can be done using organic wastes. This makes insect production environmentally friendly and sustainable. Despite these benefits, cultural perceptions and regulatory barriers remain key challenges to their widespread acceptance, particularly in Western societies. This article explores the potential of edible insects as a future source of sustainable protein, examining their nutritional value, environmental benefits, and the challenges that must be addressed to integrate them into mainstream diets.

HISTORY OF ENTOMAOPHAGY

The practice of entomophagy has been around since prehistoric times and has played an important role in human evolution. Early humans used insects as a convenient food source because insects were abundant and packed with protein and energy. The remains found by archaeologists show that insects have always been a staple food in the hunter-gatherers' diets. Even in ancient civilizations, insect eating was an everyday activity that was considered a culture. It has been proved that insects were eaten in places like ancient Greece and Rome, where insects such as cicada and beetle larva were considered a luxury. The consumption of insects is quite common in Asia, Africa, and Latin America. Insects such as silkworm pupa from China, grasshoppers from Mexico, and termites from Africa are some examples of this phenomenon. In the period of colonization and industrialization, the way people looked at insects being consumed changed, especially in Western countries. The more agriculture and livestock farming were practiced, the more people's diets included domesticated animals, and the practice of eating insects

faded away. Gradually, the culture began seeing bugs as dirty or poor people's food, giving rise to a stigma present in many modern developed nations.

COMMON EDIBLE INSECTS AND THEIR NUTRITIONAL COMPOSITION

While entomophagy became less popular in certain areas, it continued to be common throughout much of the planet. It is said that over two billion people consume insects across the globe, and there are over two thousand edible bug species known to us. Over the past decades, the rising concern about food security and environment issues has brought people's interest back to insects as protein sources.

However, modern science and various international agencies have taken it upon themselves to market entomophagy as a means of overcoming the food problems of the future by attempting to find methods of raising insects as well as processing and marketing insect products like powders and snacks. This means that the evolution of entomophagy from the initial necessity that it was to what it is today – a sustainable means of addressing food problems – is a demonstration of human adaptability in the face of different circumstances.

COMMON EDIBLE INSECTS AND THEIR NUTRITIONAL COMPOSITION

Edible insects are highly nutritious and provide a rich source of protein, fats, vitamins, and minerals. Their nutritional composition varies depending on species, developmental stage, and diet, but many insects are comparable or superior to conventional livestock products.

Insect	Scientific Name	Protein (% dry weight)	Fat (%)	Key Nutrients	Remarks
Crickets	<i>Acheta domesticus</i>	60–70%	10–20%	Iron, Calcium, Vitamin B12	High-quality protein; widely used in protein powders
Mealworms	<i>Tenebrio molitor</i> (larvae)	45–55%	25–35%	Zinc, Magnesium, Healthy fats	Energy-dense; rich in omega-6 fatty acids
Grasshoppers / Locusts	<i>Orthoptera</i> spp.	50–65%	10–15%	Iron, Phosphorus, Fiber	Low fat, high protein
Silkworm pupae	<i>Bombyx mori</i>	50–60%	20–30%	Calcium, Iron, B vitamins	Rich in essential fatty acids
Termites	<i>Isoptera</i> spp.	35–40%	30–45%	Iron, Calcium	High energy due to fat content
Black soldier fly larvae	<i>Hermetia illucens</i>	40–45%	25–35%	Calcium, Lauric acid	Efficient waste-to-protein converter
Beetle larvae	Various species	40–65%	15–30%	Potassium, Phosphorus	Widely consumed in tropical regions
Ants	<i>Formicidae</i> spp.	40–50%	10–15%	Vitamin C, Calcium	Consumed as delicacies

EDIBLE INSECT PROTEIN SUSTAINABLE THEN CONVENTIONAL FOOD LIKE MUTTON, BEEF, CHICKEN

Insects that are edible have been identified as an environmentally friendly way of getting proteins. Edible insects are a source of high-quality protein, which contains 40-70% protein on dry basis, essential amino acids, fats, vitamins, and other minerals. Moreover, insects provide more nutrition value than traditional proteins as well as being a healthier way of consuming proteins. One major advantage of using insects as a protein source is their efficient feed conversion. Since insects consume less food to produce similar levels of protein than livestock does, insects offer higher efficiency in feeding. For instance, crickets use less food in their production of proteins than cows and sheep. Another reason why insects are better than other protein sources is their low carbon footprint as they generate low amounts of greenhouse gases, use less water and occupy less land area compared to livestock such as cows and sheep. In addition, insects can be raised using organic waste products, leading to waste minimization



and promoting sustainable recycling. The quick growth and breeding capabilities of insects facilitate large-scale production as well. On the other hand, the traditional rearing of animals requires a lot of resources, causes environmental stress, and is inefficient in producing protein from food. Thus, edible insects are an excellent choice to replace meat and fish.

PROSPECTS AND CHALLENGES

Edible insects present vast possibilities as a means of sustainable protein production considering the current rise in global demand for food and environmental issues. These are extremely efficient producers, utilizing fewer amounts of land and water and emitting lower greenhouse gas emissions than conventional livestock. With their excellent nutritive value, containing quality proteins, essential amino acids, healthy fatty acids, vitamins, and minerals, edible insects can be used to tackle problems like malnutrition and food security especially in underdeveloped parts of the world. In addition, developments in insect farming and innovative processing methods including insect flours and protein isolations have widened their usage in various sectors including foods, animal feeds, and pharmaceuticals. This industry also offers great potential economically through provision of jobs and utilization of organic waste as feed among others.

Nevertheless, some problems should be overcome before edible insects become widely accepted. First of all, cultural and psychological obstacles still pose a problem because many people find insects unappetizing or unsafe. Legal framework regarding the use of such food in various countries is not elaborated yet, thus making it hard to produce, market, and trade the product on an international level. Food safety becomes another obstacle since there is always a risk that insects may cause some form of allergy, like seafood does. Moreover, technological and financial aspects related to mass production need to be improved as well. Insects processing may involve significant expenses and requires high-quality standards and proper logistics, which is still quite an issue. Finally, a lack of information and knowledge regarding their health benefits is an obstacle to their wide acceptance. Hence, overcoming the mentioned issues can contribute to their successful implementation in the food industry.

ADVANTAGES

Edible insects present multiple benefits when it comes to their composition, making them a perfect sustainable food option. Firstly, they contain good quality protein with all essential amino acids needed by humans; thus, they can be compared to conventional animal-based protein sources. Second, insects have healthy fats such as unsaturated fatty acids that are essential for cardiovascular health. Moreover, edible insects can be rich sources of nutrients, including vitamins (B12 vitamins, particularly), iron, zinc, calcium, and magnesium, which prevent nutrient deficiencies. The third benefit relates to the ability of edible insects to have higher feed conversion ratios than conventional meat sources, meaning more protein will be produced with minimal feed. Finally, edible insects can be rich sources of bioactive compounds such as chitin and antimicrobial peptides. Thus, they can improve gut microbiota health and immunity.

CONCLUSION

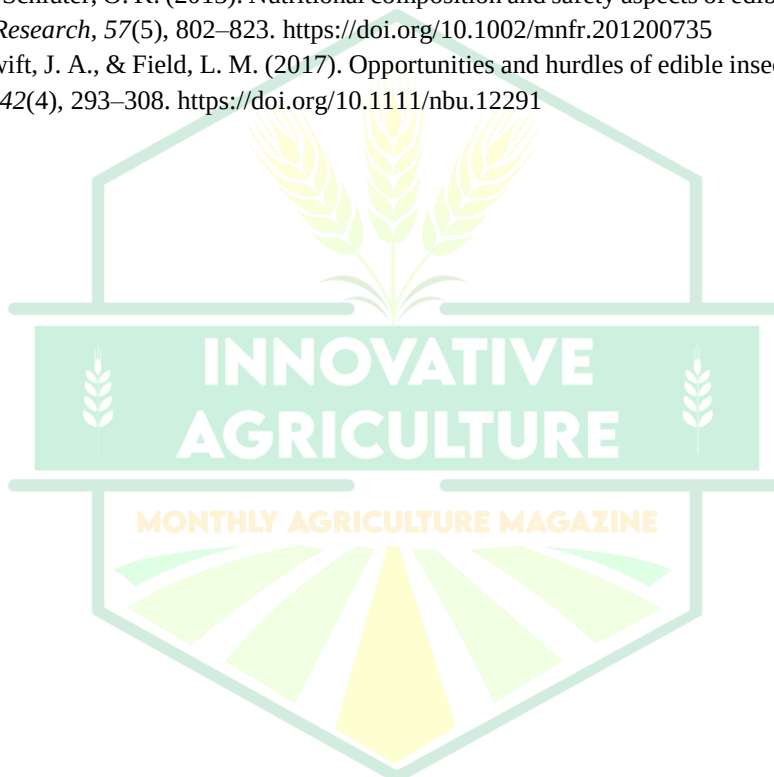
Edible insects emerge as an extremely promising option that could address the ever-increasing need for sustainable food sources in the world. The high nutritional value of insects, including proteins, fats, vitamins, and minerals, provides an alternative source of nutrition as compared to traditional food sources. Apart from health considerations, insect production presents many environmental benefits, such as decreased greenhouse gas emissions and reduced feed-to-body mass ratios. Although there are various hurdles, such as cultural perceptions, lack of regulation, and scalability concerns, scientific innovations may solve these obstacles. Edible insects are set to play a vital role in future sustainable food systems.

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Role of Biofertilizers and Biostimulants in Vegetable Crop Production



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Abstract

Vegetable crops, by their very nature, demand high nutrient inputs and intensive care to achieve both abundant yields and good quality. However, relying too heavily on synthetic fertilizers has led to deteriorating soil health, imbalanced nutrition, pollution problems, and even drops in productivity. In response, biofertilizers and biostimulants are gaining ground as practical, environmentally gentle alternatives for growing vegetables more sustainably. Biofertilizers introduce helpful microorganisms that boost nutrient availability through fixing atmospheric nitrogen, unlocking soil phosphorus, or producing growth-promoting compounds. Biostimulants, which include seaweed extracts, humic matter, protein hydrolysates, amino acids, and beneficial microbial byproducts, work differently: they enhance the plant's own physiological functioning, improve tolerance to stresses like drought or salinity, and help roots take up nutrients more efficiently. When used together in vegetable production, these biological inputs have been shown to improve seed germination, vegetative development, flowering, final yield, and post-harvest quality, while also reviving soil microbial life and cutting down reliance on chemical agrochemicals. With global vegetable demand rising rapidly, moving toward such sustainable intensification is becoming urgent. This review examines the main types of biofertilizers (for example, rhizobia, phosphate-solubilizing microbes, and arbuscular mycorrhizal fungi) and biostimulants, explaining how each works, where they are most effective, and what benefits they bring. It also looks at the powerful effects of applying them together, particularly how they help vegetables withstand environmental stresses. Finally, the discussion addresses current limitations such as inconsistent performance in the field and difficulties with product shelf life and outlines future directions, including better formulation methods and integration with precision farming, to make bio-inputs a reliable cornerstone of resilient vegetable production.

Keywords: Biofertilizers, Biostimulants, Sustainable agriculture, Vegetable crops, Soil health, Plant growth promotion, Integrated nutrient management, Plant growth-promoting rhizobacteria (PGPR), Arbuscular mycorrhizal fungi (AMF), Seaweed extract, Protein hydrolysate, Abiotic stress tolerance, Nutrient use efficiency, Solanaceous crops, Leafy greens

1. Introduction

Vegetables are indispensable for global food and nutritional security, contributing significantly to human health and agricultural economies worldwide. Their intensive production, however, has become heavily dependent on synthetic fertilizers and pesticides to achieve high yields. This overreliance has led to serious consequences, including soil fertility decline, environmental contamination through eutrophication and greenhouse gas emissions, accumulation of chemical residues in produce, and rising production costs. Moreover, with the need to increase vegetable output by an estimated 50–70% by 2050 under changing climatic conditions, there is an urgent call for innovative, eco-efficient strategies that can sustain productivity while minimizing ecological harm.

In response to growing concerns over climate change, food safety, and ecological balance, sustainable agricultural practices are gaining momentum. Among these, the use of biological inputs broadly categorized as biofertilizers and biostimulants has emerged as a promising approach to enhance crop performance while

preserving soil health. Although often used interchangeably, these two categories serve distinct functions. Biofertilizers consist of living microorganisms that colonize the rhizosphere or plant tissues and improve nutrient availability through natural processes such as biological nitrogen fixation, phosphate solubilization, and production of growth-promoting substances. Biostimulants, as defined by the European Biostimulant Industry Council (EBIC), contain substances or microorganisms whose primary role is to stimulate plant physiological processes enhancing nutrient uptake, nutrient use efficiency, tolerance to abiotic stress, and crop quality independently of their nutrient content.

Integrating biofertilizers and biostimulants into vegetable production systems offers multiple benefits, including improved crop growth, higher yield and quality attributes, reduced dependence on chemical inputs, and greater environmental sustainability. This review aims to: (i) clarify the mechanisms of action of the major classes of biofertilizers and biostimulants; (ii) critically evaluate their documented effects on vegetable crops, focusing on yield, quality parameters, and stress resilience; (iii) explore the synergistic potential arising from their combined application; and (iv) identify current challenges and future research priorities to facilitate mainstream adoption of these biological inputs in sustainable vegetable cultivation.

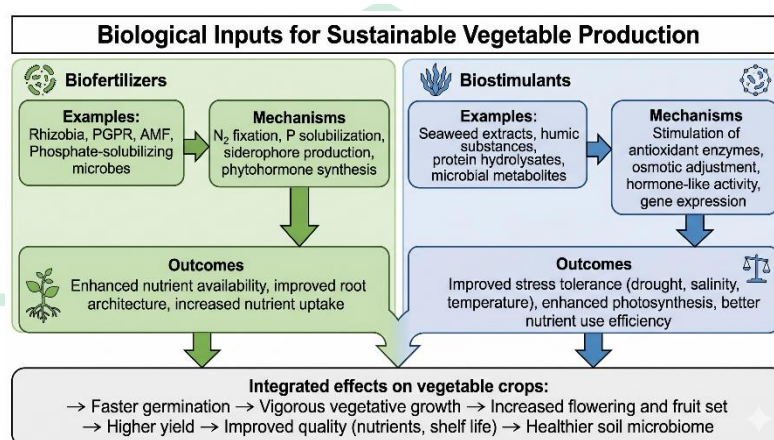


Figure 1: A schematic flow diagram illustrating the mechanisms and benefits of biofertilizers and biostimulants. It visually separates the pathways: biofertilizers (green) enhance nutrient provisioning, while biostimulants (blue) modulate physiological and stress responses, with a central merged pathway leading to improved vegetable crop performance.

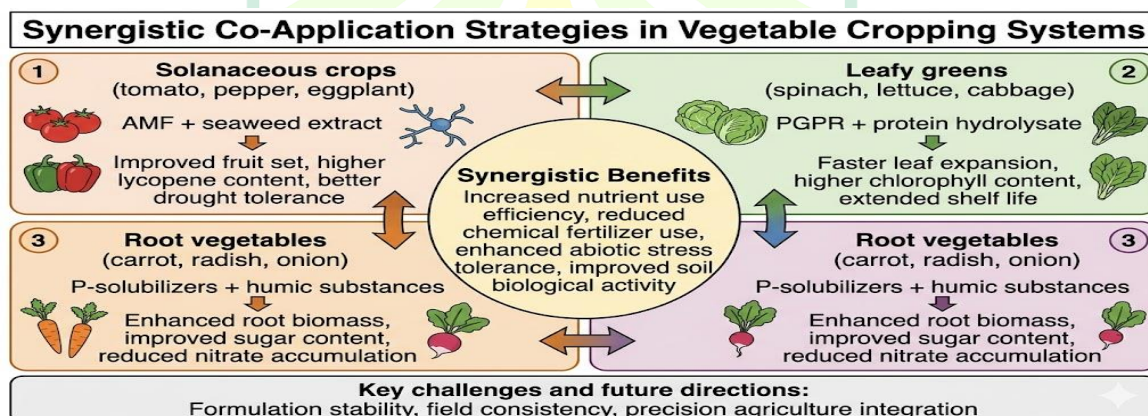


Figure 2: An infographic highlighting synergistic effects when biofertilizers and biostimulants are applied together, tailored to specific vegetable crop groups (Solanaceous crops, Leafy greens, and Root vegetables). Arrows and feedback loops indicate how these tailored strategies maximize specific benefits like nutrient efficiency, stress tolerance, and overall product quality while enhancing soil health.

2. Biofertilizers: Mechanisms and Efficacy in Vegetable Crops

Biofertilizers are biological formulations containing living or latent beneficial microorganisms that colonize the plant rhizosphere or internal plant tissues to promote growth primarily through enhancing nutrient availability

and uptake. Recent global evidence confirms that their adoption is gaining considerable momentum. A comprehensive meta-analysis of 384 studies and 2,657 observations found that biofertilizer application increases overall vegetable yield by an average of 17.9%, with fruit vegetables showing a 19.3% increase, leaf vegetables 18.6%, root vegetables 18.1%, and legumes 13.9%. Beyond yield enhancement, the same analysis reported that nitrogen uptake improved by 36.3%, phosphorus by 32.3%, and potassium by 28.4%, alongside increases in soil bacterial diversity and microbial biomass.

2.1 Nitrogen-Fixing Biofertilizers

Biological nitrogen fixation (BNF) is the microbial conversion of atmospheric dinitrogen into ammonia, a plant-available nitrogen form. For vegetable production systems, which are inherently nitrogen-demanding, BNF serves a critical function.

Symbiotic nitrogen fixers: Rhizobia (including *Rhizobium*, *Bradyrhizobium*, and *Sinorhizobium* spp.) form root nodules on leguminous vegetables such as green beans, peas, and lentils. They can displace 50–75% of synthetic nitrogen fertilizer in these crops without yield penalties. Recent studies confirm that rhizobial inoculation substantially improves nodulation, nitrogen fixation, and grain yields, though the magnitude of response is highly dependent on local soil conditions and the specific legume species being grown.

Asymbiotic (free-living) nitrogen fixers: Genera including *Azotobacter*, *Azospirillum*, and *Clostridium* fix nitrogen in the rhizosphere of non-leguminous vegetables (e.g., tomato, cabbage, cucumber). *Azospirillum brasilense*, for instance, has been shown to increase the marketable yield of lettuce by 15–25%, an effect attributable to both nitrogen fixation and the concurrent production of phytohormones that stimulate root development. Recent research has also highlighted the importance of *Azotobacter* spp. in vegetable systems. In spinach, for example, co-application of *Azotobacter vinelandii* with moderate rates of urea (less than 50 kg ha⁻¹) enhanced seed germination energy, leaf dry biomass, total antioxidant activity, and leaf potassium content. Similarly, in onion, the combination of rabbit manure with *Azotobacter chroococcum* significantly increased bulb diameter, individual bulb weight, and total yield, while simultaneously boosting the concentration of bioactive metabolites such as phenolic compounds and flavonoids. A field study on cucumber also reported that *Azotobacter salinestris* spray can serve as a sustainable approach to promote plant growth while enhancing soil microbiological diversity.

2.2 Phosphate Solubilizing and Mobilizing Biofertilizers

Phosphorus (P) is an essential macronutrient that remains highly immobile in most agricultural soils, where a large proportion exists in insoluble forms unavailable to plants. Two complementary microbial strategies have been developed to address this limitation: solubilization and mobilization.

Phosphate-solubilizing bacteria (PSB): These include species such as *Bacillus megaterium*, *Bacillus licheniformis*, *Pseudomonas striata*, and fungal species like *Aspergillus niger*. They secrete low-molecular-weight organic acids, chelating agents, and phosphatases that convert insoluble calcium, iron, or aluminum phosphates into soluble forms of orthophosphate readily taken up by plant roots. Recent advancements have focused on formulating liquid PSB products with enhanced stability and shelf life. In a two-year field evaluation, a liquid PSB formulation containing *Bacillus licheniformis* PRPSB10 and *Pseudomonas putida* PRPSB38 significantly improved phosphorus uptake and tuber yield in potato, achieving an average 16.2% yield increase over the control alongside favorable economic returns (net profit of ₹44,876 ha⁻¹ and a benefit-cost ratio of 2.52).

Phosphate-mobilizing microorganisms (PMM): The most prominent representatives are arbuscular mycorrhizal fungi (AMF), including *Glomus* and *Rhizophagus* species. AMF form extensive extraradical hyphal networks extending well beyond the root P-depletion zone, acquiring phosphorus and trace elements (zinc, copper) in exchange for plant carbohydrates. A recent controlled greenhouse study on tomato evaluated the potential of AMF inoculation with four *Glomus* species (*G. claroideum*, *G. etunicatum*, *G. fasciculatum*, and *G. mosseae*) under reduced nitrogen and phosphorus doses. The results demonstrated that *Glomus mosseae* inoculation significantly increased plant height by 14%, stem diameter by 22.25%, dry matter by 23.59%, yield by 38.57%, nitrogen uptake by 16.40%, and phosphorus uptake by 37.5% compared to un-inoculated controls. Additionally, fruit quality parameters improved, with ascorbic acid concentration rising by 16.75% and fruit firmness by 18.45%. The study concluded that AMF inoculation combined with low nitrogen and phosphorus supply is a promising strategy for

improving greenhouse tomato production on a commercial scale while minimizing environmental and health risks. Co-inoculation of PSB with AMF often produces additive or synergistic benefits, as the bacteria can solubilize previously unavailable P sources that the fungal hyphae subsequently transport to the plant.

2.3 Potassium and Zinc Solubilizers

Potassium-solubilizing bacteria (KSB) such as *Bacillus mucilaginosus* and *Frateuria aurantia* secrete organic acids that release potassium from silicate minerals (e.g., feldspar and mica) present in the soil matrix. The mechanism involves acidolysis, chelation, and the production of extracellular polysaccharides that enhance mineral weathering. A recent field study in potato cultivation demonstrated that *Bacillus mucilaginosus* applied in combination with mushroom farm residues and full recommended potassium fertilizer significantly improved plant height, total leaf surface area, chlorophyll content, marketable tuber yield (43.74 Mg ha^{-1}), total tuber number (10.77 per plant), and starch production, with all these parameters exceeding those of unfertilized controls. In integrated management strategies for potato, combining *B. megaterium*, *B. mucilaginosus*, and *Azotobacter* with rock phosphate and potassium feldspar achieved the highest tuber starch content (314.05 mg g^{-1} fresh weight) and yield (42 tons ha^{-1}), while simultaneously reducing operating costs by 11% and increasing profits by 40.9% compared to conventional chemical fertilizer practices.

Zinc-solubilizing bacteria (ZnSB), notably certain *Pseudomonas* and *Bacillus* species, enhance the bioavailability of zinc (Zn) by releasing organic acids, siderophores, and other metal-chelating compounds into the rhizosphere. This mechanism converts insoluble Zn compounds such as ZnO and $\text{Zn}_3(\text{PO}_4)_2$ into soluble Zn^{2+} ions accessible to plant roots. Their application is particularly critical in Zn-deficient calcareous soils, where they support Zn biofortification of vegetable crops and contribute to nutritional security. Recent studies have proposed ZnSB consortia as a promising approach for enhancing Zn content in edible plant parts through mechanisms involving acidification of the rhizosphere and secretion of low-molecular-weight organic acids that complex Zn ions.

2.4 Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR constitute a functionally diverse group of rhizosphere-colonizing bacteria that enhance plant growth through multiple concurrent mechanisms beyond simple nutrient provisioning. These include phytohormone synthesis (auxins, gibberellins, cytokinins), 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity that lowers stress ethylene levels, siderophore production facilitating iron acquisition, and antibiosis against soilborne plant pathogens. The efficacy of PGPR across vegetable systems has been documented extensively. A field study on okra using PGPR isolates from beach ridge interspersed with swale (BRIS) soil specifically *Paraburkholderia unamae*, *Bacillus amyloliquefaciens*, and *Enterobacter asburiae* demonstrated that inoculation allowed a 30% reduction in NPK fertilizer application while improving leaf number by 27.85%, fruit number by 28.56%, yield per plant by 27.90%, and total plant dry biomass by 25.83%. Furthermore, PGPR application increased soil bacterial count by 22.79% and net photosynthesis by 5.27%. More recently, a study on pepper using a co-fermented water-dispersible granule formulation containing *Burkholderia pyrrocinia* P10 and *Bacillus flexus* HGD12 achieved a remarkable 60.04% increase in yield compared to 100% chemical fertilizer treatment, alongside increases in ascorbic acid (51.79%), total phenolics (130.08%), and total flavonoids (77.63%). Interestingly, while PGPR inoculation of sweet potato in nutrient-poor sandy soils of Thailand did not significantly affect yield ($p > 0.05$), it did significantly increase protein and fiber content of tubers ($p < 0.01$) while reducing carbohydrate content, suggesting genotype- and soil-specific responses. In cucumber, *Pseudomonas simiae* WCS417 inoculation induced iron-deficiency responses and rhizosphere acidification, effectively mitigating Fe chlorosis and improving plant growth under Fe-limited conditions. Field inoculation of lettuce with a consortium containing *Pseudomonas protegens* B21-024 and *Pseudomonas putida* B21-029 was also found to significantly increase shoot dry weight, highlighting the potential of *Pseudomonas* consortia for promoting leafy green production under commercial growing conditions.

2.5 Emerging Trends and Practical Considerations

Recent developments have refined our understanding of the conditions under which biofertilizers perform optimally. The large-scale meta-analysis identified soil pH, available phosphorus, and total nitrogen as the primary drivers of biofertilizer effectiveness, with yield gains being particularly pronounced in low-nutrient soils

(low total N, available P, and soil organic matter) with neutral to slightly alkaline pH. This finding has significant practical implications for targeted biofertilizer application strategies. Moreover, *Bacillus megaterium* NCT-2 has recently been demonstrated to function as a multifunctional agent that simultaneously addresses salinization-driven nutrient imbalances and reshapes keystone microbial taxa to restore soil plant homeostasis in secondary salinized soils, further expanding the applicability of biofertilizers to marginal production environments.

The evidence reviewed collectively indicates that biofertilizers are not a uniform solution but rather a diverse toolkit that must be matched carefully to specific vegetable crop types, soil conditions, and production goals. When applied appropriately and particularly when integrated with complementary biostimulants as discussed in the following section they offer a robust pathway for reducing synthetic agrochemical inputs while maintaining or enhancing vegetable crop productivity and quality.

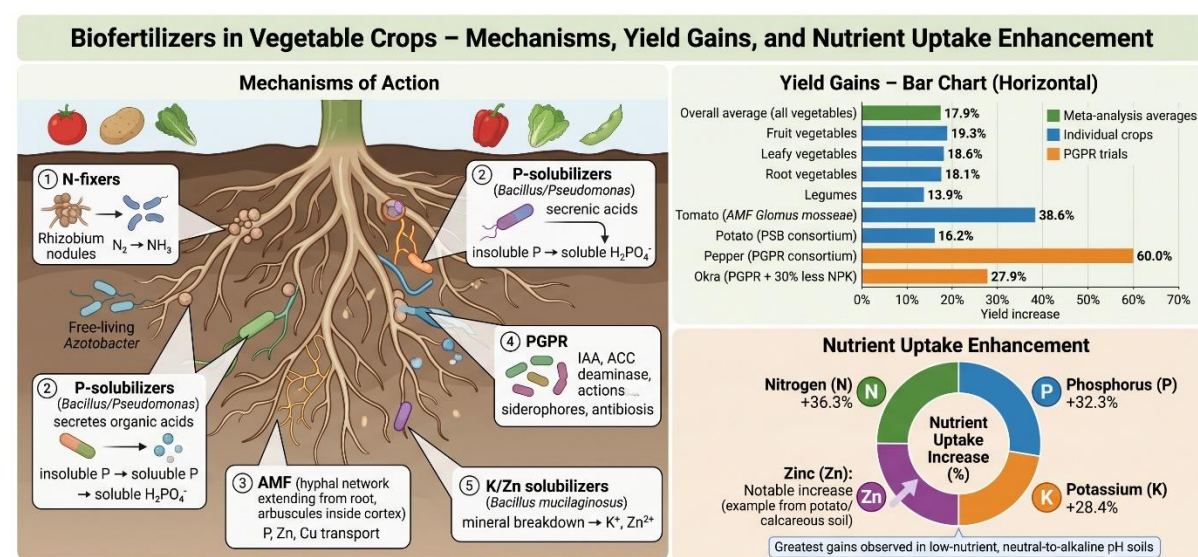


***Figure 2. Integrated overview of biofertilizer functions and performance in vegetable crop systems.** (Top) Mechanisms of major biofertilizer types in the rhizosphere: nitrogen fixation (symbiotic and free-living), phosphate solubilization, mycorrhizal nutrient mobilization, PGPR-mediated growth promotion (phytohormones, ACC deaminase, siderophores), and potassium/zinc solubilization. (Middle) Quantitative yield responses from a meta-analysis of 384 studies and recent field trials. Overall yield increase yield increase enhances 17.9%, with fruit vegetables showing 19.3%. The highest reported gains are in pepper (60.0% with PGPR) and tomato (38.6% with AMF). (Bottom) Average improvements in nutrient uptake: nitrogen (+36.3%), phosphorus (+32.3%), and potassium (+28.4%), with notable zinc biofortification in potato and calcareous soil systems. Enhanced effects are consistently observed under low-fertility and neutral-to-alkaline pH conditions.

3. Mechanisms of Biofertilizers and Types of Biostimulants

Biofertilizers enhance vegetable crop performance through several well-defined mechanisms. They convert atmospheric nitrogen into plant-available forms via biological nitrogen fixation, reducing dependence on synthetic nitrogen fertilizers. Phosphate-solubilizing microorganisms secrete organic acids and enzymes that convert insoluble soil phosphates into soluble forms readily taken up by roots. Many biofertilizers also synthesize phytohormones such as auxins, gibberellins, and cytokinins, which promote root development and overall plant growth. Additionally, beneficial microbes improve soil biological properties and nutrient cycling, while certain strains suppress soil-borne pathogens through competition, antibiosis, and induced systemic resistance. In contrast to biofertilizers, biostimulants do not primarily supply nutrients but rather modulate plant physiology through diverse mechanisms. Humic substances, derived from lignite or compost, act as root architecture modulators by increasing root hair density and H^+ -ATPase activity, thereby enhancing the uptake of nitrate, sulfate, and ferric iron. Protein hydrolysates and amino acids, produced by enzymatic hydrolysis of animal or plant proteins, function as metal chelators that improve iron and zinc transport in the phloem and serve as precursors for stress-protective molecules such as proline. Seaweed extracts, primarily from brown algae like *Ascophyllum nodosum* and *Ecklonia maxima*, contain betaines, mannitol, laminarin, and trace hormones that enhance seed germination, delay senescence via cytokinin activity, and induce systemic acquired resistance against fungal pathogens. Finally, certain plant growth-promoting rhizobacteria act as microbial biostimulants, producing indole-3-acetic acid, exhibiting ACC deaminase activity to reduce stress ethylene levels, and releasing volatile organic compounds that modulate plant growth functions where nutrient provisioning remains secondary to physiological regulation.

Table 1. Summary of major biofertilizer mechanisms and biostimulant types relevant to vegetable crop production. Biofertilizers primarily enhance nutrient availability and uptake through fixation, solubilization, and phytohormone synthesis. Biostimulants modulate plant physiological processes via root architecture changes, metal chelation, stress signaling, and hormone-like activity, with minimal direct nutrient contribution.

Category	Agent / Substance	Source / Examples	Primary Mechanism(s)	Documented Effects on Vegetables
Biofertilizers	Nitrogen-fixing microorganisms	<i>Rhizobium</i> , <i>Azotobacter</i> , <i>Azospirillum</i>	Conversion of atmospheric N_2 to plant-available ammonia	Reduced N fertilizer requirement; increased protein content in leguminous vegetables
	Phosphate-solubilizing microorganisms	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Aspergillus</i>	Secretion of organic acids and phosphatases; conversion of insoluble P to soluble $H_2PO_4^-$	Improved P uptake, root development, and fruit set
	Plant growth-promoting rhizobacteria (PGPR)	<i>Pseudomonas fluorescens</i> , <i>Bacillus subtilis</i>	Phytohormone synthesis (auxins, gibberellins, cytokinins); ACC deaminase; siderophores; antibiosis	Enhanced root growth, stress tolerance, and disease suppression
	Mycorrhizae (AMF)	<i>Glomus</i> , <i>Rhizophagus</i> spp.	Extraradical hyphal network; enhanced water and nutrient (P, Zn, Cu) acquisition	Improved nutrient uptake, biomass, and yield under low-P conditions
Biostimulants	Humic substances	Lignite, compost (humic and fulvic acids)	Root architecture modulation; increased H^+ -ATPase activity	Enhanced root hair density; improved NO_3^- , SO_4^{2-} , Fe^{3+} uptake; increased fruit yield
	Protein hydrolysates & amino acids	Enzymatic hydrolysis of animal/plant proteins	Metal chelation (Fe, Zn); precursors for stress molecules (proline)	Increased chlorophyll, nitrate reductase activity, yield; reduced leaf nitrate accumulation
	Seaweed extracts	<i>Ascophyllum nodosum</i> , <i>Ecklonia maxima</i> (brown algae)	Betaines, mannitol, laminarin, trace cytokinins/auxins; induction of systemic acquired resistance	Enhanced germination, delayed senescence, improved fruit set under heat stress, increased lycopene
	Microbial biostimulants (non-biofertilizer PGPR)	<i>Bacillus amyloliquefaciens</i> , <i>Paraburkholderia phytofirmans</i>	IAA production; ACC deaminase; volatile organic compounds (VOCs); modulation of ethylene levels	Upregulated defense genes; enhanced antioxidant enzymes; tolerance to drought and salinity stress

4. Integrated Application of Biofertilizers and Biostimulants: Synergistic Effects and Mechanisms

4.1 Definition of Biostimulants

Biostimulants are substances or microorganisms that, when applied to plants or the rhizosphere, stimulate natural physiological processes to enhance nutrient uptake, nutrient use efficiency, tolerance to abiotic stress, and crop

quality. Unlike fertilizers, their primary function is not to supply nutrients directly but to modulate plant metabolism and performance.

4.2 Types of Biostimulants Used in Vegetable Crops - Biostimulants are natural or synthetic substances that stimulate a vegetable crop's natural processes. They enhance nutrient uptake, improve abiotic stress tolerance (e.g., heat, drought), and boost crop quality/yields. They are classified by their active ingredients.

Main Effects of Biostimulant Types on Vegetable Crops

Type	Source	Main Effects on Vegetables
Seaweed extracts	Marine algae (e.g., <i>Ascophyllum nodosum</i> , <i>Ecklonia maxima</i>)	Enhanced growth, stress tolerance, delayed senescence
Humic substances	Decomposed organic matter (lignite, compost, leonardite)	Improved nutrient uptake, root architecture modulation
Protein hydrolysates	Enzymatic hydrolysis of plant or animal proteins	Enhanced metabolic activity, metal chelation, stress protection
Amino acids	Natural amino compounds (e.g., proline, glycine, glutamic acid)	Improved stress resistance, osmoregulation
Chitosan	Crustacean shells (chitin derivative)	Disease resistance, growth promotion, elicitation of defense responses
Microbial biostimulants	Beneficial microbes (e.g., <i>Bacillus amyloliquefaciens</i> , <i>Paraburkholderia phytofirmans</i>)	Root growth promotion, nutrient mobilization, phytohormone production

4.3 Mechanisms of Action of Biostimulants

Biostimulants exert their beneficial effects on vegetable crops through several complementary mechanisms:

4.3.1 Improved Nutrient Uptake – Biostimulants enhance root architecture, increase root hair density, and upregulate the activity of membrane transport proteins such as H⁺-ATPase, thereby improving the absorption efficiency of macronutrients (nitrogen, phosphorus, potassium) and micronutrients (iron, zinc).

4.3.2 Enhanced Photosynthesis – They stimulate chlorophyll synthesis, increase photosynthetic pigment concentrations, and improve the efficiency of light reactions and carbon fixation, leading to greater biomass accumulation.

4.3.3 Stress Tolerance – Biostimulants help vegetable crops tolerate a range of abiotic stresses, including drought, salinity, temperature extremes, and oxidative stress. They achieve this through the accumulation of osmoprotectants (proline, glycine betaine), upregulation of antioxidant enzymes (superoxide dismutase, catalase, peroxidase), and modulation of stress-responsive gene expression.

4.3.4 Root Development – By producing or mimicking phytohormones (auxins, cytokinins, gibberellins) and stimulating cell division and elongation, biostimulants promote vigorous root growth, which in turn enhances water and nutrient acquisition from deeper soil layers.

4.3.5 Improved Quality Parameters – Biostimulants increase the concentration of health-promoting compounds in vegetable produce, including vitamins (ascorbic acid, tocopherols), phenolic compounds, flavonoids, carotenoids (lycopene, β -carotene), and antioxidant capacity. They also improve flavor attributes (sugar content, organic acid balance) and extend post-harvest shelf life by reducing oxidative degradation and delaying senescence.

4.4 Synergistic Effects of Combined Biofertilizer and Biostimulant Application

The most significant advances in sustainable vegetable production have emerged from the integrated application of biofertilizers and biostimulants. When used together, these two categories of biological inputs create positive feedback loops that amplify their individual benefits. A biofertilizer, such as arbuscular mycorrhizal fungi (AMF), improves phosphorus and water status, while a biostimulant, such as seaweed extract or protein hydrolysate, primes stress tolerance mechanisms and further optimizes root architecture. The result is a system where nutrient availability, uptake efficiency, and physiological resilience are simultaneously enhanced.

Case Example - Tomato under Moderate Salinity Stress:

In controlled studies, individual applications of biofertilizers or biostimulants produced measurable but moderate benefits. AMF inoculation alone increased phosphorus uptake and improved the potassium-to-sodium ratio in tomato leaves, helping to mitigate ionic toxicity. Protein hydrolysate applied alone increased chlorophyll concentration and the activity of antioxidant enzymes, providing some protection against oxidative damage. However, the combination of AMF and protein hydrolysate produced striking synergistic outcomes. Compared to untreated controls, the combined treatment resulted in a 40% higher marketable yield, outperforming either agent applied alone. Furthermore, leaf sodium accumulation was reduced by 50%, indicating a marked improvement in salinity tolerance. This case demonstrates that the integrated application of complementary biological inputs can substantially exceed the sum of their individual effects.

Additional Example – Lettuce with Nitrogen-Fixing Bacteria and Humic Acids:

In lettuce production, the combination of *Azospirillum* (a nitrogen-fixing biofertilizer) with humic substances (a biostimulant) allowed a 50% reduction in synthetic nitrogen fertilizer application. Remarkably, this reduced-input strategy achieved the same or even higher head weight compared to full chemical nitrogen regimes, while maintaining leaf nitrate content within safe limits for human consumption. This example highlights the potential of integrated biological inputs to lower production costs, reduce environmental nitrogen pollution, and safeguard food quality.

4.5 Practical Implications for Integrated Nutrient Management

The evidence reviewed above supports a shift from single-input strategies toward integrated nutrient management (INM) frameworks that deliberately combine biofertilizers and biostimulants. Successful integration requires attention to several practical considerations:

- **Crop-specific matching:** Solanaceous crops (tomato, pepper, eggplant) respond particularly well to AMF combined with protein hydrolysates or seaweed extracts. Leafy greens (lettuce, spinach, cabbage) show strong responses to nitrogen-fixing bacteria combined with humic substances or amino acids. Root vegetables (potato, carrot, onion) benefit from phosphate-solubilizers combined with chitosan or seaweed extracts.
- **Timing and mode of application:** Biofertilizers are most effective when applied as seed treatments or soil drenches at planting, establishing beneficial microbial colonization early. Biostimulants can be applied as foliar sprays or root drenches at critical phenological stages (e.g., transplanting, flowering, fruit set) to modulate physiological responses.
- **Reduction of synthetic inputs:** Integrated application consistently allows a 25–50% reduction in synthetic fertilizer use without yield penalties, provided that soil baseline fertility is moderate and application timing is optimized.
- **Soil and environmental conditions:** Synergistic effects are most pronounced in low-fertility soils, neutral to slightly alkaline pH, and under abiotic stress conditions (salinity, drought, temperature extremes). In high-fertility soils with optimal conditions, the marginal benefits of biological inputs may be smaller, although quality improvements (phytochemical content, shelf life) are still frequently observed.

4.6 Summary

The integrated application of biofertilizers and biostimulants represents a paradigm shift from conventional, input-intensive vegetable production toward a more balanced, biologically driven system. Biofertilizers enhance the pool of available nutrients in the rhizosphere, while biostimulants improve the plant's intrinsic capacity to acquire those nutrients and tolerate environmental stresses. When applied together, these inputs generate synergistic effects that increase yield, improve product quality, reduce dependency on synthetic agrochemicals, and enhance the resilience of vegetable cropping systems to climate-induced stresses. Future research should focus on optimizing application protocols for specific crop–region combinations and developing commercial formulations that maintain stability and efficacy under field conditions.

5. Mitigation of Abiotic Stress in Vegetables Using Biofertilizers and Biostimulants

Abiotic stresses particularly salinity, drought, and temperature extremes constitute major constraints to vegetable crop productivity worldwide. Unlike synthetic agrochemicals, which offer little or no stress-protective function,

biofertilizers and biostimulants actively enhance the physiological resilience of plants through multiple complementary mechanisms.

5.1 Salinity Stress

Salinity imposes both osmotic and ionic toxicity on vegetable crops, leading to reduced growth, nutrient imbalance, and premature senescence. Several biological inputs have demonstrated efficacy in mitigating salt stress. Arbuscular mycorrhizal fungi (AMF) improve potassium-to-sodium homeostasis in plant tissues and upregulate the activity of antioxidant enzymes such as superoxide dismutase (SOD) and peroxidase (POD), as documented in eggplant and pepper. Plant growth-promoting rhizobacteria (PGPR) that possess 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity lower stress-induced ethylene levels, thereby reducing senescence and promoting root growth under saline conditions, as shown in tomato.

5.2 Drought Stress

Water deficit limits photosynthesis, nutrient transport, and biomass accumulation. Seaweed extracts containing betaines act as osmoprotectants, helping maintain cellular turgor and stomatal regulation, which increases leaf relative water content. These effects have been observed in bean and zucchini. Mycorrhizal fungi contribute to drought tolerance by extending hyphal networks far beyond the root depletion zone, enhancing water uptake from deeper soil layers. Additionally, mycorrhizae produce glomalin, a glycoprotein that improves soil aggregation and water retention, as demonstrated in cucumber.

5.3 Temperature Extremes

High-temperature stress disrupts protein folding and photosynthetic efficiency. Protein hydrolysates have been shown to upregulate heat shock proteins (HSPs) and maintain photosynthetic capacity in tomato under heat stress conditions. Low-temperature stress, on the other hand, compromises membrane fluidity and induces chilling injury. Microbial biostimulants enhance membrane stability and promote the accumulation of cryoprotectant compounds, as reported in pea and broccoli.

5.4 Summary Table of Stress Mitigation Mechanisms

Stress Type	Biological Input	Primary Mechanism	Vegetable Example
Salinity	Arbuscular mycorrhizal fungi (AMF)	Improved K ⁺ /Na ⁺ homeostasis; increased SOD and POD activity	Eggplant, Pepper
Salinity	PGPR with ACC deaminase	Reduced ethylene-induced senescence; improved root growth	Tomato
Drought	Seaweed extract (betaines)	Osmoprotection; stomatal regulation; increased leaf relative water content	Bean, Zucchini
Drought	Arbuscular mycorrhizal fungi (AMF)	Enhanced water uptake via hyphal networks; glomalin-mediated soil stability	Cucumber
High temperature	Protein hydrolysates	Upregulation of heat shock proteins (HSPs); maintained photosynthetic efficiency	Tomato
Low temperature	Microbial biostimulants	Enhanced membrane stability; cryoprotectant accumulation	Pea, Broccoli
Stress Type	Biological Input	Primary Mechanism	Vegetable Example

6. Impact on Vegetable Quality and Post-Harvest Characteristics

A critical advantage of biofertilizers and biostimulants over synthetic fertilizers is their positive modulation of product quality traits, including phytochemical content, organoleptic properties, and shelf life. These improvements not only enhance nutritional value but also increase market acceptability and reduce post-harvest losses.

6.1 Phytochemical Enhancement

Biostimulants consistently elevate the concentration of secondary metabolites with health-promoting properties. Seaweed extracts increase glucosinolates in broccoli and anthocyanins in eggplant. Humic substances raise

lycopene and β -carotene levels in tomato, enhancing both antioxidant capacity and visual appeal. These phytochemical increases are associated with upregulation of key biosynthetic enzymes and stress signaling pathways.

6.2 Organoleptic Properties

Protein hydrolysates improve flavor-related traits by increasing total soluble solids (TSS), which primarily consist of sugars, and titratable acidity. In tomato and pepper, these changes result in a more balanced flavor profile and higher consumer preference. The effect is linked to enhanced carbon assimilation and improved translocation of photoassimilates to fruits.

6.3 Shelf Life Extension and Food Safety

Reduced nitrate accumulation is a notable benefit, particularly for leafy greens such as spinach and lettuce, where high nitrate levels pose health concerns. Biostimulants lower nitrate content by enhancing nitrate reductase activity and improving nitrogen use efficiency. Additionally, increased antioxidant capacity correlates with slower post-harvest senescence and reduced oxidative degradation. In PGPR-treated lettuce, shelf life at 4°C was extended by 3–4 days, attributed to reduced microbial spoilage and delayed tissue deterioration.

7. Crop-Specific Responses to Biofertilizers and Biostimulants

Different vegetable groups exhibit distinct responses to biological inputs, necessitating tailored recommendations.

7.1 Tomato

Application of *Azotobacter* (nitrogen-fixing biofertilizer) combined with seaweed extract significantly improves plant height, fruit yield, lycopene content, and post-harvest shelf life. The synergy between nutrient provisioning and physiological modulation is particularly pronounced in this high-value solanaceous crop.

7.2 Chilli (Hot Pepper)

PGPR and amino acid-based biostimulants enhance flowering intensity, fruit set percentage, and capsaicin content. Capsaicin, the pungency-determining alkaloid, is positively influenced by stress-priming compounds present in these biostimulants.

7.3 Cabbage and Cauliflower

Mycorrhizal inoculation improves nutrient uptake particularly phosphorus and micronutrients leading to better head and curd quality. Enhanced mineral nutrition also reduces physiological disorders such as tip burn.

7.4 Cucurbits (Cucumber, Pumpkin, Melon)

Humic acid combined with phosphate-solubilizing bacteria improves vine length, leaf area, fruit number, and overall fruit quality. The effect is mediated by improved root architecture and phosphorus availability.

7.5 Onion and Garlic

Biofertilizers, including *Azotobacter*, *Azospirillum*, and phosphate solubilizers, increase bulb size, enhance sulfur metabolism (important for flavor and pungency), and extend storage life by reducing post-harvest sprouting and decay.

8. Overall Benefits of Biofertilizers and Biostimulants in Vegetable Production

Parameter	Specific Benefits
Soil health	Improved microbial diversity, enhanced soil organic matter, better soil structure and aggregation
Nutrient efficiency	Enhanced nutrient availability (N, P, K, Zn, Fe), improved uptake and utilization efficiency
Crop yield	Increased productivity across fruit, leafy, root, and leguminous vegetables (average 18% gain)
Crop quality	Better nutritional composition (vitamins, antioxidants, lycopene, glucosinolates) and market quality (color, flavor, shelf life)
Environmental impact	Reduced reliance on synthetic chemical fertilizers, lower nitrate leaching and greenhouse gas emissions
Economic benefits	Lower input costs, reduced dependency on imported fertilizers, sustainable production with higher profit margins

The accumulated evidence supports the integration of biological inputs into mainstream vegetable production systems. The following table summarizes the multi-dimensional benefits.

9. Integrated Use of Biofertilizers and Biostimulants in Sustainable Vegetable Production

9.1 Rationale for Integrated Application

The integrated application of biofertilizers, biostimulants, and reduced rates of chemical fertilizers constitutes an effective nutrient management strategy for sustainable vegetable production. This approach enhances nutrient-use efficiency, synchronizes nutrient release with crop demand, and maintains ecological balance. Rather than relying solely on synthetic inputs, integrated nutrient management (INM) leverages the complementary functions of biological inputs biofertilizers improving nutrient availability and biostimulants modulating plant physiology to achieve higher productivity with lower environmental footprints.

9.2 Advantages of Integration

The integration of biological inputs with reduced chemical fertilizers offers multiple benefits:

- **Reduced chemical fertilizer dependency** Replacement of 25–50% of synthetic nitrogen and phosphorus without yield penalties.
- **Enhanced soil fertility** Improved microbial diversity, organic matter content, and soil structure.
- **Improved resilience under climate stress** Better tolerance to drought, salinity, and temperature extremes.
- **Better nutrient synchronization** Matching nutrient release with crop uptake periods, reducing losses.
- **Sustainable productivity** Maintaining or increasing yields over the long term while preserving natural resources.

9.3 Practical Implementation Strategies

Successful integration requires attention to crop-specific needs, local soil conditions, and appropriate application methods. Seed treatment with biofertilizers at planting establishes beneficial rhizosphere colonization, while foliar or soil application of biostimulants at critical phenological stages (transplanting, flowering, fruit set) maximizes physiological benefits. The simultaneous or sequential application of complementary inputs such as AMF with protein hydrolysates or *Azospirillum* with humic substances produces synergistic effects that exceed the sum of individual contributions.

10. Constraints and Challenges in Widespread Adoption

Despite demonstrated efficacy under experimental conditions, the large-scale adoption of biofertilizers and biostimulants faces several practical constraints.

10.1 Short Shelf Life and Formulation Instability

Many microbial formulations, particularly those containing living bacteria or fungi, have limited shelf stability. Viability declines rapidly under ambient storage conditions, especially in tropical climates with high temperature and humidity. Maintaining a consistent population of viable microorganisms from production to field application remains a significant technical challenge.

10.2 Variable Field Performance

Field-scale results often vary considerably from controlled greenhouse studies. Environmental factors such as soil type, temperature, moisture, pH, and competition with native soil microflora influence the survival and activity of introduced microorganisms. Consequently, a product that performs well in one location or season may show inconsistent or even negligible effects elsewhere.

10.3 Lack of Farmer Awareness and Technical Knowledge

Limited technical knowledge among farmers restricts the adoption of biological inputs. Many growers are unfamiliar with proper application methods (seed coating, soil drench, foliar spray), optimal timing, and compatible tank-mix partners. Misconceptions about the efficacy of bio-products compared to chemical fertilizers further hinder acceptance.

10.4 Storage and Transportation Issues

Improper handling during storage and transport reduces microbial viability and product efficacy. Cold chain infrastructure is often lacking in rural areas of developing countries, where vegetable production is intensive. Packaging that allows gas exchange while preventing contamination is required but adds to production costs.

10.5 Regulatory Fragmentation and Quality Standardization

The absence of harmonized definitions, quality standards, and registration requirements across global markets impedes commercialization. Products labeled as "biofertilizer" or "biostimulant" in one country may not meet the criteria of another, creating barriers for manufacturers and uncertainty for farmers.

10.6 Knowledge Transfer Gaps

Optimal application protocols including dose, timing, frequency, and method are crop- and product-specific. However, such detailed recommendations are often unavailable to extension services and farmers, leading to suboptimal use and disappointing results.

11. Future Prospects and Research Priorities

To fully harness the potential of biofertilizers and biostimulants in vegetable production systems, future research and development should focus on the following priority areas.

11.1 Development of Multi-Strain Microbial Consortia

Single-strain inoculants often fail under variable field conditions due to competition or limited functional breadth. Designing synthetic microbial consortia containing complementary strains (e.g., nitrogen fixers, phosphate solubilizers, PGPR, and biocontrol agents) can provide more robust and predictable benefits. Advances in genomics and metabolomics (omics-guided selection) enable the identification of strains with synergistic functions and environmental resilience.

11.2 Nanotechnology-Based Formulations

Encapsulation of biostimulant compounds or beneficial microbes in biodegradable nanoparticles offers several advantages: protection from environmental degradation, controlled release, improved shelf life, and targeted delivery to the rhizosphere or plant tissues. Nanoformulations can also enhance the stability of sensitive molecules such as proteins, amino acids, and phytohormones.

11.3 Climate-Resilient Bio-Inputs

As climate change intensifies abiotic stresses (drought, salinity, heat), there is an urgent need to develop or screen microbial strains and biostimulant compounds that remain effective under extreme conditions. Stress-tolerant PGPR, thermotolerant AMF, and biostimulants that upregulate heat shock proteins or osmoprotectants are particularly valuable.

11.4 Integration with Precision Agriculture

Aligning bio-input application with precision agriculture tools can optimize their effectiveness. Decision support systems, soil sensors, and remote sensing can guide the timing and dosage of biostimulants based on real-time crop water status, nutrient demand, or stress indicators. Variable-rate application technologies can also reduce waste and improve cost-effectiveness.

11.5 Long-Term Ecosystem Studies

Most studies report short-term (single season) effects of biological inputs. Long-term assessments are needed to understand the cumulative impacts of repeated applications on native soil biodiversity, nutrient cycling, greenhouse gas emissions, and the development of resistance or shifts in microbial community structure.

11.6 Commercialization and Quality Standardization

Efforts to standardize quality control protocols, establish shelf-life testing methods, and harmonize regulatory frameworks across regions will facilitate market growth. Public-private partnerships can support the production of affordable, high-quality formulations with consistent field performance.

11.7 Farmer Education and Extension

Investment in training programs, demonstration plots, and easily accessible extension materials is essential to raise awareness and build technical capacity. Participatory approaches that involve farmers in evaluating bio-inputs on their own fields can accelerate adoption.

12. Conclusion

Biofertilizers and biostimulants represent powerful, complementary tools for sustainable vegetable crop production. Biofertilizers enhance nutrient access through microbial activities such as nitrogen fixation, phosphate solubilization, and mycorrhizal symbiosis. Biostimulants including humic substances, protein hydrolysates, seaweed extracts, and microbial metabolites improve plant physiology, stress resilience, nutrient

use efficiency, and final product quality. Their greatest potential lies in integrated, synergistic application, which can reduce synthetic fertilizer dependency by 25–50% while improving yield stability under climate-induced stresses.

The application of these biological inputs improves plant growth, nutrient uptake, crop yield, quality attributes (phytochemicals, flavor, shelf life), and soil health, while simultaneously reducing the environmental hazards associated with excessive chemical fertilizer use, such as nitrate leaching, eutrophication, and greenhouse gas emissions. Crop-specific responses evident in tomato, chilli, cabbage, cucurbits, onion, and garlic demonstrate the versatility of these inputs across diverse production systems.

For this potential to be realized at scale, several challenges must be addressed. These include short shelf life and formulation instability, variable field performance due to environmental factors, lack of farmer awareness, storage and transportation issues, regulatory fragmentation, and knowledge transfer gaps. Future research should prioritize multi-strain microbial consortia, nanotechnology-based formulations, climate-resilient bio-inputs, precision agriculture integration, long-term ecosystem studies, and commercialization standards. Wider adoption also requires improved extension services, supportive policies, quality control mechanisms, and further research on crop-specific, location-specific recommendations.

As the agricultural sector moves toward a circular, low-input, and climate-smart model, biofertilizers and biostimulants will be indispensable for producing nutritious, safe, and affordable vegetables for a growing global population. Their integration into mainstream production systems contributes directly to sustainable agriculture, food security, and environmental stewardship.

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The Silent Giants: Forest-Based Industries Behind Modern Living



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Abstract

Forest-based industries are a vital yet often unnoticed part of modern life, providing raw materials for construction, paper, furniture, medicines, packaging, and eco-friendly products. This article explores the importance of both timber and non-timber forest products in supporting economies, livelihoods, and everyday human needs. Major industries such as timber processing, paper and pulp, bamboo and cane, herbal medicine, furniture manufacturing, and rubber production are discussed for their economic and social contributions. These industries generate employment for millions of people, especially in rural and tribal communities, while also supporting trade and industrial growth. The article also highlights the environmental significance of sustainably managed forests through carbon storage, renewable resource use, and biodegradable alternatives to plastics. Key challenges including deforestation, illegal logging, industrial pollution, and climate change are examined. The study concludes that sustainable forest-based industries are essential for balancing economic development, environmental conservation, and long-term human well-being.

Keywords - Forest-based industries, Sustainable forestry, Non-timber forest products, Green economy, Forest conservation

Introduction

When we think of forests, images of wildlife corridors, biodiversity hotspots, and carbon sinks come to mind. Rarely do we pause to consider the wooden desk we sit at, the paper we write on, the rubber sole of our shoe, or the herbal tablet we swallow. Yet every one of these everyday objects has its origin in a forest somewhere on Earth. Forests cover roughly **4.06 billion hectares** —



about 31% of the world's total land area (Food and Agriculture Organization [FAO], 2025). Beyond their ecological role, they form the raw-material backbone of a vast network of industries that silently power modern lifestyles. Timber frames our homes; pulp fills our libraries; bamboo furnishes eco-conscious kitchens; resins coat our medicines; essential oils perfume our living rooms. This article explores how these "silent giants" shape economies, communities, and daily life — and what it will take to sustain them (Kumar et al., 2024).

Understanding Forest-Based Industries

Forest-based industries are those that use forest resources — whether timber or non-timber — as primary raw materials. They span two major resource categories:

Timber Forest Products (TFPs) include logs, sawn wood, plywood, veneers, and wood pulp extracted directly from trees. Non-Timber Forest Products (NTFPs) encompass bamboo, cane, medicinal plants, resins, gums, essential oils, honey, and a host of other biological materials harvested without felling trees (FAO, 2025).

These industries are further classified by scale: *large-scale industries* such as the paper, plywood, and rubber sectors operate globally with mechanised processes; *small-scale and cottage industries* — woodcraft, basket-weaving, herbal preparation — sustain rural and tribal livelihoods and represent an irreplaceable cultural heritage.

Major Forest-Based Industries

Forest-Based Industry	Raw Material Used	Major Products	Role in Daily Life
Timber Industry	Wood logs	Construction wood, plywood, doors	Housing and infrastructure
Paper & Pulp Industry	Bamboo, wood pulp	Paper, cardboard, notebooks	Education and packaging
Furniture Industry	Hardwood, softwood	Tables, chairs, cabinets	Home and office use
Bamboo & Cane Industry	Bamboo, cane	Baskets, mats, handicrafts	Eco-friendly household products
Herbal & Medicinal Industry	Medicinal plants	Ayurvedic medicines, cosmetics	Healthcare and wellness
Rubber Industry	Latex from rubber trees	Tyres, gloves, footwear	Transportation and medical use

A. Timber and Wood Industry

The timber industry is the oldest and largest forest-based sector. Wood remains indispensable in construction — from structural framing and flooring to roofing and interior panelling. Plywood and veneers are critical in both housing and infrastructure. According to the FAO's 2025 report, industrial roundwood production rose 2% in 2024 to reach **1.96 billion cubic metres**, while wood-based panel production expanded 5% to 393 million cubic metres. Engineered wood products such as cross-laminated timber (CLT) have surged, accounting for nearly 20% of global wood-based panel output in 2025 — a reflection of growing demand for sustainable construction materials (FAO, 2025).

B. Paper and Pulp Industry

Paper may be one of civilisation's most understated inventions. From textbooks and newspapers to food packaging and medical wrappings, its reach is universal. The EU pulp and paper sector alone employs around **647,000 workers** across 21,000 companies, generating an annual turnover of approximately €180 billion. Globally, around **405 million tonnes** of paper and paperboard are produced each year — a figure that could double by 2050 if current trends continue.



Wood pulp production climbed 3% in 2024 to reach 189 million tonnes, with international trade expanding 2% to an all-time high of 73 million tonnes, according to FAO data. The packaging segment has become the dominant growth driver, propelled by the e-commerce boom and a global push to replace single-use plastics with paper-based alternatives (European Commission, 2024).

"The paper industry is the fourth largest sector when it comes to energy consumption — and also a pioneer in making the EU's low-carbon bioeconomy an industrial reality." — European Commission

C. Furniture and Handicraft Industry



Wood furniture is a global trade colossus. Teak, rosewood, oak, and sheesham are crafted into household and office furniture that combines aesthetic appeal with durability. Traditional woodcraft — Bidriware inlays, Rajasthani carved furniture, Scandinavian joinery — carries cultural identity and commands premium export prices. India's furniture and wood products sector contributes significantly to rural employment,

with artisan clusters in states like Rajasthan, Uttar Pradesh, and Kerala serving both domestic and international markets.

D. Bamboo and Cane Industry

Bamboo is one of the world's fastest-growing plants — some species can grow nearly a metre per day — and it has emerged as a critical eco-friendly material. Bamboo is used in construction, furniture, textiles, baskets, and even as a substitute for plastic (Kumar et al., 2024). The bamboo and cane industry is a vital rural handicraft sector. It utilizes renewable,



lightweight, and durable materials to create everything from fine furniture and woven baskets to decorative mats and agricultural tools. Driven by eco-conscious consumer trends, it remains a primary income source for millions of artisans globally. In India alone, bamboo-based industries support the livelihoods of over 13 million people, particularly in north-eastern states (Sharma & Singh, 2023). As sustainability gains commercial urgency, bamboo is increasingly positioned as the "green steel" of the 21st century.

E. Herbal and Medicinal Industry



Forests are the world's original pharmacies. More than 80% of the global population relies on plant-based medicines for primary healthcare (World Health Organization [WHO], 2023), according to the World Health Organization. Forest-derived botanicals — neem, turmeric, ashwagandha, brahmi, arjuna — underpin the Ayurvedic and Unani pharmaceutical

sectors. India's herbal products market is among the world's fastest-growing, with exports of medicinal plant products exceeding \$1 billion annually. Modern pharmaceutical research continues to draw on forest biodiversity for new drug leads, from anti-cancer alkaloids to antimicrobial compounds (WHO, 2023).

F. Rubber, Resin, and Essential Oil Industries

Natural rubber from *Hevea brasiliensis* remains irreplaceable in high-performance tyre manufacturing, surgical gloves, and aerospace applications. Resins such as dammar, copal, and shellac find uses in paints, varnishes, adhesives, and even food coatings. Essential oils — eucalyptus, sandalwood, cedarwood, patchouli — are the backbone of the global aromatherapy, personal care, and fragrance industries, which together represent a multi-billion-dollar market.



Role of Forest-Based Industries in Modern Living

The daily footprint of forest industries is invisible precisely because it is so pervasive. Walk through a home and find timber framing, paper packaging in the kitchen, rubber seals on appliances, essential-oil diffusers in the living room, and an Ayurvedic supplement in the medicine cabinet. Every item is a forest product in disguise.

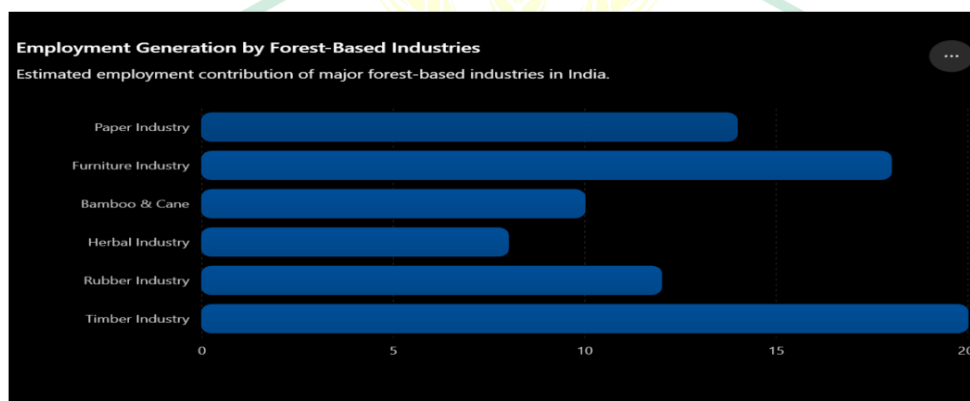
The economic contribution of forest industries extends beyond direct employment. The sector supports a cascade of downstream industries — construction, publishing, pharmaceuticals, cosmetics, food processing — multiplying its economic impact many times over. In India, NTFPs contribute an estimated 40–60% of household income for forest-dwelling communities. Tribal women form the backbone of NTFP collection, and cottage-

industry schemes in herbal processing and bamboo handicrafts have demonstrably improved female financial independence across South and Southeast Asia.

Sector	Contribution
Employment Generation	Provides jobs to millions in rural and tribal areas
Export Earnings	Woodcrafts, paper, herbal products exported globally
Rural Development	Supports cottage and small-scale industries
Industrial Growth	Supplies raw materials for manufacturing
Environmental Benefits	Encourages renewable and biodegradable products

Product	Forest Source	Daily Use
Paper	Wood pulp	Books, newspapers, packaging
Furniture	Timber	Household and office use
Rubber	Latex	Tyres, gloves, shoes
Herbal Medicine	Medicinal plants	Healthcare
Bamboo Products	Bamboo	Baskets, furniture, decor
Essential Oils	Forest herbs	Cosmetics and aromatherapy

Environmental Significance



Paradoxically, well-managed forest industries can be among the most environmentally beneficial sectors. Trees are a renewable resource: replanted forests sequester carbon, restore watersheds, and maintain biodiversity corridors. The European Union, targeting a 55% reduction in greenhouse gas emissions by 2030, has embedded wood biomass — largely a forest-industry byproduct — into its renewable energy strategy, with 12% of total EU energy already derived from biomass as of 2024. (Forest Stewardship Council [FSC], 2024).

Bamboo and paper products are at the forefront of replacing single-use plastics. Paper straws, bamboo cutlery, and recycled packaging are tangible everyday examples of forest industries contributing to a circular economy. Certification systems — the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) — now govern responsible harvesting across hundreds of millions of hectares, linking market access to sustainability standards.

"More than 90% of the world's forests are regenerating naturally, and global net loss of forest area has been reduced by more than half since the 1990s." — FAO, 2025

Challenges

- **Deforestation & resource depletion:** Overharvesting, especially of high-value tropical hardwoods, continues in unregulated markets. Over 22% of the world's natural forests are under partial or full logging bans.
- **Illegal logging:** Estimated to account for 15–30% of global wood trade, illegal logging undermines legal markets, accelerates biodiversity loss, and deprives governments of revenue. (Brown & Wilson, 2022).

- **Industrial pollution:** The paper and pulp industry is the fourth largest energy consumer globally and a significant water user — mill effluents, if untreated, severely impact aquatic ecosystems.
- **Climate change:** Shifting precipitation, increased wildfire frequency, and pest outbreaks are reducing forest productivity and threatening plantation-based supply chains. (Brown & Wilson, 2022).



A Sustainable Future: Innovations and Solutions

The trajectory of forest-based industries is increasingly shaped by technology and policy. Smart forestry — drones for canopy monitoring (Kumar et al., 2024), AI-driven harvest planning, satellite deforestation alerts — is a fast-growing sub-sector, with the smart forestry market projected to reach **\$4.2 billion by 2033** at a CAGR of 12.3%. These tools reduce waste, improve yield, and enable near-real-time enforcement of sustainable harvesting rules. Government policy is equally vital. India's Compensatory Afforestation Fund, the EU Forest Strategy for 2030, and Brazil's REDD+ programmes represent a new generation of interventions that attempt to square the circle — sustaining industrial output while expanding forest cover and biodiversity. (FAO, 2025)

Conclusion

The Giants Must Not Fall Silent

Forest-based industries are one of the most consequential yet least discussed drivers of modern living. They employ tens of millions, contribute hundreds of billions to global GDP, sustain indigenous cultures, and — when managed responsibly — protect the very ecosystems they depend on. The global forestry and logging market, valued at \$342 billion in 2024, is projected to approach \$634 billion by 2032. These are not marginal numbers; they represent an industrial ecosystem as vital as any other (Kumar et al., 2024).

The challenge ahead is not to choose between forests and industry, but to ensure that industrial demand flows through sustainable channels — certified supply chains, replanted landscapes, circular processes, and empowered communities. Forests have served humanity for millennia without asking for recognition. The least we can do is manage them wisely (FAO, 2025).

"Forests are the silent giants powering industries, supporting livelihoods, and sustaining the rhythm of modern life."

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Improved Crop Varieties: A Key Pathway to Enhance Farmer's Income in India



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Abstract

Improved crop varieties play a crucial role in enhancing agricultural productivity, profitability, and sustainability in modern farming systems. These varieties are developed through systematic breeding approaches and possess superior characters such as high yield potential, resistance to pests and diseases, tolerance to abiotic stresses, and improved quality attributes. The adoption of improved varieties enables farmers to achieve higher production with efficient utilisation of resources, thereby increasing net income. Additionally, early maturity and adaptability of these varieties facilitate multiple cropping and reduce the risks associated with climate variability. In horticultural crops, improved hybrids and varieties further contribute higher returns due to better quality and market demand. Despite their advantages, challenges such as limited awareness and access to quality seeds hinder widespread adoption. This article highlights the significance of improved varieties as a cost-effective and sustainable strategy for increasing farmer's income and ensuring agricultural resilience.

Keywords: Crop productivity, farmer income, hybrid seeds, improved varieties, stress tolerance

Introduction

Agriculture is the primary source of livelihood for the majority of the Indian population. Still farmers are facing multiple challenges, such as high input costs, climate variability, declining soil fertility, and limited land resources. Increasing farmer's income under these constraints requires innovative, cost-effective, and sustainable solutions. Improved crop varieties is one solution, which played a key role in transforming agriculture in the past and continues to do so in the present. These varieties are capable of producing high yields, withstanding stress conditions, and meeting market demands. By improving productivity and reducing risks, they contribute significantly to enhance farmer's income and livelihood security (Roy et al., 2021; Srivastava & Warshini, 2024).

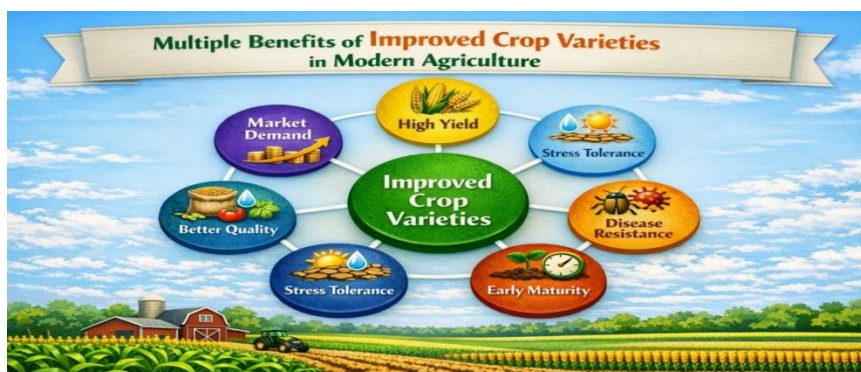
Improved varieties

Improved varieties are crop varieties developed through scientific breeding techniques to incorporate desirable traits such as early maturity, higher yield potential, resistance to pests and diseases, tolerance to drought, salinity, and temperature stress, improved quality and shelf life. They are developed through breeding methods such as selection, hybridisation, mutation breeding, and advanced breeding techniques. Before the release, these varieties are tested across multiple locations to ensure their adaptability and stability (Meena & Kaur, 2023; Basantaray et al., 2024).

Key traits and their benefits

Table 1. Important traits of improved varieties and their benefits

Trait	Benefit to farmers
High-yielding potential	Increased production and income
Pest and disease resistance	Reduced crop losses and pesticide costs
Early maturity	Allows multiple cropping
Stress tolerance	Stable yield under adverse conditions
Uniform growth	Easy crop management and harvesting
Better quality produce	Higher market price
Longer shelf life	Reduced post-harvest losses



Role of improved varieties in increasing farmers' income

1. Increased yield potential

Improved varieties have significantly higher yield potential compared to traditional varieties. Under proper management, they can increase yield by 20–50% or even more. This increase directly enhances farmer's income without requiring additional land (Roy et al., 2021).

2. Reduction in the cost of cultivation

Improved varieties often possess resistance to major pests and diseases, reducing the need for chemical pesticides. This lowers the cost of cultivation and increases net returns. Additionally, their efficient use of fertilisers and water further reduces input costs (Roy et al., 2021).

3. Climate resilience and risk reduction

With changing climatic conditions, crop failures have become more frequent. Improved varieties with tolerance to drought, heat, or salinity ensure stable yields even under adverse conditions, thereby reducing income risk for farmers (Srivastava & Warshini, 2024).

4. Early maturity and multiple cropping

Short-duration varieties allow farmers to harvest crops earlier and cultivate additional crops within the same year. This increases cropping intensity and overall farm income (Meena & Kaur, 2023).

5. Improved quality and market value

Improved varieties produce uniform, attractive, and high-quality produce that meets market preferences. This helps farmers to obtain better prices, especially in fruits and vegetables, where quality plays a major role in determining market value (Basantaray et al., 2024).

Economic advantage of improved varieties

Table 2. Comparison between traditional and improved varieties (Roy et al., 2021)

Parameter	Traditional Variety	Improved Variety
Yield (t/ha)	2.5	4.0
Cost of cultivation (₹/ha)	40,000	45,000
Gross return (₹/ha)	75,000	1,40,000
Net return (₹/ha)	35,000	95,000
Benefit: Cost ratio	1.8	3.1

Note: Values are indicative and may vary depending on crop and location.



Role in Horticultural Crops

Horticultural crops offer higher income potential per unit area, and improved varieties further enhance this advantage such as higher yields and uniform produce, better quality, shelf life, and market demand. Varieties suitable for protected cultivation provide off-season production also.

Input use efficiency

Table 3. Input use efficiency in traditional and improved varieties (Meena & Kaur, 2023).

Input	Traditional varieties	Improved varieties
Fertilizer efficiency	Moderate	High
Water use efficiency	Low	Improved
Pest control cost	High	Reduced
Labour requirement	Higher	Optimized

Improved varieties ensure better conversion of inputs into output, increasing profitability.

Contribution to Sustainable Agriculture

Improved varieties contribute to sustainability by reducing excessive use of chemicals, conserving water resources, enhancing resilience to climate change and promoting efficient land use. These factors help maintain long-term productivity and income stability.

Challenges in adoption

Despite their benefits, adoption is limited due to a lack of awareness among farmers, high cost of hybrid seeds, the limited availability of quality seeds and inadequate extension services

Recommendations for Farmers

- Select varieties suitable for local agro-climatic conditions
- Use certified seeds from reliable sources
- Follow recommended agronomic practices
- Integrate improved varieties with proper nutrient and pest management
- Seek guidance from agricultural experts

Conclusion

Improved crop varieties are a powerful tool for enhancing farmer's income by increasing productivity, reducing risks, and improving produce quality. They provide a sustainable solution to the challenges faced by modern agriculture, including climate change and resource limitations. For small and marginal farmers, improved varieties offer an opportunity to achieve higher returns with limited resources. However, their full potential can be realised only through increased awareness, better access to quality seeds, and proper technical support.

In conclusion, improved varieties serve as a foundation for profitable and sustainable agriculture. Their widespread adoption will not only improve farmers' livelihoods but also contribute to national goals such as food security and agricultural development.

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Why Livestock Diseases Matter Even to Urban Populations



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Introduction

Livestock diseases are often considered a concern limited to farmers, veterinarians, and rural communities. However, in today's inter-connected world, diseases affecting animals have far-reaching consequences that extend well beyond villages and agricultural regions. Urban populations, despite having little direct interaction with livestock, are deeply affected by animal diseases through impacts on food security, public health, the economy, trade, and environmental sustainability. Outbreaks of livestock diseases can disrupt supply chains, increase food prices, threaten employment, and even contribute to the emergence of zoonotic infections that affect humans. Therefore, livestock health is no longer solely an agricultural issue but an important component of national and global well-being.

The livestock sector contributes significantly to food production, nutrition, rural livelihoods, and economic development. Millions of people depend on animals for milk, meat, eggs, leather, wool, transportation, and income generation. Urban consumers rely heavily on rural livestock production systems for their daily supply of nutritious animal-derived food products. Consequently, diseases affecting livestock have a direct impact on urban life, even if the connection is not immediately visible.

Livestock Diseases and Food Security

One of the most important ways livestock diseases affect urban populations is through food security. Diseases such as Foot-and-Mouth Disease (FMD), Avian Influenza, African swine fever, mastitis, brucellosis, and lumpy skin disease can severely reduce animal productivity. Infected animals produce less milk, gain less body weight, suffer reproductive losses, and may even die. During major outbreaks, governments often impose restrictions on animal movement and trade to prevent disease spread, leading to shortages of animal products in markets.

When livestock production declines, urban consumers experience increased prices of milk, meat, eggs, and other animal products. Inflation in food prices particularly affects low- and middle-income households that depend on affordable nutrition. In densely populated cities, disruptions in food supply chains can rapidly create shortages and market instability. Thus, maintaining livestock health is directly linked to ensuring stable and affordable food supplies for urban populations.

Public Health and Zoonotic Diseases

Many livestock diseases are zoonotic, meaning they can spread from animals to humans. Over the past few decades, several major global health crises have originated from animal populations. Diseases such as avian influenza, swine flu, rabies, brucellosis, bovine tuberculosis, and even emerging coronaviruses have highlighted the close relationship between animal and human health.

Urban populations may not work directly with animals, but they remain vulnerable through food consumption, environmental exposure, travel, and global trade. Rapid urbanization, increased human-animal interactions, and international movement of goods and people have increased the risk of zoonotic disease transmission. Wet markets, improper food handling, and inadequate biosecurity measures can facilitate disease spread into cities.

The COVID-19 pandemic demonstrated how animal-origin diseases can disrupt global health systems, economies, education, transportation, and everyday life. This has reinforced the importance of the "One Health" concept, which recognizes that human health, animal health, and environmental health are closely interconnected. Protecting livestock health therefore contributes significantly to protecting public health.

Economic Impact beyond Rural Areas

Livestock diseases cause enormous economic losses not only to farmers but also to industries and consumers in urban regions. Outbreaks can affect food processing industries, dairy cooperatives, meat supply chains, pharmaceutical industries, leather industries, transportation sectors, and export markets. Many urban businesses depend directly or indirectly on livestock production systems.

For example, an outbreak of FMD may lead to international trade bans on animal products, causing national economic losses worth billions of dollars. Reduced productivity and higher disease control costs can affect the entire agricultural economy, eventually influencing national inflation and employment rates. Urban populations may experience higher living costs, job insecurity, and reduced availability of quality food products.

Additionally, governments spend substantial resources on disease surveillance, vaccination campaigns, outbreak management, compensation schemes, and veterinary infrastructure. These expenditures ultimately involve public funds that impact the broader economy and taxpayers, including urban residents.

Impact on Nutrition and Human Well-Being

Animal-derived foods are important sources of high-quality protein, vitamins, minerals, and essential fatty acids. Milk, meat, eggs, and fish contribute significantly to balanced human nutrition, especially for children, pregnant women, and elderly individuals. Livestock diseases that reduce food production can therefore negatively affect nutritional security in urban populations.

Rising prices of animal products may force economically weaker sections of society to reduce consumption of nutritious foods, potentially leading to protein deficiency and micronutrient malnutrition. Children are particularly vulnerable because inadequate nutrition during early development can impair physical growth, immunity, and cognitive development.

Thus, controlling livestock diseases indirectly contributes to improving public health and nutritional outcomes among urban populations as well.

Environmental and Ecological Concerns

Livestock diseases can also influence environmental sustainability and ecological balance. During severe outbreaks, mass culling of animals may become necessary to contain infection spread. Disposal of carcasses and biological waste can create environmental challenges, including soil and water contamination if not managed properly.

Uncontrolled disease outbreaks may also encourage excessive use of antibiotics and disinfectants, contributing to antimicrobial resistance and environmental pollution. Antimicrobial resistance has emerged as a major global public health concern because resistant pathogens can spread through food chains, water systems, and human contact.

Climate change is further influencing the distribution and emergence of livestock diseases. Changes in temperature, rainfall patterns, humidity, and vector populations are affecting disease transmission dynamics worldwide. Urban populations are increasingly impacted by these ecological disturbances through food insecurity, economic instability, and public health risks.

The Role of Globalization and Urbanization

Modern transportation and globalization have made the world highly interconnected. Livestock products, animals, feed ingredients, and agricultural commodities move rapidly across regions and international borders. As a result, disease outbreaks occurring in one area can quickly affect distant cities and countries.

Urbanization has also increased demand for animal-derived foods, leading to intensification of livestock production systems. Intensive farming, high animal density, and large-scale trade networks can facilitate rapid disease spread if proper biosecurity measures are not implemented. Urban consumers are therefore indirectly linked to livestock production practices occurring far away from cities.

In addition, increasing pet ownership and urban farming practices have created new interfaces between animals and urban populations. These changing dynamics emphasize the need for improved veterinary surveillance, disease monitoring, and public awareness.

Importance of Disease Surveillance and Veterinary Research

Strong veterinary healthcare systems are essential for protecting both rural and urban populations from the consequences of livestock diseases. Disease surveillance, vaccination programs, rapid diagnostics, quarantine measures, and biosecurity practices help prevent outbreaks and reduce economic losses.

Advances in veterinary research are improving our ability to detect and control livestock diseases through modern technologies such as molecular diagnostics, nanotechnology-based biosensors, artificial intelligence, genomic surveillance, and vaccine development. Rapid disease detection enables authorities to respond quickly and prevent widespread transmission. Public investment in veterinary science and animal health infrastructure should therefore be viewed not merely as agricultural spending but as a critical investment in national health security and economic stability.

The One Health Approach

The growing recognition of the relationship between animal health, human health, and environmental sustainability has led to the adoption of the One Health approach. One Health promotes interdisciplinary collaboration among veterinarians, physicians, environmental scientists, policymakers, and public health experts to address complex health challenges collectively.

Effective control of livestock diseases requires coordinated surveillance, responsible antimicrobial use, food safety measures, environmental protection, and public education. Urban populations benefit directly from these integrated efforts through safer food supplies, improved public health preparedness, and greater economic stability.

Conclusion

Livestock diseases are not confined to farms or rural communities; they affect every section of society, including urban populations. From food security and public health to economic stability and environmental sustainability, the consequences of animal diseases extend far beyond the agricultural sector. Modern cities depend heavily on healthy livestock systems for safe and affordable nutrition, employment, trade, and overall societal stability.

As global populations continue to grow and urbanize, the importance of animal health will become even greater. Strengthening veterinary healthcare systems, supporting scientific research, improving disease surveillance, and promoting the One Health approach are essential steps toward safeguarding both rural livelihoods and urban well-being. Protecting livestock health ultimately means protecting human health, economic prosperity, and global stability.

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PHYSIOLOGICAL BASIS OF CROP YIELD



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Abstract

Crop yield is a complex trait governed by multiple physiological processes that determine plant growth, development, and productivity. Understanding the physiological basis of crop yield is essential for improving agricultural productivity under varying environmental conditions. Key processes such as photosynthesis, dry matter accumulation, and assimilate partitioning play a crucial role in determining final yield. This review synthesizes information from major studies to explain the physiological mechanisms underlying crop yield formation, including source-sink relationships, leaf area development, and environmental influences. Enhancing these physiological traits through breeding and agronomic practices can significantly improve crop productivity.

1. Introduction

Crop yield is the ultimate outcome of various physiological and biochemical processes occurring within a plant system. It is influenced by the plant's ability to intercept light, convert it into chemical energy through photosynthesis, and efficiently allocate assimilates to economically important parts such as grains or storage organs.

The physiological basis of crop yield primarily revolves around three fundamental processes:

1. Light interception
2. Biomass production (photosynthesis)
3. Dry matter partitioning

A comprehensive understanding of these processes is essential for improving yield potential and ensuring food security under changing climatic conditions.

2. Photosynthesis and Biomass Production

Photosynthesis is the primary physiological process responsible for converting solar energy into chemical energy in the form of carbohydrates. It directly determines the amount of biomass produced by a crop.

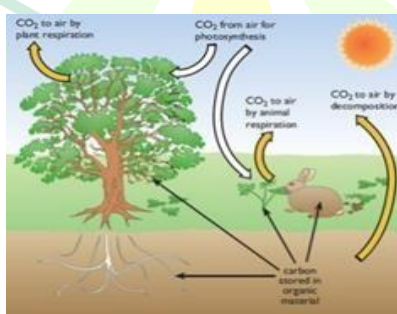


Figure 1: Photosynthesis and biomass production

Key factors influencing photosynthesis:

- Leaf area index (LAI)
- Chlorophyll content
- Stomatal conductance
- Light intensity and duration

Higher photosynthetic efficiency leads to increased biomass production, which ultimately contributes to higher yield. Crops with improved photosynthetic capacity can produce more assimilates, which are later utilized for growth and development.

3. Dry Matter Accumulation

Dry matter accumulation refers to the total biomass produced by the plant during its growth period. It is a cumulative result of photosynthesis over time.

Important aspects:

- Crop growth rate (CGR)
- Net assimilation rate (NAR)
- Duration of growth

The total dry matter produced is directly proportional to yield potential. Crops that accumulate more biomass generally produce higher yields, provided efficient partitioning occurs.

4. Partitioning of Assimilates (Source–Sink Relationship)

The distribution of assimilates from source organs (leaves) to sink organs (grains, roots, fruits) is a critical determinant of yield.

Source:

- Photosynthetically active leaves

Sink:

- Developing grains
- Storage organs

Efficient partitioning ensures that a greater proportion of assimilates is directed towards yield components such as grains. This is often expressed as the harvest index (HI).

Harvest Index:

Harvest Index = Economic yield / Biological yield

Improving harvest index is a major goal in crop improvement programs.

5. Leaf Area Development and Light Interception

Leaf area plays a vital role in determining the amount of light intercepted by the crop canopy.

Key parameters:

- Leaf area index (LAI)
- Canopy structure
- Duration of leaf area

Optimal LAI ensures maximum light interception without excessive shading. Efficient canopy architecture enhances photosynthetic efficiency and biomass production.

6. Physiological Traits Contributing to Yield

Several physiological traits contribute to improved crop yield:

6.1 Stomatal Conductance

- Regulates gas exchange
- Influences photosynthesis and transpiration

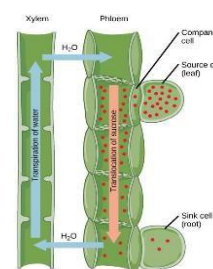


Figure 2: Source–Sink Relationship

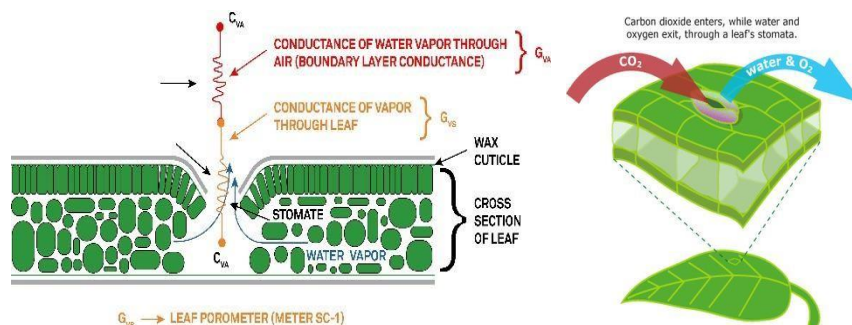


Figure 3: Stomatal Conductance

6.2 Chlorophyll Content

- Determines photosynthetic capacity

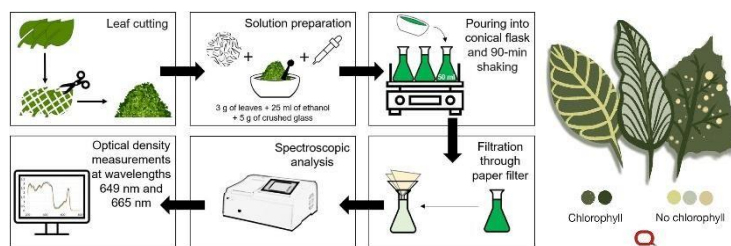


Figure 4: Chlorophyll Content

6.3 Root System Architecture

- Enhances water and nutrient uptake

6.4 Crop Duration

- Longer duration allows more biomass accumulation

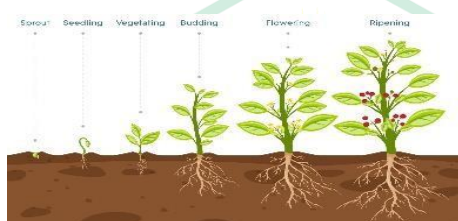


Figure 5: Crop Duration

7. Environmental Influences on Yield

Crop yield is significantly influenced by environmental factors such as:

- Temperature
- Water availability
- Soil fertility
- Light intensity

Stress conditions such as drought, salinity, and heat can reduce photosynthesis, disrupt assimilate partitioning, and ultimately decrease yield. Understanding physiological responses to these stresses is essential for developing resilient crop varieties.

8. Yield Components

Yield is determined by several components depending on the crop type:

- Number of plants per unit area
- Number of grains per plant
- Grain weight

These components are influenced by physiological processes during different growth stages.

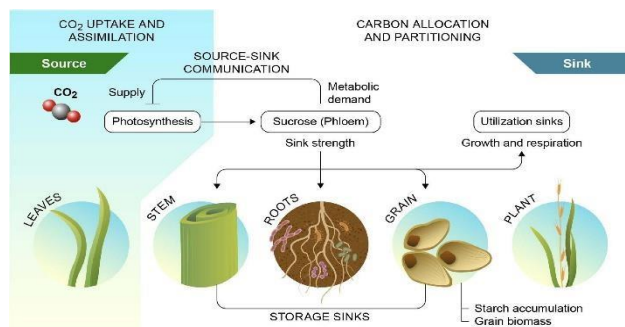


Figure 6: Yield Components

9. Integration of Physiological Processes

Crop yield is the result of the integration of multiple physiological processes:

- Light interception → Photosynthesis
- Photosynthesis → Biomass production
- Biomass → Partitioning → Yield

Efficient coordination among these processes is essential for achieving high productivity.

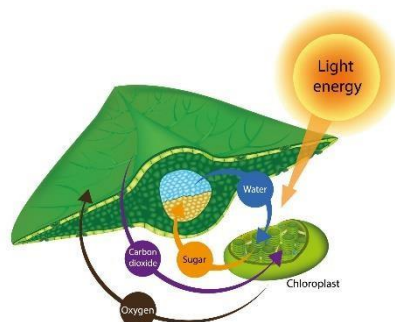


Figure 7: Integrated of physiological processes

10. Conclusion

The physiological basis of crop yield involves a complex interaction of processes including photosynthesis, dry matter accumulation, and assimilate partitioning. Improving these processes through breeding and management practices can significantly enhance crop productivity. Future research should focus on optimizing physiological traits and improving stress tolerance to ensure sustainable agricultural production.

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Biochar and Biofertilizers: Innovative Approaches for Sustainable Crop Production



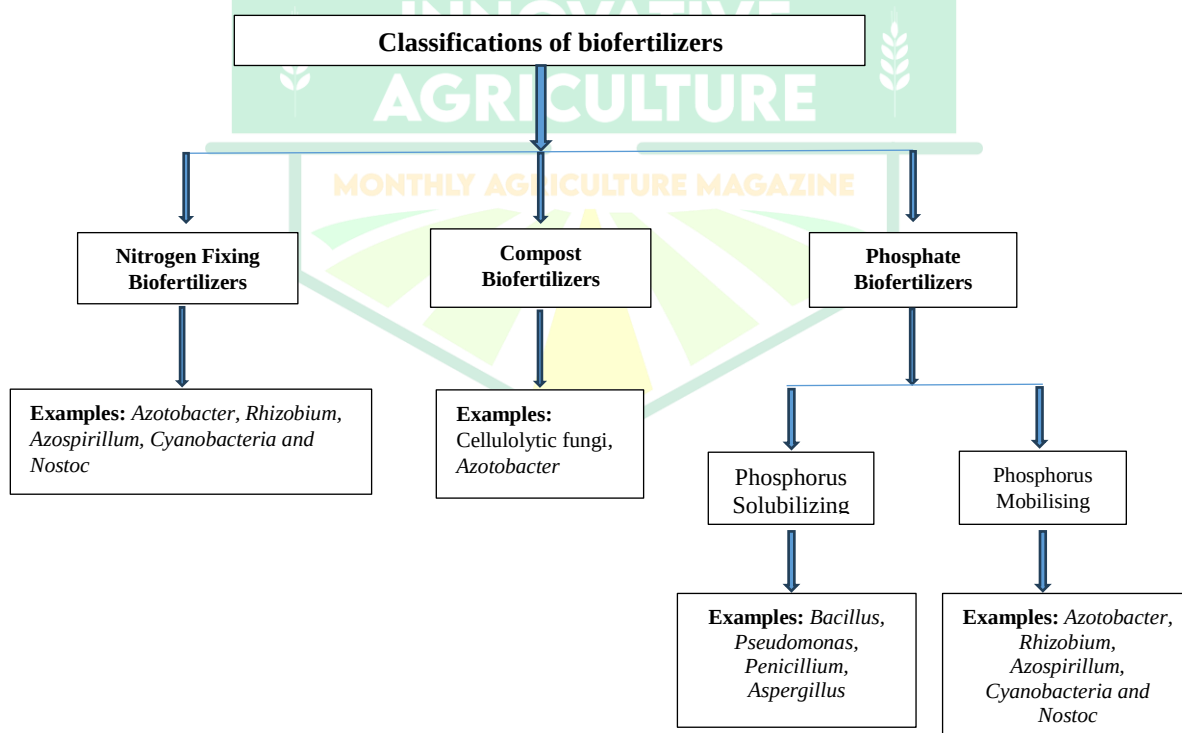
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Introduction

In the recent years several organic fertilizers have been introduced that act as natural stimulators or microbial inoculums for plant growth and development. Organic fertilizers, such as compost and manure, boost soil fertility by supplying essential nutrients, enhancing soil structure, and promoting microbial activity. The excess uses of chemical fertilizers in agriculture not only deteriorating the soil but have adverse effects on soil physio chemical properties. Therefore, a specific fertilizer includes products based on plant growth promoting microorganisms named biofertilizers or 'microbial inoculants' can be used to improve the soil health and crop productivity. One of its kind is Biochar which can be quickly produced from wood or bio mass it has a carbon content of about 70% to 80%. It improves soil structure, increases nutrient and water retention, and provides long term benefits by enhancing soil pH and carbon sequestration. Bio organic fertilizers combine organic matter with beneficial microorganisms to improve nutrient availability and plant health while supporting soil microbial activity. By having all these advantages, biomass materials are emerging as one of the most promising solutions for promoting sustainable agricultural practices.



Biochar production technique

Biochar is a charcoal-like substance used as a soil amendment. It is produced through the process of pyrolysis, in which biomass is heated at high temperature under limited oxygen conditions. Once the process starts, it becomes self-sustaining and does not require external energy. Its by-products are Syngas ($H_2 + CO$), Small amount of methane (CH_4), Organic acids and Excess heat.

Pyrolysis

Pyrolysis is the process of thermal decomposition applied to obtain high carbon-containing elements like biochar. The temperature and rate of heating applied to the stuff, among other pyrolysis parameters, affect the yield and composition of the pyrolyzed product. The temperature ranges from 400 to 600° C, and the heating rate ranges from 5 to 25° C per minute. An increase in temperature and heating rate decreased the final yield and vice versa. The final product is carried out in this method through an exit pipe connected to various cooling condensers. Multiple reactors are involved in this process, such as wagon reactors, agitated drums, kilns for sand rotating, and paddle pyrolysis kilns.

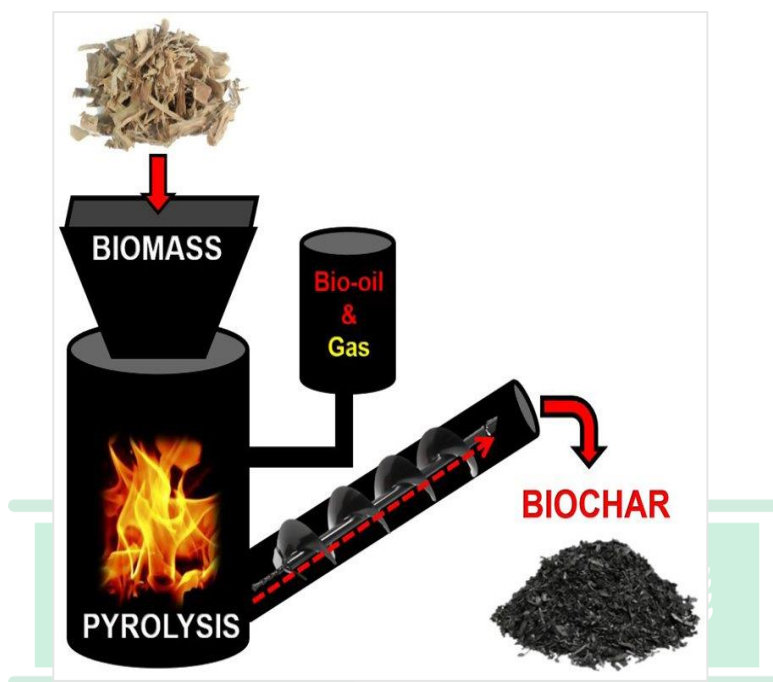


Fig 1. Schematic representation of biochar production through pyrolysis of biomass under limited oxygen conditions, producing biochar along with bio-oil and gases.

Pyrolysis	Temperature	Main Product
Slow	300-500 ° C	More Biochar
Fast	500-700 ° C	Bio oil
Gasification	>700 ° C	Syngas

Roles of biofertilizer and biochar in soil fertility and agriculture

Biofertilizers increase crop yield by 10-50%. They are cheaper, pollution free, based on renewable energy sources and also improve soil. The main and direct purposes of applying biofertilizers to soil are: to provide nutrient sources and good soil conditions for the growths of crops when used as a live body; to partially substitute and enhance the function of chemical fertilizer and then subdue the application quantities of fertilizers and still maintain the same crop yields and the capital used for making bio fertilizers is cheaper than that of chemical fertilizers and to lessen the negative effect aroused from applying chemical fertilizers to soil. Application of biofertilizers increases mineral and water uptake, root development, vegetative growth, and nitrogen fixation. They act as supplements to chemical fertilizers, promote the production of growth-promoting substances, and help control soil-borne plant pathogens. Similarly, Biochar improves soil quality and enhances crop production, although its effectiveness depends on biochar properties, soil type, and crop. Biochar is a carbon-rich material produced from plant biomass and added to soil for carbon storage and soil improvement. **Rice Husk Biochar (RHB)** is produced by burning rice husk under controlled oxygen conditions and is widely used as an experimental material. It plays an important role in improving soil fertility and agricultural productivity.

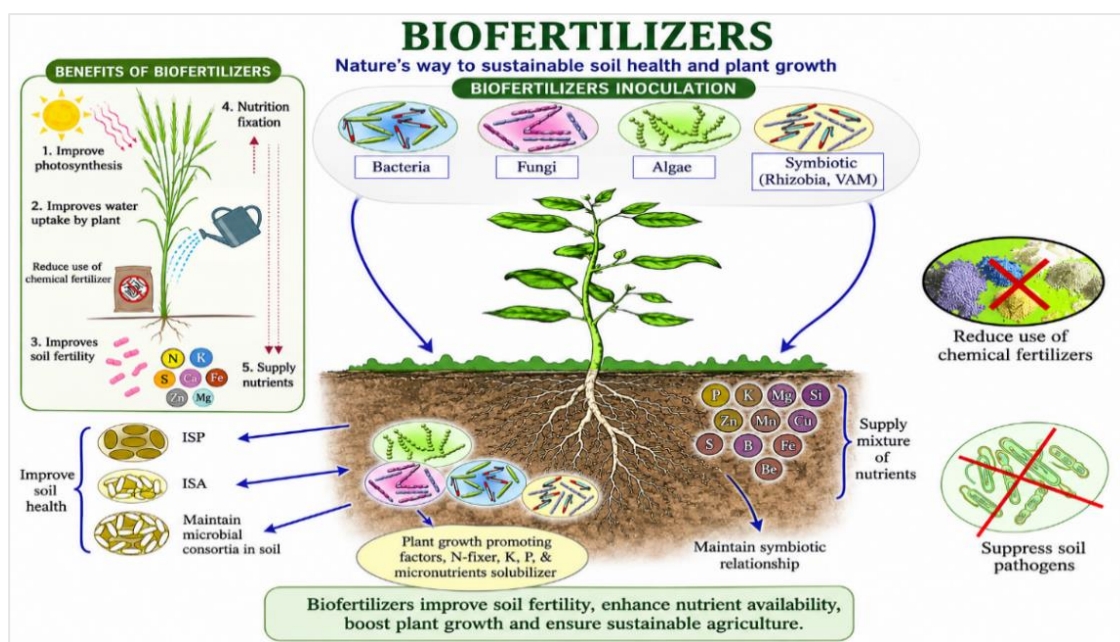


Fig. 2. Schematic representation; influence of biofertilizers on plant growth performance and soil health.
(Source: <https://doi.org/10.1016/j.crsust.2021.100063>).

Production of phycofertilizer from Algae

Algal biomass has a longer life span (post drying), is less thermos sensitive, and is more resilient for transport and storage. Therefore, algal biomass can serve as a source of nutrition and as a carrier material to form biofertilizers. Algal species produce a wide range of secondary metabolites utilized in agriculture as biofertilizers and bio pesticides. Also, weed control can be achieved either by the direct spraying of algal-based liquid pesticides or by mixing solid algae into the soil. In addition, other benefits can involve nitrogen fixation, improves soil fertility, eco friendly and suitable for paddy fields.

Nitrogen fixation and crop productivity

Nitrogen fixation is an important biological process that plays a vital role in crop production. In this process, atmospheric nitrogen gas (N_2) is converted into ammonia, which becomes available to plants. The ammonia is further converted into nitrate by soil microorganisms, making nitrogen easily accessible for plant uptake and growth.

Among the most important nitrogen-fixing microorganisms are members of the Rhizobiaceae family, commonly known as Rhizobia. These include *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Azorhizobium*, and *Mesorhizobium*. These symbiotic bacteria interact closely with host plants and form nodules in which nitrogen fixation takes place. *Azorhizobium* is unique because it forms nodules on plant stems and fixes nitrogen there. It also produces large amounts of indole acetic acid (IAA), a plant growth hormone that enhances plant development.

Azospirillum is another beneficial nitrogen-fixing bacterium known for producing plant growth-promoting substances such as IAA, gibberellins, and cytokinins. It enhances the uptake of essential nutrients like nitrogen (N), phosphorus (P), and potassium (K). Inoculation with *Azospirillum* improves root development, root exudation, water absorption, and mineral uptake. It also helps plants tolerate environmental stresses such as drought.

Mycorrhizae represent a symbiotic association between plant roots and fungi. In this mutually beneficial relationship, plants provide carbohydrates to the fungi, while the fungi improve the absorption of water and micronutrients from the soil. This association significantly enhances plant growth, nutrient uptake, and stress tolerance. Other important nitrogen fixing microorganisms include *Nostoc*, *Anabaena*, *Acetobacter*, *Bacillus megaterium*, *Azolla*, *Mycorrhizae*, and *Bacillus polymyxa*, all of which contribute to improving soil fertility and sustainable crop production.

Conclusion

The use of biochar and biofertilizers in agriculture is an emerging and important field. Biochar improves soil composition, texture, fertility, and nutrient retention, which directly enhances crop productivity. It also helps in remediation of contaminated soils, improves photosynthesis, increases carbon sequestration, and reduces greenhouse gas emissions. Similarly, biofertilizers are becoming an integral component of modern agricultural practices. They enrich the soil with nutrients, support beneficial microbial activity, and are suitable for long-term agricultural sustainability.

Both biochar and biofertilizers are eco-friendly, cost-effective, and sustainable alternatives to chemical fertilizers. Their combined use can reduce dependence on chemical inputs while improving soil health, crop productivity, and environmental quality. Therefore, wider adoption of biochar and biofertilizers in the future can provide effective strategies for sustainable agriculture and overall development of the agricultural sector.

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Don't Ignore It's My Organ of Balance: Ear Health



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Abstract

Pet owners often consider their pets a part of the family. Taking care of your furry family member's health is a big responsibility. One of the most important components of your pet's health is ear care. Many pets, especially dogs, are prone to ear infections. Ear infections in dogs can be caused by bacteria, yeast, allergies, or underlying conditions like ear mites. Signs of a dog ear infection include excessive scratching, head shaking, redness or swelling of the ear, and a foul odor. Dog ear infection management typically involves cleaning the ears with a medicated cleanser, applying prescription ear drops, and potentially using oral antibiotics or anti-inflammatory medications, depending on the severity and cause. Treatment depends on the type of infection.

Introduction

The "ear" is the organ responsible for hearing and, in mammals, maintaining balance, composed of the outer, middle, and inner ear. OR The ear is an organ of hearing and an organ of balance. It consists of the outer, middle, and inner ear. The ear's primary function is to detect and analyze sound waves, converting them into signals that the brain interprets as sound, and to maintain balance through the vestibular system.

The outer ear includes the pinna (the part you see that is made of cartilage and covered by skin, fur, or hair) and the ear canal. The pinna is shaped to capture sound waves and funnel them through the ear canal to the eardrum. In dogs, the pinnae are mobile and can move independently of each other. The size and shape of the pinnae vary by breed. The ear canal of the dog is much deeper than that of people and creates a better funnel to carry sound to the eardrum. The average dog can hear about 4 times better than the average person, including sounds at higher frequencies than can be detected by the human ear.

The middle ear includes the eardrum and a small, air-filled chamber that contains 3 tiny bones: the hammer, anvil, and stirrup. It also includes 2 muscles, the oval window, and the eustachian tube (a small tube that connects the middle ear with the back of the nose, allowing air to enter the middle ear).

The inner ear is a complex structure that includes the cochlea (the organ of hearing) and the vestibular system (the organ of balance).

Why pet ear health is important

Maintaining good ear health in pet dogs is crucial for their overall well-being, as ear infections and other conditions can cause pain, discomfort, and potentially lead to more serious health problems if left untreated.

- **Causes pain and discomfort:** Ear infections (otitis externa) are a common problem in dogs and can cause significant pain, itching, and discomfort, leading to head shaking, scratching, and reluctance to have their ears touched.
- **Quality of Life get affected:** Persistent ear problems can significantly impact a dog's quality of life, making it difficult for them to enjoy activities like playing, walking, or even sleeping.
- **Causes secondary infections:** Untreated ear infections can lead to secondary bacterial or fungal infections, which can spread beyond the ear canal and cause more serious health problems.

Hearing problems arises

In some cases, chronic or severe ear infections can damage the inner ear and lead to hearing losses. Certain dog breeds, like Basset Hounds, Chinese Shar-Pei, Labradoodles, Beagles, and Cockapoos, are predisposed to ear infections due to their ear shape or other factors. Regular ear cleaning with a veterinarian-approved solution can

help prevent ear infections and keep the ear canal healthy. Regular checks and early detection of any signs of ear problems, such as excessive scratching, head shaking, or a foul Odor, can help prevent the problem from worsening and ensure timely treatment.

Symptoms of pet Ear Infections

Pets can sometimes develop irritating and painful ear problems caused by infections. It is important to notice ear problems as early as possible so your pet can get treatment quickly. There are several signs you can look for that indicate issues with your dog's ears. Vigorously scratching the affected ear, Extreme head shaking and tilting, Dark discharge from the affected ear, Presence of Odor in the ear, Itchiness in the affected ear, Redness and swelling of the ear canal, Crusting or scabs in the ears. However, some dogs don't show symptoms of ear infections, apart from the buildup of wax and discharges in the ear canal. It is important to visit our veterinarian for regular examinations so we can catch any ear problems. Ear infections fall under several categories. Otitis externa an inflammation that causes the outer ear canal to become swollen, Otitis media means swelling in the middle of the ear canal, Otitis interna the most dangerous infection, this causes swelling in the inner ear canal

Causes of pet ear infection

Ear infections can have a variety of causes, which depend on the health and lifestyle of your dog. Allergies, (Food allergies, Environmental allergies) including skin allergies and food sensitivities, often cause ear swelling. Moisture in the ears can create a breeding environment for bacteria. Injuries in the ear canal can lead to infection. Ear mites cause discomfort and infections. Foreign bodies (such as grass awn or foxtails) that get into the ear. Endocrine issues such as hypothyroidism, Autoimmune diseases such as pemphigus, lupus, or vasculitis, Polyps (fleshy growths inside the ear canal), Certain types of cancer and trauma to the ear. Other causes of pet ear infections include hormone imbalances, deep scratches in the ears, and medical disorders. These issues can make the ear canal vulnerable to a bacterial infection and/or a yeast infection. When a dog is in pain and scratching and shaking excessively, an aural hematoma can develop. This is seen in the earflap, where ruptured blood vessels leak blood that clots, causing swelling and pain.

Common signs of dog ear infections

Redness, Odor (a yeasty, corn chip-like smell), Itching/scratching at ears, Pain, Shaking of the head, Head tilt, Discharge, Scabs or crusting around the ear flap, Swelling of the ear flap (aural hematoma). Dogs may also experience hearing loss or balance issues. Rarely, a dog ear infection may affect a pup's appetite if your dog is having system-wide effects. Dogs may have an infection in one or both ears.

Treatment

Veterinarian can diagnose your pet and prescribe a number of treatments based on the type and severity of the infection. Medicated eardrops containing antibiotics and antifungals are used to kill bacteria and yeast in the ears. We can also prescribe antiinflammatory eardrops to control swelling, along with other medications to relieve pain.

Ear cleaning is essential in treating and preventing ear infections. Your doctor can prescribe you what ear cleaning products to use and how to use. Keeping your dog's ears clean is an important part of their overall health and grooming, and can prevent or treat potential health issues, such as an infection. However, cleaning your dog's ears can be challenging especially if you've never done it before.

Since proper ear care is a necessary when caring for your beloved pup, it's important that it's performed correctly to prevent injury or damage to your dog's ears. Some ear infections can be minor, while others can be severe. Your veterinarian will guide you on the best course of treatment and follow-up care.

Cleaning process of ear

1. Make sure you have all your supplies within arm's reach. Have a petapproved cleaner, cotton balls or wipes.
2. Have support. If your dog is not used to ear cleanings, you may need another person to help hold them while you clean their ears. Restrain your dog by gently placing an arm around their neck to prevent your pup from pulling away. Use your other hand to gently stabilize their head or the back half of their body.
3. Expect a mess. Until you know how much your dog will fight or wiggle, clean your dog's ears outside or in a place that's easy to clean. A towel may be helpful to keep the rest of their body clean.

4. Be gentle. Carefully hold the exterior floppy or erect portion of your dog's ear, which is made up of hair, skin, cartilage, and blood vessels (pinnae). This will allow for entry to their ear canal.
5. Use your cleaner. Fill the ear canal with your vet-approved ear cleaner. Make sure the dog ear cleanser fills both the horizontal and vertical ear canal. Gently massage the base of your dog's ear while slowly moving your hand upward so the entire ear canal is massaged.
6. Allow your pup to shake it out. Your dog will shake their head. Shaking lets your dog expel most of the cleaner and wax on their own.

Conclusion

Most dogs recover uneventfully from ear infections. However, if your dog is having frequent or chronic ear infections, your vet will likely recommend additional testing to determine if there is an underlying cause. Long-term management may include weekly preventative ear cleaning and/or a diet change, as food allergies can be an underlying cause of infections. Regular grooming, ear cleaning, and ear maintenance are important parts of pet care. Routine ear cleansing is especially important if your dog loves to swim and most importantly if your dog's ears are red, painful, or have a bad odor, they may have an ear infection. If you spot these symptoms, don't attempt to clean your dog's ears. Contact your vet immediately your ignorance may cause serious issue to your companion.

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Rabies – Public Health Aspect



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Abstract

Rabies is a viral zoonotic disease that primarily affects brain and spinal cord and clinically occurred in two forms Furious rabies - characterized by hyperactivity and hallucinations Paralytic rabies – characterized by paralysis and coma. Although fatal once clinical signs appear, rabies is entirely vaccine preventable. Rabies is estimated to cause 59 000 human deaths annually in over 150 countries, with 95% of cases occurring in Africa and Asia. Due to underreporting and uncertain estimates, this number is likely a gross underestimate. The burden of disease is disproportionally borne by rural poor populations, with approximately half of cases attributable to children under 15 years of age. Of these cases, approximately 99% are acquired from the bite of an infected dog. Dog-mediated human rabies can be eliminated by tackling the disease at its source that is infected dogs. Making people aware of how to avoid the bites of rabid dogs, to seek treatment when bitten and to vaccinate animals can successfully disrupt the rabies transmission cycle.

Introduction

Name rabies is derived from the Latin rabies, meaning "madness" and Rabies is caused by lyssaviruses which is derived the Greek word lud or "violent". Rabies is a viral zoonotic disease that causes encephalitis in humans and other mammals. It was historically referred to as hydrophobia ("fear of water") because its victims panic when offered liquids to drink. Early symptoms can include fever and abnormal sensations at the site of exposure. These symptoms are followed by one or more of the following symptoms: nausea, vomiting, violent movements, uncontrolled excitement, fear of water, an inability to move parts of the body, confusion, and loss of consciousness. Once symptoms appear, the result is virtually always death. The time period between contracting the disease and the start of symptoms is usually one to three months but can vary from less than one week to more than one year. The time depends on the distance the virus must travel along peripheral nerves to reach the central nervous system.

Transmission of Rabies to Human:

The rabies virus is mainly transmitted from the saliva of a rabid animal when it bites or scratches a person. Licks to wounds, grazes, broken skin, or to the lining of the mouth and nose, can also transmit the virus. Dogs are responsible for up to 99% of human rabies cases, however the virus can be transmitted from the bite of any rabid animal. Human rabies cases have occurred because of bites from cats, bats, mongooses, jackals, foxes, wolves and other carnivorous animals. Worldwide, rabies due to monkey and rat bites is rare. Many animals will become aggressive and bite when they have rabies, including horses and donkeys. In animals where biting is not common, such as cattle and buffalo, transmission can still occur through exposure to saliva. Care should be taken while examining sick animals that are salivating.

The most common route of transmission is through the saliva of a rabid animal. However, the rabies virus has also been found, and could possibly be transmitted, through other bodily fluids such as tears, and nervous tissue. Rabies virus is not found in blood or faeces. There are no evidence-based reports of human rabies arising from consumption of milk, including breast milk, or cooked meat. However, consuming the meat or milk of a rabid animal is strongly discouraged. Individuals or professionals who slaughter rabiesinfected mammals and handle tissues of rabid animals may be at risk of contracting the virus through breaks in their skin. These individuals should use specialized personal protective equipment and consult infectious disease specialists if they suspect they have been exposed to rabies infected carcasses. Human-to-human transmission of rabies is extremely rare. However, caregivers should be vigilant when looking after patients with rabies and avoid contact with their saliva and other excretions. Hand washing and good personal hygiene are of upmost importance when caring for patients with rabies.

Consuming the meat from a rabid animal is strongly discouraged. Although no human cases have been documented following the consumption of uncooked meat from a rabid animal, butchering or eating a rabid animal may potentially transmit rabies. If an exposure occurs, PEP should be initiated. Cooked meat does not transmit rabies; however, it is not advisable to butcher or consume meat of any kind from an infected animal. The carcass should be buried or burned if possible, with advice from a veterinary professional.

On contact with a bat, it is recommended that to thoroughly wash the site of contact and immediately consult a physician at a health facility. Do not touch any bats. If you think your pet or domestic animal has been bitten by a bat, immediately contact a veterinarian.

Organs transplanted from rabid organ donors can transmit rabies to the organ recipient. Individuals with symptoms of encephalitis (inflammation of the brain) before death should therefore be excluded as organ donors. Human-to-human transmission has never been confirmed except in the organ transplantation situation.

Measure to be taken for a person is bitten by an animal

- ✚ Wash wounds and scratches immediately with soap or detergent and flush them thoroughly for about 15 minutes with copious amounts of water. If soap is not available, flush with water alone. Wound washing is the most effective first-aid treatment against rabies.
- ✚ Apply an iodine-containing or anti-viral medication preparation on top of the wound 15 minutes after it has been washed and flushed.
- ✚ Take the person to a health care facility for further assessment and treatment by a healthcare professional as soon as possible.
- ✚ Safely confine the biting animal, where possible, and collect information on it and the bite circumstance to provide information to the health care professional and public health officer.
- ✚ Keep the biting animal confined and under observation for 10 days.
- ✚ Assess the person's vaccination status, e.g. whether diphtheria, pertussis, tetanus (DPT) or tetanus toxoid vaccination has been given in the past. A tetanus toxoid vaccine should be administered when necessary.
- ✚ Antimicrobials can be prescribed if complication from bacterial infection is suspected.
- ✚ Analgesics can be used. AVOID covering the wound with dressings or bandages.
- ✚ DO NOT suture the wound.
- ✚ If necessary for closing large wounds, suturing should be done after infiltration of the wound with rabies immunoglobulin (RIG).
- ✚ The sutures should be loose and not interfere with free bleeding and drainage. It is well established that secondary suture of bite wounds results in better cosmetic outcomes.

Post-exposure prophylaxis (PEP) recommended pep according to type of exposure:

Category	Exposure	Immunologically naive individuals of all age groups	Previously immunized individuals of all age groups
Category I exposure	Touching or feeding animals Licks on intact skin	Wash exposed skin surfaces. No PEP required.	Wash exposed skin surfaces. No PEP required.
Category II exposure	Nibbling of uncovered skin Minor scratches or abrasion without bleeding	Wound washing and immediate vaccination:- 2-sites ID on days 0, 3 and 7 OR 1-site IM on days 0, 3, 7 and between day 14 OR 2-sites IM on days 0 and 1- site IM on days 7 ➤ RIG is not indicated	Wound washing and immediate vaccination 1-site ID on days 0 and 3 OR 4-sites ID on day 0 OR 1-site IM on days 0 and 3 ➤ RIG is not indicated
Category III exposure	Single or multiple transdermal bites or scratches - Contamination of mucous membrane with saliva from licks - Licks on broken skin Exposures due to direct contact with bats	Wound washing and immediate vaccination 2-sites ID on days 0, 3 & 7 OR 1-site IM on days 0, 3, 7 and between day 14-28 OR 2-sites IM on days 0 and 1- site IM on days 7, 21 ➤ RIG administration is recommended.	Wound washing and immediate vaccination 1-site ID on days 0 and 3 OR - at 4-sites ID on day 0 OR - at 1-site IM on days 0 & 3 ➤ RIG is not indicated

Conclusion

Rabies is 100% preventable disease and animal control and vaccination programs have decreased the risk of rabies from dogs in many countries of the world. Pre-exposure prophylaxis (Immunization) in people before they are exposed is recommended for those at high risk, including those who work with dogs and bats.

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Overview of Important Bacterial Zoonotic Diseases of Dogs



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Abstract

Zoonotic diseases (zoonoses) are infections that can be transmitted between animals and humans. Dogs, being close companions to humans, can harbor various bacterial zoonotic diseases that pose health risks. These infections are primarily spread through direct contact, bites, scratches, saliva, urine, feces, or contaminated environments. Key bacterial pathogens linked to dogs include *Leptospira* spp., *Brucella canis*, *Salmonella* spp., *Campylobacter* spp., Methicillin-resistant *Staphylococcus aureus* (MRSA), *Helicobacter* spp. etc. The clinical symptoms in humans can range from mild gastrointestinal issues to severe systemic diseases. Strategies for prevention and control involve maintaining proper pet hygiene, ensuring regular veterinary check-ups, vaccinations, deworming, responsible antibiotic use, and raising public awareness. Timely diagnosis and treatment of zoonotic bacterial infections in both dogs and humans are vital for minimizing transmission risks. A One Health approach that encompasses human, animal, and environmental health sectors is crucial for reducing the impact of bacterial zoonoses associated with dogs.

Introduction

Zoonotic diseases (zoonoses) are infections that are transmitted from animals to humans through direct contact, contaminated food or water, vectors (such as mosquitoes or ticks), or inhalation of infectious particles. These diseases can be caused by bacteria, viruses, parasites, or fungi. Dogs are a major reservoir for zoonotic infections. Dogs transmit several viral and bacterial diseases to humans. These diseases can be transmitted to human by infected saliva, aerosols, contaminated urine or feces and direct contact with the dog. bacterial infections such as *Pasteurella*, *Salmonella*, *Brucella*, *Yersinia enterocolitica*, *Campylobacter*, *Capnocytophaga*, *Bordetella bronchiseptica*, *Coxiella burnetii*, *Leptospira*, *Staphylococcus intermedius* and Methicillin resistance *Staphylococcus aureus* (MRSA) are some of the common bacterial zoonotic infections transmitted to humans by dogs (Ghasemzadeh et al., 2015).

Leptospirosis:

Leptospirosis is a disease caused by infection with *Leptospira* bacteria. These bacteria can be found worldwide in soil and water. *Leptospira* spp. is a spiralshaped bacterium. There are many strains of *Leptospira* bacteria that can cause disease, and many mammals are susceptible—including dogs, people, livestock, and certain wildlife. All dogs are at risk of leptospirosis, regardless of age, breed, lifestyle, geographic location, time of year, and other factors.

Dogs may get the infection from:

- Exposure to or drinking from slow-moving or stagnant water sources, like ponds, rivers, lakes, or streams
- Roaming on rural properties (because of exposure to potentially infected wildlife or farm animals or urine-contaminated water sources)
- Exposure to wild animals (especially rodents) or farm animals, even if in the backyard
- Contact with other dogs (such as in urban areas, dog parks, or boarding or training facilities)

Transmission to human:

- Direct contact with infected dog urine
- Contaminated water, soil, or food

- Through mucous membranes (eyes, nose, mouth) or broken skin

Symptoms in Humans:

- Fever, chills, muscle aches
- Vomiting, diarrhea, and jaundice
- Severe cases can lead to kidney damage, meningitis, liver failure, or respiratory distress

Prevention:

Vaccination of dogs: The vaccine is not considered a core vaccine but is highly recommended for at-risk dogs.

There are two main types of *Leptospira* vaccines for dogs:

- Bivalent Vaccine - Protects against two serovars of *Leptospira*.
- Quadrivalent (4-way) Vaccine - Protects against four serovars and is the most commonly used.
- Since *Leptospira* can infect humans through dog urine, vaccinating dogs also helps prevent transmission to pet owners and veterinary staff.
- Proper hygiene and sanitation
- Avoiding contact with potentially contaminated water

Campylobacteriosis:

Campylobacteriosis, a zoonotic disease caused by *Campylobacter* bacteria, can be transmitted from dogs to humans through fecal-oral contact, and pet ownership increases the risk of infection. It is a gram-negative, spiral-shaped bacteria. *Campylobacter* species are commonly isolated from faecal samples collected from dogs and cats, with the most prevalent species being *C. upsaliensis*, *C. helveticus*, and *C. jejuni* (most common) (Acke, 2018).

Predisposing factors for dogs:

Campylobacteriosis is prevalent in puppies younger than six months old or Immature animals. Besides, animals from intensive housing backgrounds, and animals with concurrent disease are especially predisposed to *Campylobacter* infection.

Transmission to human:

- Direct contact with infected dog feces
- Contaminated food or water (if dogs carry the bacteria)
- Close contact with infected puppies, especially in shelters or pet stores
- Poor hygiene (not washing hands after handling dogs)

Symptoms in Humans

- Diarrhea (sometimes bloody)
- Abdominal cramps
- Fever and nausea
- Vomiting (less common)
- Symptoms appear 2–5 days after exposure and last about a week
- In rare cases, it can lead to Guillain-Barré Syndrome (GBS), causing nerve damage and paralysis

Symptoms in Dogs

- Often asymptomatic
- Some dogs may have diarrhea, vomiting, or fever
- Puppies and immunocompromised dogs are more susceptible

Salmonellosis:

Salmonella (most commonly *Salmonella enterica*), a Gram-negative, rodshaped bacteria is the etiologic agent of salmonellosis which is a very common intestinal infection in humans and animals. Dogs can harbor and shed *Salmonella*, a bacterium that can cause salmonellosis in humans, making them a zoonotic threat. Various reports have pointed to the transmission of antibiotic-resistant *Salmonella* from dogs to humans (Kenney et al., 2025). The prevalence of *Salmonella* spp. in dogs is not fully understood since dogs can serve as asymptomatic carriers and excrete the bacteria with no clinical demonstrations (Askari et al., 2020).

Transmission to human

- Direct contact with infected dog feces, saliva, or vomit

- Contaminated food or water (especially raw pet food)
- Close contact with infected dogs, especially puppies
- Poor hygiene (not washing hands after handling dogs or cleaning up feces)

High-Risk Groups: Young children, elderly individuals, pregnant women, and immunocompromised people are at higher risk for severe illness.

Symptoms in Humans

- Diarrhea (sometimes bloody)
- Fever and chills
- Abdominal cramps
- Nausea and vomiting
- Headache and muscle pain
- Symptoms appear 6–72 hours after exposure and can last 4–7 days
- Severe cases may cause dehydration, sepsis, or reactive arthritis

Clinical symptoms in Dogs

- Many dogs carry Salmonella without symptoms
- Some may show:
 - ✚ Diarrhea (sometimes with mucus or blood)
 - ✚ Vomiting and fever
 - ✚ Lethargy and loss of appetite
 - ✚ Abdominal pain

Brucellosis:

Canine brucellosis, caused by *Brucella canis* (primary species affecting dogs), is a zoonotic disease, meaning it can be transmitted from dogs to humans, and it is a major public health concern, especially in certain regions where it's endemic (Hensel et al., 2018). *Brucella canis* is a gram-negative, intracellular coccobacillary bacterium that primarily causes reproductive failure in dogs. *B. canis* infection in dogs occurs predominantly through ingestion, inhalation, or contact with aborted fetuses or placenta, vaginal secretions, or semen.

Transmission:

Human *B. canis* infections are mainly acquired through the oronasal route by direct contact with infected dogs. Some of the ways of transmission are as follows

- Direct contact with infected bodily fluids (urine, saliva, blood, vaginal discharge, semen)
- Breeding with an infected dog
- Handling aborted fetuses or stillborn puppies
- Inhalation of aerosolized bacteria (in kennels, breeding facilities)
- Contaminated objects (bedding, food bowls, or medical equipment)
- Laboratorial manipulation of the agent without protection is another relevant source of infection.

High-Risk Groups:

- Veterinarians, breeders, and kennel workers
- People with weakened immune systems

Symptoms in Humans (Rare but Possible)

Flu-like symptoms:

- Fever and chills
- Sweating (especially at night)
- Fatigue and muscle/joint pain
- Loss of appetite
- Headaches

Chronic infections can lead to:

- Arthritis
- Neurological issues

- Endocarditis (inflammation of the heart lining)

Symptoms in Dogs

- Reproductive issues:
 - ✚ Infertility in both males and females
 - ✚ Miscarriages, stillbirths, or weak puppies

Other signs:

- Lethargy and weight loss
- Enlarged lymph nodes
- Spinal pain (in severe cases)

Prevention

- Testing and screening: Before breeding, ensure dogs are free from *Brucella canis*.
- Good hygiene: Wear gloves when handling newborn puppies or cleaning kennels
- Proper sanitation: Disinfect kennels, bedding, and medical equipment regularly
- Quarantine infected dogs: Brucellosis is chronic and difficult to cure in dogs

Treatment

- In Humans: Long-term antibiotics (e.g., doxycycline and rifampin)
- In Dogs: No reliable cure; infected dogs are often neutered/spayed and managed, but euthanasia may be recommended in severe cases

Helicobacteriosis (Gastric Infection):

Helicobacter pylori is one of the most common bacterial infections and is widespread globally. *H. pylori* is a microaerophilic gram-negative helix bacterium that specifically infects the stomach lining.

In dogs, the most common species are: *Helicobacter canis*, *Helicobacter felis* and *Helicobacter heilmannii* (Neiger and Simpson, 2000). Some *Helicobacter* species have zoonotic potential, meaning they can be transmitted from dogs to humans and may cause gastrointestinal diseases such as gastritis, ulcers, and even stomach cancer in rare cases (Kubota-Aizawa et al., 2021).

Transmission: Dogs can carry *Helicobacter* in their stomach and intestines without showing symptoms. The bacteria may spread to humans through:

- Direct Contact – Contact with dog feces or saliva, licking, or contaminated fur.
- Fecal-Oral Route – Contact with infected dog feces.
- Contaminated Water & Food – Ingesting food or water contaminated by infected dogs.

High risk group:

includes children, the elderly, and those with weakened immune systems.

Symptoms in dogs: Dogs often show mild or no symptoms, but in some cases, they may develop:

- Chronic vomiting
- Diarrhea
- Loss of appetite
- Weight loss
- Abdominal pain

Symptoms in Humans: When *Helicobacter* is transmitted to humans, it can cause:

- Nausea & vomiting
- Abdominal pain
- Acid reflux (heartburn)
- Bloating
- Peptic ulcers
- Chronic gastritis (stomach inflammation)

In severe cases, long-term infection with *Helicobacter pylori* (a related species) has been linked to stomach cancer.

Treatment of Helicobacter Infection

In Dogs:

- Combination Antibiotic Therapy – Amoxicillin, Metronidazole, Clarithromycin

- Proton Pump Inhibitors (PPIs) – Omeprazole to reduce stomach acid.
- Supportive Care – Hydration and a balanced diet.

In Humans:

- Triple Therapy – Two antibiotics + PPI (e.g., Clarithromycin, Amoxicillin, Omeprazole).
- Hygiene Measures – Prevent reinfection by avoiding contaminated food and water

Methicillin-Resistant Staphylococcus aureus: MRSA is a type of antibiotic-resistant bacteria that can infect both humans and animals, including dogs. While dogs are not the primary source of MRSA infections in humans, they can carry and transmit MRSA through direct contact Guimarães et al., 2023; Khairullah et al., 2023).

Transmission: Dogs can carry MRSA on their skin, in their nose, or in wounds without showing symptoms. The bacteria can spread through:

- Direct Contact – Petting, cuddling, or handling an infected dog's skin, nose, or wounds.
- Bites or Scratches – MRSA can enter through open wounds.
- Contaminated Objects – Dog bowls, bedding, collars, and grooming tools.

People at higher risk include immunocompromised individuals, young children, the elderly, and veterinary staff.

Symptoms in dogs: Dogs may not always show symptoms, but when infected, they can develop:

- Skin infections – Red, swollen sores, abscesses, or wounds that do not heal.
- Ear infections – Chronic, resistant ear infections.
- Respiratory issues – Pneumonia (rare but severe).
- Urinary tract infections (UTIs) – Recurrent UTIs
- **Symptoms of MRSA in Humans:**
- Skin infections – Boils, abscesses, redness, and pain.
- Wound infections – Infected cuts that do not heal.
- Pneumonia – Cough, fever, difficulty breathing.
- Sepsis (Severe Cases) – Life-threatening infection spreading in the bloodstream.

Treatment of MRSA in Dogs: MRSA is resistant to common antibiotics, so treatment involves:

- Targeted Antibiotics – Based on lab testing to find effective medication.
- Wound Care – Cleaning and draining infected areas.
- Hygiene & Isolation – Preventing spread to humans and other pets.
- Avoid Overuse of Antibiotics – Prevents further resistance.

General Prevention for bacterial zoonoses from Dogs:

1. Good Hygiene Practices

- Handwashing – Wash hands after handling dogs, cleaning their waste, or touching their food and toys.
- Avoid Face Licking – Dogs' saliva may contain bacteria like Pasteurella or Helicobacter.
- Proper Waste Disposal – Promptly clean up and dispose of dog feces to reduce contamination.
- Sanitizing Dog Items – Regularly clean dog bowls, bedding, and grooming tools.

2. Routine Veterinary Care

- Regular Check-ups – Early detection and treatment of infections.
- Deworming & Flea Control – Reduces bacterial infections linked to parasites.
- Vaccination – Protects against bacterial zoonoses like leptospirosis and brucellosis.
- Responsible Antibiotic Use – Prevents antibiotic resistance in zoonotic bacteria.

3. Safe Handling of Dog Food & Water

- Avoid Raw Meat Diets – Raw food can carry Salmonella and Campylobacter.
- Provide Clean Water – Prevents exposure to Leptospira from contaminated sources.
- Store Dog Food Properly – Prevents bacterial contamination.

4. Reducing Environmental Risks

- Keep Living Areas Clean – Regularly disinfect surfaces dogs frequently use.
- Control Rodents & Wildlife Exposure – Prevents infections like leptospirosis and salmonellosis.

- Limit Dog Interaction with Strays – Reduces the risk of disease transmission.

5. Preventing Human Infection

- Use Protective Gloves – When handling sick dogs or cleaning wounds.
- Avoid Contact with Dog Urine & Feces – Prevents leptospirosis and other bacterial infections. □ Monitor High-Risk Groups – Children, elderly, and immunocompromised individuals should take extra precautions.

6. Awareness & Education

- Educate Pet Owners – About zoonotic risks and prevention.
- Report Symptoms Early – Seek medical and veterinary care if signs of infection appear.
- Promote the One Health Approach – Collaboration between veterinarians, doctors, and public health officials.

By following these preventive measures, the risk of bacterial zoonoses from dogs can be significantly reduced, ensuring the health of both pets and humans.

Conclusion

Bacterial zoonotic diseases of dogs represent a significant public health concern due to the close association between dogs and humans. Dogs can act as reservoirs of various pathogenic bacteria, transmitting infections through direct contact, contaminated environments, or improper hygiene practices. Although many of these infections may remain asymptomatic in dogs, they can lead to serious health complications in humans, particularly among vulnerable groups such as children, the elderly, and immunocompromised individuals. Effective prevention and control require a comprehensive approach that includes maintaining proper hygiene, ensuring regular veterinary care, timely vaccination, responsible use of antibiotics, and safe handling of pet food and waste. Public awareness and education play a crucial role in minimizing risks. Adopting the One Health approach, which integrates human, animal, and environmental health, is essential for reducing the burden of zoonotic diseases. By promoting responsible pet ownership and coordinated efforts among veterinarians, healthcare professionals, and the community, the transmission of bacterial zoonoses from dogs to humans can be significantly minimized, ensuring the health and well-being of both animals and people.

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Recognizing Eye Emergencies in Dogs: A Guide to Their Importance



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Abstract

Ocular emergencies in dogs are critical conditions that require immediate recognition and prompt veterinary intervention to prevent irreversible vision loss or damage to the eye. This article highlights the importance of early identification and management of common eye emergencies, including corneal ulcers, proptosis, foreign body injuries, glaucoma, lens luxation, chemical burns, and retinal detachment. These conditions may arise due to trauma, infections, systemic diseases, or environmental exposures, and are often associated with clinical signs such as redness, pain, discharge, squinting, and sudden loss of vision. Delayed treatment can lead to severe complications, including permanent blindness. The article also emphasizes essential first-aid measures and preventive strategies, such as regular eye examinations, avoiding exposure to harmful substances, and monitoring behavioral changes in pets. Increasing awareness among pet owners about the early warning signs and urgency of ocular conditions is crucial for timely intervention and improved prognosis. Ensuring rapid and appropriate care can significantly enhance the chances of preserving vision and maintaining overall ocular health in dogs.

Introduction

Eye sight plays a vital role in a dog's overall health and well-being. Healthy eyes are essential for optimal vision, yet they are highly sensitive and more vulnerable to trauma and systemic disorders. Ocular problems demand prompt attention, as certain emergencies can be critical if vision or the integrity of the eye is to be preserved. Timely intervention is therefore crucial to prevent permanent damage to the eyes or loss of vision. Some common ocular emergencies encountered in dogs that need immediate attention are:

1. Corneal Ulcer

Corneal ulcer is a break in the continuity of corneal surface that can result from trauma, foreign bodies, or infections. Dog remains in pain and discomfort with redness or 40 squinting of eye. Immediate treatment is of utmost importance to prevent further eyeball rupture. Treatment includes topical and systemic antibiotics, anti-inflammatory drugs, or blood-derived products (serum or platelet-rich-plasma) instillation. Severe cases not responding to medical therapy may need surgical intervention.

2. Proptosis (Protruded Eyeball)

It is the most acute ocular emergency among all emergencies. In this condition the eyeball is displaced from its normal position, that is often result of trauma or injury due to accidents and fighting with other dogs. As a result of trauma, eyelids entrapment occurs behind the eye that potentially reduces the vitality of globe and may cause loss of vision. Small breeds, viz. Shih Tzu, Pug, Puggle and Lhasa Apso are more prone for the condition even with the slightly higher force exerted during handling. Prominent eye globes, large palpebral fissure and shallow orbit are the risk factors for proptosis in these breeds. This emergency condition can only be treated surgically and thus requires immediate veterinary attention to re-position the eye and prevent further damage to the optic nerve.

3. Foreign Body Trauma

Foreign bodies like dirt, grass pieces, thorn or other small particles can get trapped in the eye causing trauma to cornea and other structures of eye. Dog shows signs of pain, pawing at the eyes, tearing, redness and squinting. Presence of foreign body for an extended period of time and continuous scratching by pet might be possible reason

of corneal ulcer. The foreign body need to be flushed out or removed by a veterinarian only, as attempt to dislodge foreign body by pet owners could result into worsening of condition including eyeball rupture.

4. Glaucoma

Glaucoma is a condition with increased pressure inside the eye. It is an ocular emergency as it directly damages the optic nerve. If left untreated, results in potential loss of vision, as it is one of the leading causes of irreversible blindness in pets. Glaucomatous eyes are visible as bulged eyes in its normal orbit position, often with squinting, corneal opacity and red painful eyes. Immediate medical attention is needed to reduce intraocular pressure and if possible, surgery to relieve pressure. Bilateral glaucomatous eyes are more worrisome as they might be associated with some systemic problems too. Systemic 41 hypertension, renal pathology and systemic malignancy conditions are often associated with bilateral glaucomatous eyes. The condition is also sometimes seen concurrently with other ocular problems such as retinal detachment. Retinal detachment and glaucoma are said to be cause and sequelae to each other. In such conditions prognosis is usually less favourable. Immediate medical therapy for reducing eye pressure is of paramount importance to prevent worsening of the condition. The aims of glaucoma treatment are to prevent further vision loss and decrease the pain caused by eye pressure elevation. This should be always kept in mind that it is impossible to restore vision that has been lost due to glaucoma. Thus, it is advisable to get pet treated for high ocular pressure as soon as possible to save the vision. Certain types of glaucoma require lifelong treatment. The owner must understand that the disease can never be fully cured and the aim of therapy is to stabilize the intraocular pressure. When medical therapy no longer gives satisfying results, surgical intervention is necessary to save the eye.

5. Lens luxation

Lens luxation is the displacement of the lens from its normal position. It is often due to either weak zonule fibres that hold lens in its position or in long-standing cases of cataract. Pet shows signs of pain, blindness, cloudiness in the cornea or redness in eye. Persistent presence of lens in anterior location causes complications such as glaucoma. Hence, the condition is managed by surgical removal of the lens to prevent further damage to the eye.

6. Chemical Burns

Dogs are prone to exposure to household chemicals, cleaning products, or any toxins. On exposure of eyes to any of the chemicals, dogs show signs of sudden pain, redness, tearing, and possible vision loss. In such situations pet parents are advised to rinse the eye with saline solution or water immediately and seek emergency veterinary care with proper history sharing of type of chemical to the veterinarian.

7. Retinal Detachment

In retinal detachment condition, the retina becomes separated from the underlying tissue, that could occur due to trauma or any other ocular and systemic disease. Dog shows sudden loss of vision, abnormal eye movements, and dilated pupils that do not respond to light. Long standing cases of the condition results in increase in eye pressure causing glaucomatous eyes. Retinal detachment can only be managed by surgical repair, but the outcome depends on the extent of the detachment.

Prevention and first aid in ocular emergencies:

Prevention: Regular eye check-ups and preventing trauma can help reduce the risk of ocular emergencies.

First aid:

- In case of suspected trauma, keep the dog calm and avoid touching the eye.
 - For mild irritation or discharge, gently flush the eye with normal saline solution.
 - For serious injuries, such as proptosis or a deep corneal ulcer, seek emergency veterinary care immediately.
- Thus, owners are advised to continuous monitor any change in the appearance of the eye such as any sudden vision loss or bulging of the eye, severe redness, cloudiness, or discharge from eye, injury to the eye from trauma or foreign bodies and activity of their pets like continuous squinting or pawing at the eye. In all cases of ocular emergencies, timely treatment is crucial to preserve dog's sight and overall eye health and to prevent complications and permanent damage to the eye. If in doubt, always consult with a veterinarian as soon as possible.

Conclusion

Ocular emergencies in dogs constitute a group of critical conditions that demand immediate attention to safeguard vision and maintain ocular integrity. Conditions such as corneal ulcers, proptosis, glaucoma, lens luxation, retinal

detachment, and chemical injuries can rapidly progress to irreversible blindness if not treated promptly. Early recognition of clinical signs such as redness, pain, discharge, squinting, and sudden vision loss plays a crucial role in ensuring timely veterinary intervention. Educating pet owners about first-aid measures and the urgency of seeking professional care is equally important. Ultimately, a proactive approach combining awareness, prevention, and prompt treatment is essential to preserve vision, alleviate pain, and improve the quality of life in dogs.

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