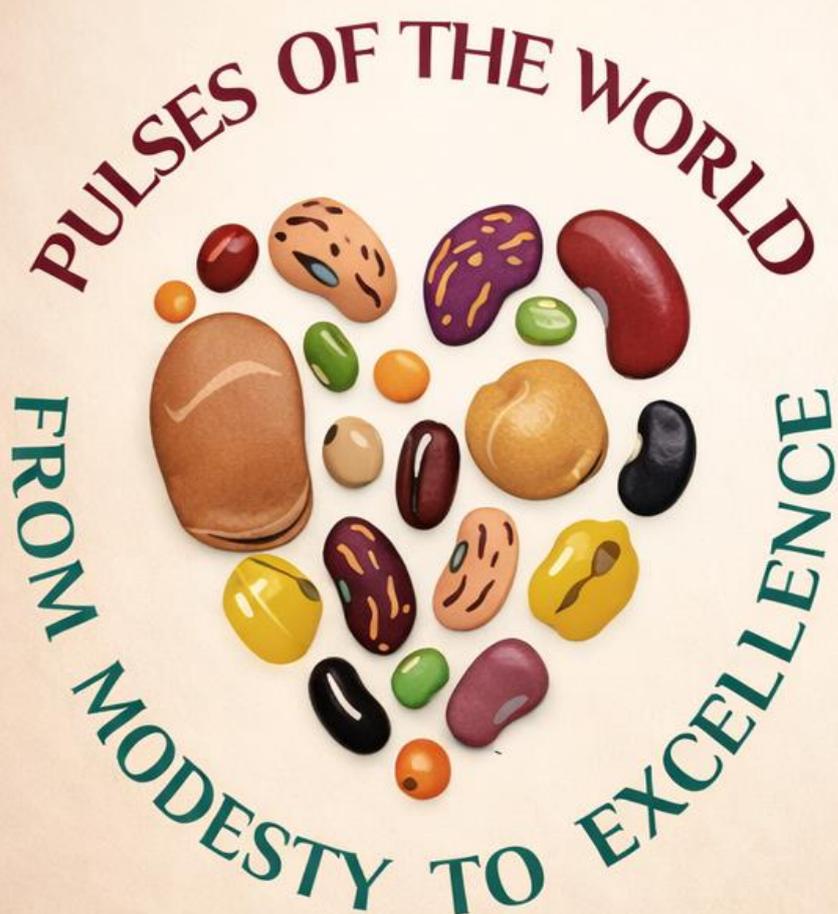


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Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) in the Paddy: How India's First Genome-Edited Rice is Changing the Future of Food security



Dr. A. A. Mohod¹ and G. R. Jamode²

¹Agronomy Section, Shri Shivaji Agriculture College, Amravati

²Ph.D. Scholar, Department of Agronomy, PDKV, Akola

For decades, the word "genetically modified" (GM) has sparked intense debate in India. However, a quiet revolution has recently taken place in the laboratories of the Indian Council of Agricultural Research (ICAR) that bypasses the old "foreign DNA" controversy while delivering the climate-resilient crops our planet desperately needs.

In May 2025, India reached a historic milestone by launching its first two genome-edited rice varieties: DRR Dhan 100 (Kamala) and Pusa DST Rice 1. Unlike their GM predecessors, these plants were not built with "foreign" genes; instead, scientists used "molecular scissors" to precisely tweak the plant's own genetic code.

The Molecular Scissors: How It Works

At the heart of this breakthrough is CRISPR-Cas9, a technology often described as a GPS-guided pair of scissors. Traditional plant breeding is like a slow game of chance—crossing two plants and hoping the offspring gets the right traits. GMO technology is like adding a new chapter from a different book into the plant's DNA library.

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Genome editing (specifically SDN1 and SDN2 categories) is different. It doesn't add anything from the outside. Instead, it finds a specific "typo" or a gene that limits growth and simply edits it. Because these changes could technically occur in nature through natural mutations, the Indian government (under the Ministry of Environment, Forest and Climate Change) exempted these varieties from the strict and lengthy regulations that govern GM crops. The distinction between SDN-1, SDN-2, and SDN-3 is the "legal and scientific divide" that allowed these rice varieties to reach farmers without the decade-long delays usually seen with GMOs.

In India, the Ministry of Environment, Forest and Climate Change (MoEF&CC) officially exempted SDN-1 and SDN-2 from stringent biosafety regulations in 2022, provided they are free from foreign DNA.

1. SDN-1: The "Delete" Key (Used for Kamala)

SDN-1 (Site-Directed Nuclease 1) is like using a delete key. It creates a double-strand break in the DNA at a specific spot. The cell then tries to repair this break on its own through a process called Non-Homologous End Joining (NHEJ).

Because this repair is slightly "messy," it usually results in a small insertion or deletion of genetic letters. This effectively knocks out or silences the gene.

- In Rice: For the Kamala variety, scientists silenced the *CKX2* gene. This gene normally degrades cytokinin (a growth hormone). By "deleting" the gene's function, cytokinin levels stay high, leading to more grains per plant.

2. SDN-2: The "Edit" Key

SDN-2 is more precise. It involves creating a DNA break but also providing a tiny "repair template" (a small piece of DNA) that the cell uses to fix the break. This allows scientists to make a specific point mutation—changing a single "letter" in the DNA code to a more desirable one found in nature.

Key Detail: No new DNA is left behind; the template simply guides the plant's own repair machinery to rewrite its own code.

3. SDN-3: The "Insert" Key (The GMO Category)

SDN-3 involves inserting a large piece of DNA, often a whole new gene from a different species (like a bacterial gene in Bt Cotton). This is categorized as transgenic or Genetically Modified (GM). Unlike SDN-1 and 2, these are subject to heavy regulation because they introduce truly "foreign" elements to the plant's genome.

CRISPR

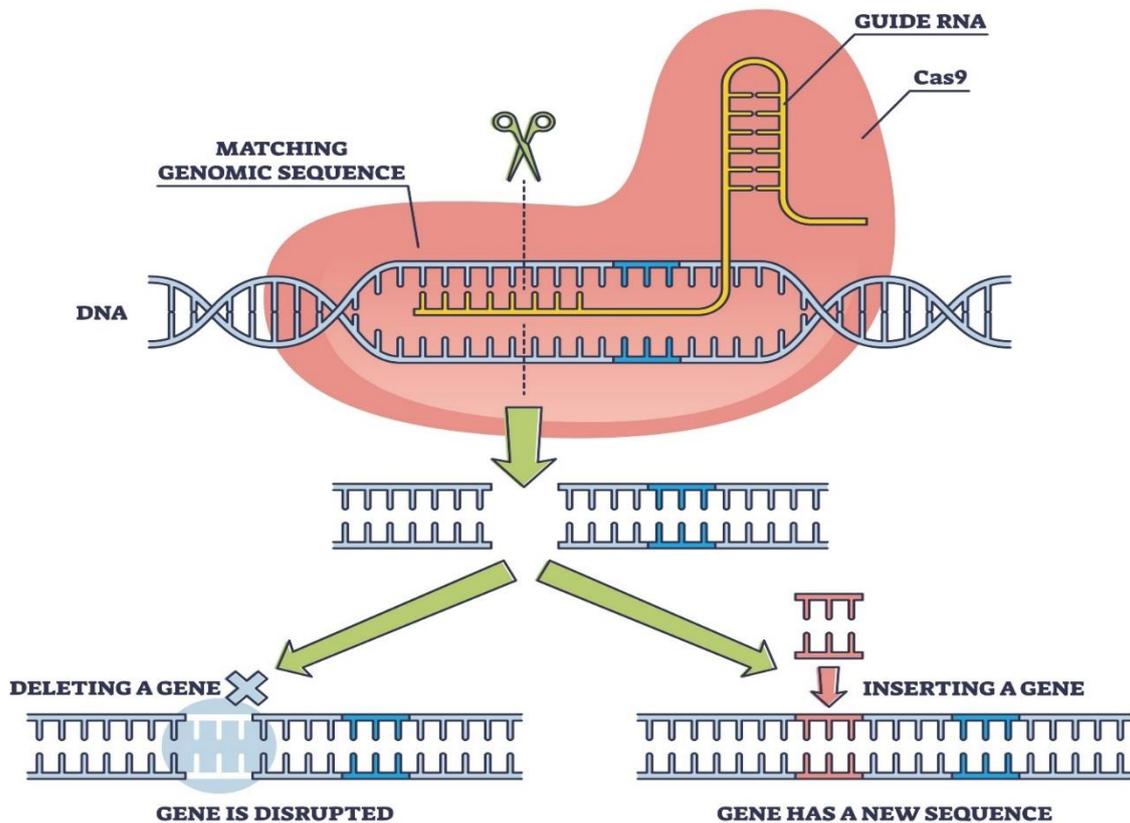


Figure No. 1. Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)

Table No 1: Why the Labels Matter

Feature	SDN-1	SDN-2	SDN-3
Mechanism	Simple break & random repair	Template-guided precise repair	Insertion of new genes
Result	Gene "Knock-out"	Precise "Edit"	New "Transgene"
Foreign DNA	None	None	Present
India Regulation	Exempt (non-GMO)	Exempt (Non-GMO)	Strict (GMO)
Complexity	Low	Medium	High

Why This is a Game-Changer

Before the 2022 policy change, even a simple SDN-1 edit was treated like a GMO. This meant years of multi-location trials and environmental impact assessments. Now, if a scientist can prove (using molecular data) that the final plant has zero traces of the CRISPR machinery and no foreign DNA, it is treated almost like a naturally bred variety. This cut the path to the market from 15 years down to roughly 5 years. The two varieties address the "Big Three" challenges of modern Indian farming: yield, water scarcity, and soil health.

- DRR Dhan 100 (Kamala): Developed from the beloved *Samba Mahsuri* rice, Kamala was edited to silence the *CKX2* gene. This gene normally acts as a "brake" on grain production. By removing the brake, scientists increased the number of grains per panicle, leading to a 19% yield increase. Remarkably, it matures 20 days earlier than the parent variety, allowing farmers to clear their fields sooner and save significant amounts of water.

- Pusa DST Rice 1: This variety targets the *DST* (Drought and Salt Tolerance) gene. Developed by ICAR-IARI in New Delhi, it is designed for the harsh reality of climate change. In saline-stressed soils (common in coastal areas and parts of North India), it yields up to 30.4% more than the parent *MTU 1010* variety.

Why This Matters for the Planet?

The benefits of these crops extend far beyond the farmer's pocketbook.

1. **Water Savings:** Because Kamala matures faster, it requires about three fewer irrigation cycles. If grown on 5 million hectares, it could save an estimated 7,500 million cubic meters of water.
2. **Lower Emissions:** Shorter durations in flooded fields mean less time for soil microbes to produce methane, a potent greenhouse gas. These varieties are expected to reduce methane emissions by approximately 20%.
3. **National Security:** Rice is India's most critical foodgrain. With a yield that outperforms conventional varieties even under stress, genome-edited rice provides a safety net for a growing population in an unpredictable climate.

Genome editing sounds futuristic, it is much faster than traditional breeding. Developing a new variety traditionally takes 10–12 years; with CRISPR, it can be achieved in just 3–5 years.

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Climate Change–Driven Water Scarcity: A Comparative Assessment of Irrigation Stress and Water Governance Responses



Kiran Meena, Manish Yadav

Ph.D. Scholar, Division of Agronomy, Agriculture University, Kota, Rajasthan, India

Email: yadavmanu31199@gmail.com

Abstract

Climate change has transformed freshwater systems from renewable resources into contested, scarcity-driven challenges, particularly for irrigation-dependent agriculture, which consumes 70% of global withdrawals while supporting 40% of food production. This article examines climate-driven water scarcity—marked by disrupted hydrology, heightened evapotranspiration, and unreliable precipitation—alongside governance-mediated factors like institutional inertia and weak regulation that amplify vulnerabilities. Through comparative assessments of regions such as the Indo-Gangetic Plain, North China Plain, Colorado River Basin, and southern Europe, it reveals an efficiency-resilience paradox: systems optimized for yield under stable climates falter amid volatility, exacerbated by the energy-water nexus and supply-side paradigms. Ecological degradation, socio-economic inequities, and governance trade-offs are analyzed, highlighting the need for adaptive strategies including regulatory caps, transparent data systems, and participatory management. Ultimately, effective water governance must shift from expansion to scarcity management, integrating climate robustness, equity, and resilience to safeguard food security under uncertainty.

Keywords: Climate-driven scarcity, Irrigation stress, Water governance, Efficiency-resilience trade-off, Energy-water nexus, Adaptive management

1. Introduction

In the Anthropocene, freshwater systems have shifted from being perceived as renewable and locally manageable resources to critically constrained and increasingly contested systems. Climate change has accelerated this transition by disrupting long-established hydrological patterns, intensifying droughts, altering precipitation regimes, and increasing evaporative losses. Water scarcity—once treated as a localized or seasonal concern—has now emerged as a structural condition influencing food security, rural livelihoods, ecosystem stability, and political relations across regions. Irrigated agriculture sits at the centre of this transformation. Globally, irrigation accounts for nearly 70% of freshwater withdrawals and supports approximately 40% of food production on less than 20% of cultivated land (FAO, 2021). Most irrigation systems were designed under assumptions of climatic stationarity—that historical rainfall, river flows, and recharge rates would remain broadly predictable. These assumptions are now invalid. Climate variability has exposed deep vulnerabilities in irrigation-dependent regions, particularly where governance systems remain rigid, fragmented, or misaligned with emerging hydrological realities. In many cases, water scarcity is not merely the outcome of declining supply, but the result of institutional inertia that prevents timely adaptation. This article argues that climate change–driven water scarcity must be understood as a coupled environmental–governance challenge. Through a comparative assessment, it examines how climate change reshapes irrigation systems and evaluates the effectiveness of existing water governance responses across diverse agro-ecological and institutional contexts.

2. Defining the Core Dichotomy

To analyse climate-related water scarcity with analytical rigour, it is necessary to distinguish between two interlinked but conceptually distinct dimensions.

a) Climate-Driven Water Scarcity

Climate-driven water scarcity arises from rising temperatures, altered precipitation patterns, declining snowpack, glacier retreat, and increased frequency of extreme events. Unlike classical scarcity associated with aridity, this form is characterized by heightened uncertainty in both timing and spatial distribution of water. Rising temperatures increase evapotranspiration losses from crops and soils, thereby raising irrigation demand even

when total rainfall remains unchanged. Precipitation increasingly occurs in short, intense events that exceed soil infiltration and storage capacity, reducing effective availability. In snow-fed systems such as the Himalayas and the Rocky Mountains, earlier snowmelt reduces late-season river flows that historically supported irrigation during critical dry periods.

b) Governance-Mediated Water Scarcity

Governance-mediated scarcity emerges when institutional arrangements, policy frameworks, and incentive structures amplify physical water stress. Weak groundwater regulation, rigid allocation rules, fragmented administrative authority, and energy subsidies that encourage excessive pumping convert manageable scarcity into chronic crisis. Regions with comparable climatic exposure often experience markedly different outcomes depending on governance capacity. Scarcity, therefore, is not solely a biophysical phenomenon but is co-produced by climate dynamics and human decision-making systems.

Table 1. Structural Drivers of Climate Change–Driven Water Scarcity

Dimension	Climate Signal	Governance / Demand Link
Temperature rise	Increased evapotranspiration	Higher irrigation withdrawals
Rainfall variability	Short, intense precipitation	Inadequate storage and allocation
Cryosphere decline	Reduced base river flows	Seasonal mismatch with demand
Groundwater stress	Lower recharge rates	Weak regulation and subsidies

3. Comparative Assessment I: Irrigation Stress and the Efficiency Paradox

3.1 Irrigation Productivity versus Reliability

Irrigation expansion has long been associated with yield stability and food security. In the short term, irrigation buffers crop against rainfall variability and enables intensified production. Under climate stress, however, this apparent efficiency increasingly conceals systemic fragility. The Indo-Gangetic Plain illustrates this paradox. Declining monsoon reliability has driven widespread dependence on groundwater pumping. While yields initially improved, falling water tables have increased energy costs, reduced well viability, and excluded smallholders from access, undermining both economic and social sustainability. Comparable dynamics are evident in northern China's North China Plain and in parts of Iran and Pakistan. Thus, systems optimized for maximum output under stable climatic conditions become highly vulnerable under climatic volatility, revealing an efficiency–resilience trade-off.

3.2 The Energy–Water Nexus

As surface water becomes less reliable, irrigation increasingly depends on fossil energy. Deeper pumping, pressurized irrigation systems, and inter-basin transfers substantially raise energy demand. Costs rise non-linearly as groundwater levels decline, disproportionately affecting marginal and resource-poor farmers. In the western United States, irrigation in the Colorado River Basin continues despite declining flows, supported by historical allocation agreements and subsidies that delay scarcity signals. The result is institutional inertia that sustains overuse even as reservoirs reach record lows.

4. Comparative Assessment II: Sustainability Dimensions

4.1 Ecological Sustainability

Climate-driven water scarcity has profound ecological consequences. Reduced river flows degrade wetlands, alter sediment transport, and threaten aquatic biodiversity. Excessive groundwater extraction causes land subsidence and irreversible aquifer damage, as documented in India, Iran, Mexico, and parts of the United States. Southern Europe provides a clear illustration. Prolonged droughts combined with intensive irrigation have accelerated soil salinization and reduced ecosystem resilience in Spain and Italy. Climate change shortens recovery intervals between drought events, pushing agro-ecosystems closer to ecological thresholds.

4.2 Socio-Economic Resilience and Equity

Water scarcity redistributes risk unevenly across social groups. Large commercial farms often adapt through capital-intensive technologies, while smallholders face declining access and rising costs. In Sub-Saharan Africa, irrigation expansion without robust governance risks reinforcing inequality and triggering local conflicts over shared water sources. Gendered impacts are significant. Women, who play central roles in agricultural labour and

water management in many regions, bear disproportionate burdens as water becomes scarce and collection distances increase.

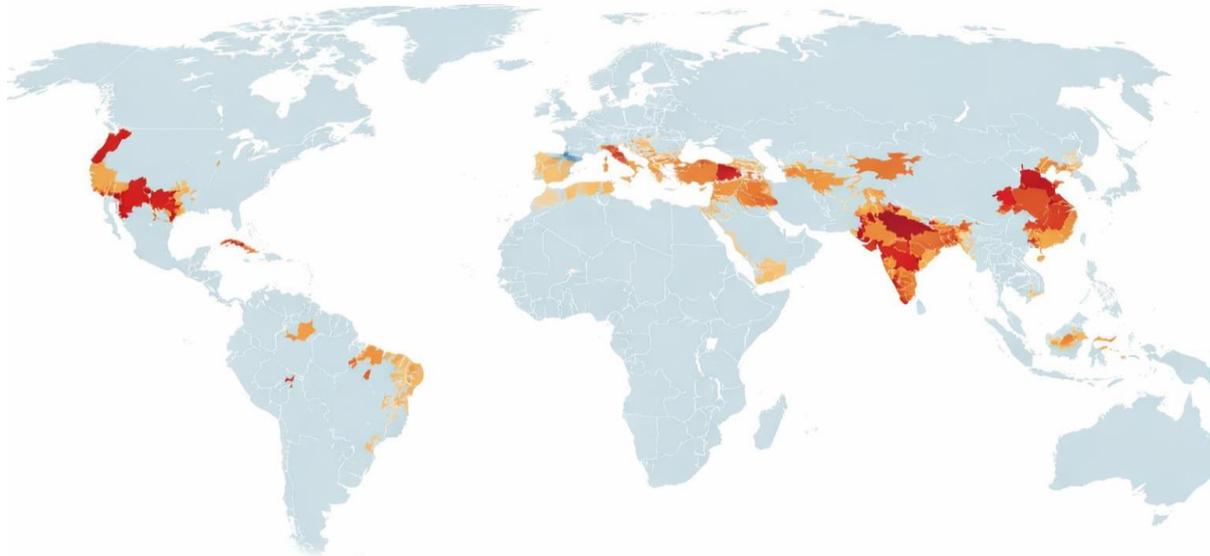


Fig 1. Regions where irrigation demand exceeds sustainable water availability under climate stress

Table 2. Governance Trade-offs under Climate-Induced Water Scarcity

Governance Tool	Efficiency	Equity	Climate Robustness
Regulatory caps	High	Medium	High
Water pricing	Medium	Low-Medium	Medium
Infrastructure expansion	Medium	Medium	Low
Open water data systems	High	High	High

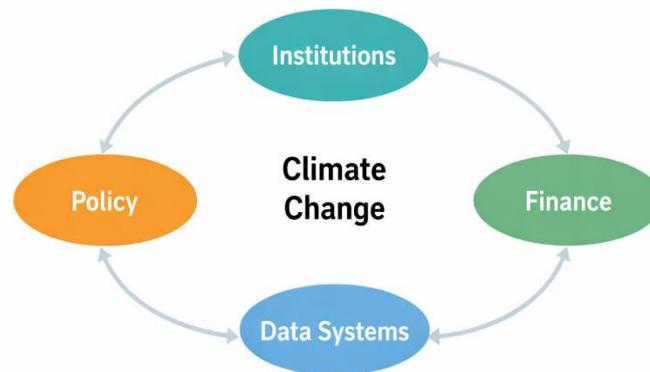


Fig 2. Integrated Water Governance Framework Core governance pillars required for managing water scarcity under climate change.

5. The Fallacy of Supply-Side Water Management

For decades, water policy has been dominated by supply-side solutions—dams, canals, and inter-basin transfers—built on the assumption that scarcity can be engineered away. Climate change exposes the structural limits of this paradigm. Altered precipitation regimes, shrinking snowpacks, and rising evapotranspiration mean that “new supply” is increasingly illusory or prohibitively expensive. Each additional unit of water now requires disproportionate investments in energy, finance, and ecological sacrifice.

Much like industrial fishing systems dependent on fossil fuel subsidies and distant-water fleets, modern irrigation has entered a phase of hydrological deficit spending. Groundwater aquifers are mined rather than managed, rivers are over-allocated on paper, and ecological flows are treated as residuals. The result is a self-reinforcing trap: as water becomes scarcer, farmers drill deeper, pump harder, and invest in energy-intensive infrastructure simply to maintain current yields. This masks scarcity in the short term while accelerating long-term collapse. Climate change turns this strategy from risky to untenable. Variability, not just mean decline, undermines rigid infrastructure designed for historical hydrology. Large dams lose reliability under erratic inflows, while canal-based systems struggle to adapt to sudden droughts or floods. In this context, modernization that focuses solely on efficiency gains—such as drip irrigation or canal lining—can backfire by enabling expansion of irrigated area, a phenomenon well documented as the rebound or Jevons effect. A hybrid governance pathway is therefore essential. This involves placing enforceable limits on extraction, reforming perverse incentives such as free power or flat water charges, and strengthening local institutions capable of collective decision-making. Technological tools—remote sensing, digital metering, and decision-support systems—should serve governance goals, not replace them. Modernization must enhance adaptive capacity and ecological resilience, rather than amplify vulnerability through deeper dependence on overstressed water systems.

6. Conclusion

Climate change-driven water scarcity represents a fundamental challenge to irrigation-dependent food systems and exposes the structural limitations of legacy water governance models. While irrigation has historically enabled agricultural intensification and yield stability, its future viability depends far less on expanding physical supply and far more on governing scarcity under conditions of uncertainty. Climate change has transformed water from a predictable production input into a volatile risk factor, demanding institutional responses that are flexible, anticipatory, and socially inclusive. Comparative evidence across regions demonstrates that water crises are shaped as much by institutional choices as by climatic stress. Regions that have reformed allocation rules, regulated groundwater extraction, and invested in transparent data systems show greater adaptive capacity and reduced vulnerability. In contrast, systems that rely on historical entitlements, politically protected subsidies, and fragmented administrative authority tend to delay adjustment, allowing ecological degradation and social inequities to deepen. Climate change magnifies these governance failures by narrowing the margin for error and accelerating feedback loops between scarcity, energy use, and environmental decline. Importantly, effective adaptation does not imply uniform solutions. The pathways available to water-scarce regions vary depending on hydrology, socio-economic conditions, and institutional capacity. However, several cross-cutting principles emerge. First, scarcity must be explicitly acknowledged and incorporated into planning, replacing growth-oriented paradigms with risk-based management. Second, governance frameworks must balance efficiency with equity, ensuring that adaptation measures do not disproportionately burden smallholders, marginalized communities, or downstream users. Third, data transparency—through open access to hydrological information, remote sensing, and monitoring platforms—must become a cornerstone of water governance, enabling accountability and informed decision-making.

The transition toward adaptive water governance will inevitably involve political and social trade-offs. Reducing over-extraction, reallocating water rights, and reforming subsidies can provoke resistance, particularly where irrigation is closely tied to livelihoods and food security. Yet delaying these reforms carries higher long-term costs, including irreversible aquifer depletion, ecosystem collapse, and heightened conflict over dwindling resources. Climate change thus reframes water governance as not merely a technical challenge, but a societal choice about sustainability, resilience, and intergenerational equity. Ultimately, long-term water and food security will depend on governance systems capable of operating under sustained climatic uncertainty. Adaptive, equity-oriented frameworks that integrate ecological limits, institutional accountability, and stakeholder participation offer the most credible pathway forward. In an era where water scarcity is no longer an exception but a defining condition, the capacity to govern scarcity effectively will determine the resilience of agricultural systems and the societies that depend on them.

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Engineered Soils: The Technosols Concept in Urban Pedology



Yugajyoti Barik¹, Richi Kisku², Monalisha Das³ and Harsh Thakur⁴

^{1,2,3}Ph.D. Scholars, College of Agricultural Engineering & Technology, OUAT, Bhubaneswar

⁴Masters Scholar, College of Agricultural Engineering & Technology, OUAT, Bhubaneswar

For most of human history, soil was something we inherited, a gift of geology and time. It takes nature roughly 500 years to manufacture just one inch of topsoil through the slow weathering of parent rock and the decomposition of organic matter. But as we reach 2026, the global population's shift toward "megacities" has created a crisis: we are paving over our best land while demanding more food and flood protection than ever before. The solution is not to look for more land, but to build it. Scientists are now moving beyond traditional agriculture into the realm of Urban Pedology, creating "Technosols", designer soils engineered from the debris of the modern world.



The Pedological Architecture: Building a Soil from Scratch

In traditional soil science, we categorize soils by their "horizons" (layers). A Technosol ignores the traditional O, A, and B horizons of the forest floor. Instead, it is a vertical "sandwich" of human-derived materials designed to perform specific chemical and physical tasks.

The Mineral Matrix

The "bones" of a Technosol often come from Demolition and Construction Waste (CDW). Crushed concrete and brick are not merely fillers; they provide a high-surface-area matrix that mimics the mineralogy of volcanic soils.

- **pH Buffering:** Concrete contains calcium carbonate, which can help neutralize acidic rain—a common problem in polluted urban centers.
- **Macroporosity:** Unlike natural clay, which can compact and suffocate roots, crushed brick provides "macropores" that allow for gas exchange, ensuring that roots never run out of oxygen.

The Organic Engine

To bring this mineral skeleton to life, scientists integrate Biochar and Functionalized Compost. Biochar- created through the pyrolysis of organic waste, acts as a "microbial hotel." Its porous structure protects beneficial fungi and bacteria from urban heat stress. When combined with composted municipal green waste, it creates a slow-release nutrient system that can last for decades without the need for synthetic fertilizers.

Component	Function	Origin
Crushed Brick/Concrete	Provides structure and drainage	Demolition sites
Biochar	Holds water and sequesters carbon	Agricultural waste
Green Compost	Delivers essential N-P-K nutrients	Urban food waste
Mycorrhizal Fungi	Connects roots for nutrient swap	Lab-grown cultures

The "Sponge City" and the Hydrology of 2026

One of the most critical scientific applications of Technosols is the management of the Urban Hydrological Cycle. In a traditional "grey" city, rainfall is a liability. It hits asphalt, picks up hydrocarbons and heavy metals (lead, zinc, cadmium), and rushes into water bodies.

Bio-Filtration and Cation Exchange

Technosols are engineered with high Cation Exchange Capacity (CEC). This is a measure of how well the soil can "grab" onto positively charged pollutants.

- The Mechanism: As storm water percolates through a Technosol layer, the negatively charged surfaces of biochar and organic matter bind to heavy metal ions, stripping them from the water.
- The Result: Water that leaves the bottom of a Technosol layer is often cleaner than the water that entered it.

Furthermore, the hydraulic conductivity of these soils is tuned to be 10 to 20 times higher than natural urban soil. During a "one-in-a-hundred-year" storm, a Technosol-lined park acts as a pressure-valve, absorbing millions of liters of water and releasing it slowly over several days, preventing sewer overflows.

Biohacking the Tomato: Nutrient Tailoring

The most radical frontier of Technosol research is Nutrient Density Engineering. In natural agriculture, we are limited by the parent rock of the region. If the local rock is low in Selenium, the crops will be too. In a Technosol, we have the "God-mode" of mineralogy. By adding specific mineral "dopants" like Zeolites or Basalt Dust to the soil mix, we can ensure that urban-grown produce is nutritionally superior to its rural counterparts.

Case Study: A 2025 study in Singapore's vertical farms demonstrated that "Technosol-plus" environments, soils inoculated with specific Arbuscular Mycorrhizal Fungi (AMF)- produced leafy greens with 40% higher Vitamin K content and significantly higher antioxidant levels compared to standard hydroponic systems.

This is shifting the conversation from "How do we feed the world?" to "How do we nourish the world?"

The Challenges: Microplastics and Regulation

Despite the promise, the science of Technosols is not without its "dirt." The primary concern for 2026 is the presence of Emerging Contaminants.

- Microplastics: When we use recycled urban waste, we risk introducing microplastics into the food chain.
- Longevity: Because Technosols are "young" soils, we are still learning how they age. Do they compact after ten years? Does the pH shift too rapidly?

To address this, the International Union of Soil Sciences (IUSS) has recently proposed new Technosol Standardization Protocols. These require every engineered soil to have a "Digital Passport," tracking its chemical origin and its predicted lifecycle, ensuring that the "upcycled" soil of today doesn't become the toxic waste of tomorrow.

Conclusion: The Earth, Version 2.0

We are no longer just inhabitants of the Earth; we are its architects. Technosols represent a fundamental shift in the Circular Economy. We are taking the debris of our past, our old buildings, our food waste, and our industrial byproducts, and turning them into the foundation of our future survival. The "Alchemy of Dirt" is no longer a

myth. It is a precise, data-driven science that is turning our concrete jungles into the most productive ecosystems on the planet.

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From Data to Dreams - The Evolution of Credit Information Companies in India: A Journey Towards Financial Inclusion



Lingampalli Srinivasu

AGM & Faculty

State Bank Institute of Rural Development (SBIRD), Gachibowli, Hyderabad 500019

"The true power of financial inclusion lies in transforming data into opportunities, enabling every Indian to dream beyond their circumstances and build a future of dignity and prosperity." – Dr Amartya Sen

Introduction: The financial landscape of India has undergone a profound transformation over the past few decades, driven by concerted efforts to enhance access to credit and foster financial inclusion. At the heart of this transformation lies the evolution of Credit Information Companies (CICs), which have played a pivotal role in reducing information asymmetry, improving credit decision-making, and extending financial services to underserved populations.

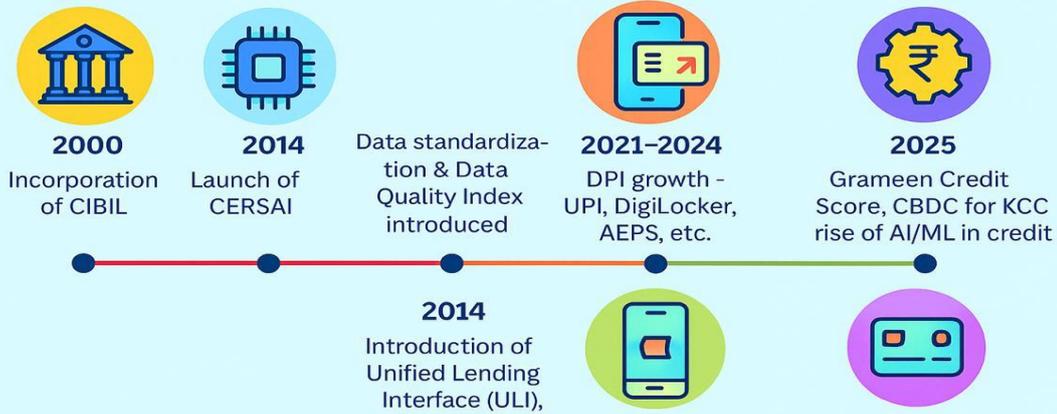


This article traces the historical development of CICs in India, examines the challenges they have faced, and explores the regulatory and technological advancements that have shaped their growth. Furthermore, it delves into the broader ecosystem of digital infrastructure and emerging technologies that complement the role of CICs, paving the way for a more inclusive and resilient financial system.

Genesis of Credit Information Companies in India: The concept of credit information bureaus in India emerged from a recognition by the Reserve Bank of India (RBI) of the need to create a centralized repository for credit-related data. In 1999, the RBI established a Working Group to explore the feasibility of setting up a Credit Information Bureau that would collect and disseminate credit information from lending institutions to the financial system. This initiative was driven by the understanding that access to accurate and comprehensive credit data could mitigate risks for lenders, enhance transparency, and facilitate access to credit for borrowers.

Following the recommendations of the Working Group, the Credit Information Bureau (India) Limited (CIBIL) was incorporated in 2000 as India's first CIC. Over the subsequent years, the sector expanded with the establishment of three additional CICs: Equifax Credit Information Services, Experian Credit Information Company of India, and CRIF High Mark Credit Information Services. These entities were tasked with collecting, collating, and sharing credit information to enable informed lending decisions, thereby fostering a more robust and inclusive credit ecosystem.

Milestones in India's Credit Reporting Journey



The establishment of CICs marked a significant milestone in India's financial history. By providing lenders with access to borrowers' credit histories, CICs reduced the information gap that had historically hindered credit access, particularly for individuals and small businesses without established financial records. This development laid the foundation for greater financial inclusion, enabling creditors to underwrite both secured and unsecured loans with greater confidence.

Challenges in the Early Years: Despite their transformative potential, CICs faced significant challenges in their formative years. One of the primary obstacles was the inconsistent quality of data submitted by lending institutions. Inaccurate, incomplete, or outdated data undermined the reliability of credit reports, limiting their utility for lenders. Additionally, shortcomings in consumer protection mechanisms posed a barrier to the widespread acceptance of CICs. Borrowers often faced difficulties in accessing their credit reports, rectifying errors, or resolving grievances, which eroded trust in the system.

To address these issues, the RBI constituted a committee in 2013 to examine the challenges facing the CIC sector and recommend remedial measures. The committee's findings highlighted the need for standardized data formats, improved data quality, and enhanced consumer protection frameworks. Based on these recommendations, the RBI introduced significant policy changes in 2014, including:

- **Standardization of Data Formats:** The RBI mandated uniform data formats for individual, corporate, and microfinance borrower segments to ensure consistency and comparability of credit information across institutions.
- **Technical Working Group:** A Technical Working Group, comprising representatives from various regulated entities, was institutionalized to oversee data submission processes and address technical challenges.
- **Data Quality Index:** A Data Quality Index was introduced to monitor and improve the quality of data submitted by credit institutions, incentivizing lenders to provide accurate and timely information.

These reforms marked a turning point for CICs, enhancing their credibility and utility within the financial system. By addressing data quality and consumer protection concerns, the RBI laid the groundwork for a more robust and reliable credit reporting ecosystem.

Regulatory Measures to Enhance CIC Operations: In recent years, the RBI has introduced a series of regulatory measures to further strengthen the operations of CICs and address persistent challenges. These

measures have focused on improving data quality, ensuring faster grievance redressal, and enhancing consumer empowerment. Key initiatives include:

- **Free Full Credit Report (FFCR):** CICs are now mandated to provide individuals with free access to their full credit reports annually. This measure enhances transparency and empowers consumers to monitor their credit profiles.
- **Internal Ombudsman:** CICs are required to appoint internal ombudsmen to handle customer grievances efficiently, ensuring timely resolution of disputes.
- **Integration with RBI's Ombudsman Scheme:** The RBI extended its Integrated Ombudsman Scheme to CICs, providing an additional layer of recourse for consumers dissatisfied with grievance redressal outcomes.
- **Compensation Framework:** A framework was introduced to compensate customers for delays in rectifying errors in their credit information, incentivizing CICs to prioritize accuracy and responsiveness.
- **Increased Frequency of Credit Reporting:** The RBI mandated more frequent updates to credit data, moving from monthly to fortnightly reporting, to ensure that credit information reflects borrowers' current financial status.
- **Disclosure of Defaulters:** CICs are required to publish lists of suit-filed accounts and wilful defaulters on their websites, enhancing transparency and deterring deliberate defaults.

These measures have significantly improved the operational efficiency of CICs, fostering greater trust among consumers and lenders alike. By prioritizing data accuracy and consumer empowerment, the RBI has ensured that CICs remain integral to the credit ecosystem.

The Role of CICs in Financial Inclusion: The establishment and evolution of CICs have been instrumental in addressing one of the most pressing challenges in India's financial system: information asymmetry. Twenty-five years ago, the lack of accessible and reliable credit information posed a significant barrier to credit access, particularly for the financially excluded. Small businesses, rural populations, and individuals without formal financial histories were often unable to secure loans due to the high cost of information gathering and the inherent risks for lenders.



CICs have played a critical role in bridging this gap by providing lenders with comprehensive credit histories, enabling them to assess borrowers' creditworthiness with greater accuracy. This has facilitated the expansion of both secured and unsecured lending, particularly in underserved segments. For instance, access to credit information has given creditors the confidence to underwrite unsecured loans, which were previously considered high-risk. Prime borrowers, who may have been overlooked due to information gaps, have also benefited from improved access to credit.

Moreover, CICs have contributed to financial inclusion by enabling lenders to make data-driven decisions, reducing reliance on subjective or relationship-based lending practices. This has been particularly impactful for micro, small, and medium enterprises (MSMEs), which constitute a vital component of India's economy. By providing accurate credit information, CICs have helped MSMEs access formal credit, reducing their dependence on informal sources of financing.

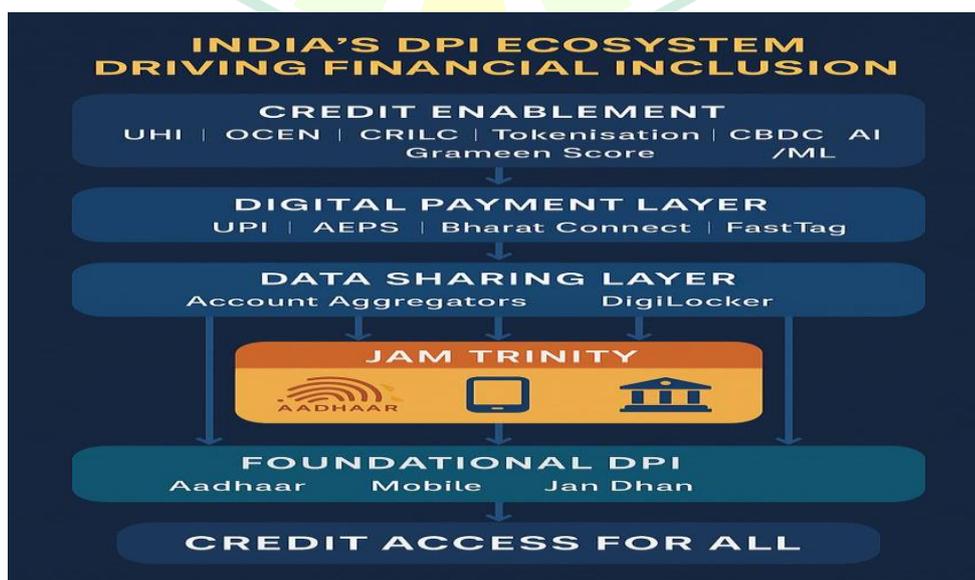
Complementary Mechanisms and Emerging Technologies: While CICs have been a cornerstone of India's credit reporting ecosystem, they are not the only mechanism for addressing information asymmetry. The digitalization of financial services and the electrification of records have created new opportunities to harness data for credit assessment and financial inclusion. The rise of FinTechs, advancements in digital public infrastructure (DPI), and the integration of alternative data sources have complemented the role of CICs, creating a more dynamic and inclusive financial ecosystem.

Central Registry of Securitisation Asset Reconstruction and Security Interest of India (CERSAI): Established in 2011 under the Securitisation and Reconstruction of Financial Assets and Enforcement of Security Interest (SARFAESI) Act, CERSAI was initially tasked with maintaining a registry of security interests. Over time, it has evolved into a comprehensive database covering immovable, movable, and intangible properties, as well as assignments of receivables. By providing creditors with access to information on encumbered or attached properties, CERSAI enhances transparency and reduces the risk of fraudulent transactions. Its integration with court orders and attachment orders further strengthens its utility as a tool for credit risk management.

Central Repository of Information on Large Credits (CRILC): Introduced in 2013, CRILC is a specialized repository managed by the RBI to collect and disseminate information on large credits extended by scheduled commercial banks, all-India financial institutions, and certain non-banking financial companies. CRILC provides critical insights into credit exposures, enabling financial institutions to monitor and manage credit risk effectively. It also supports the RBI's supervisory risk assessment by identifying potential vulnerabilities in the financial system.

Digital Public Infrastructure (DPI): India's DPI has been a game-changer in the financial services sector, integrating technology, markets, and governance to deliver public goods. Key components of DPI include:

- **Unified Payments Interface (UPI):** A flagship instant mobile payment system that enables seamless, interoperable transactions across bank accounts and apps.
- **Aadhaar Digital ID:** A biometric-based identification system covering over a billion adults, facilitating secure and verifiable identity authentication.
- **Aadhaar Payment Bridge (APB):** A platform for direct cash transfers to beneficiaries' bank accounts, enhancing the efficiency of government welfare programs.



- **Aadhaar Enabled Payments System (AEPS):** An interoperable network for biometric-based cash withdrawals and deposits, particularly in underserved areas.
- **DigiLocker:** A digital locker for storing verifiable credentials, reducing paperwork and enhancing accessibility.
- **Bharat Connect (formerly Bharat Bill Payments System):** A platform for bill fetching and payment, streamlining utility payments.
- **FastTag:** A near-field communication-based system for toll and parking collections.

The **Account Aggregator Framework**, another critical component of DPI, enables consented sharing of financial data across institutions. Introduced in 2016, this framework has grown rapidly, with financial institutions increasingly adopting it to facilitate credit delivery. The inclusion of the Goods and Services Tax Network (GSTN) as a financial information provider is expected to boost cashflow-based lending to MSMEs, further advancing financial inclusion.

Unified Lending Interface (ULI): Launched as part of India's DPI, the Unified Lending Interface (ULI) is designed to simplify and democratize credit access by providing lenders with seamless access to verified borrower data. ULI leverages the **JAM Trinity** (Jan Dhan Accounts, Aadhaar, and Mobile Phones) and integrates with platforms like UPI to create a robust digital lending infrastructure. Its ability to tap into alternative data sources, such as digitized land records and cooperative databases, enables lenders to extend credit to borrowers without formal financial histories. ULI's integration with the National Bank for Agriculture and Rural Development's (NABARD) e-KCC portal is expected to extend credit access to customers of District Central Co-operative and Regional Rural Banks, previously excluded from formal digital channels.

Looking ahead, ULI's potential to incorporate data from e-commerce platforms and gig economy apps could further expand credit access for small sellers, delivery workers, and freelancers, fostering greater financial inclusion.

Impact on Credit Access and Financial Inclusion: The combined impact of CICs, DPI, and other digital initiatives has been transformative for India's credit landscape. Household debt as a percentage of GDP has risen to approximately 43% in 2024, driven primarily by an increase in the number of borrowers rather than a rise in average indebtedness. Over the past five years, bank credit under the retail/personal loan category has grown at a compound annual growth rate (CAGR) of approximately 17%, reflecting robust demand for credit. The Financial Inclusion Index, which measures the extent of financial inclusion, has improved significantly from 49.9 in 2019 to 64.2 in 2024, indicating progress in reducing frictions in credit delivery and enhancing financial access.

These outcomes underscore two critical trends:

1. **Improved Credit Availability:** The availability of credit to individual borrowers has expanded significantly, driven by better access to credit information and digital infrastructure.
2. **Reduced Frictions in Credit Delivery:** The decline in information asymmetry and the adoption of technology-driven solutions have streamlined credit processes, making formal credit more accessible to underserved populations.

Empowering the MSME Sector: The MSME sector, which comprises over 7.34 crore enterprises and contributes nearly one-third of India's GDP and 46% of exports, is a critical driver of economic growth. However, MSMEs have historically faced challenges in accessing formal credit due to information asymmetry, excessive documentation, and lack of transparency. CICs have played a pivotal role in addressing these challenges by providing creditors with reliable credit reports, reducing reliance on relationship-based lending, and enabling fact-based credit assessments.

Digital initiatives, such as the Account Aggregator Framework and ULI, have further enhanced credit access for MSMEs by leveraging alternative data sources, such as cash flow information and GSTN data. These developments have enabled lenders to offer cashflow-based lending solutions, reducing the dependence on collateral and expanding credit access to smaller enterprises.

The Rise of FinTechs: The emergence of FinTechs has been a game-changer in India's financial services landscape. By leveraging technology, FinTechs have lowered the cost and complexity of delivering financial services, particularly to underserved and unserved populations. In FY 2024, FinTechs processed approximately

47% of small-ticket personal loans (less than ₹1 lakh) by count, demonstrating their significant impact on retail lending.



FinTechs have also fostered collaboration with traditional financial institutions, bridging gaps in credit origination and supply chain finance. These partnerships have been particularly impactful in rural and remote areas, where physical infrastructure and human resource constraints have historically limited access to financial services.

Open Credit Enablement Network (OCEN) and Open Network for Digital Commerce (ONDC): The Open Credit Enablement Network (OCEN) is a pioneering initiative that facilitates interactions among lenders, borrowers, and loan service providers on a common platform. By integrating alternative data sources, such as cash flow information, OCEN enables lenders to make more informed credit decisions, streamlining credit delivery.



The potential integration of OCEN with the Open Network for Digital Commerce (ONDC) could further democratize credit access, enabling MSMEs to participate in digital commerce and fostering broader economic growth.

Central Bank Digital Currency (CBDC) and Tokenisation: The RBI's exploration of Central Bank Digital Currency (CBDC) for credit disbursement represents a forward-looking approach to financial inclusion. A pilot

project by a commercial bank for tenant farmer lending under Kisan Credit Cards demonstrates the potential of programmable CBDC to ensure end-use monitoring. By tracking livelihood activities, this model enables tenant farmers to access formal credit without land records, creating a replicable framework for collateral-free loans to micro-enterprises, street vendors, and artisans.

Tokenisation, the process of creating digital representations of financial or real assets on programmable platforms, offers another avenue for enhancing credit delivery. By tokenizing assets such as trade receivables, SMEs can improve their collateral offerings, narrow the information gap and enhance their creditworthiness. Tokenisation also enables simultaneous asset transfer and payment, reducing counterparty risk and minimizing the need for collateral.

The Role of AI and Machine Learning: Artificial Intelligence (AI) and Machine Learning (ML) are transforming credit delivery by enabling lenders to assess creditworthiness using alternative data sources. For individuals without formal credit histories, AI/ML algorithms can analyse data from diverse sources—such as mobile transactions, utility payments, and e-commerce activity—to generate accurate credit profiles. This advancement is poised to mainstream alternative data, making it a critical tool for expanding credit access to underserved populations.

AI/ML also streamlines credit assessments, risk evaluations, and compliance processes, such as Know Your Customer (KYC) procedures. By automating these workflows, lenders can reduce administrative costs and accelerate loan disbursements, making small-ticket loans viable even in remote regions. Microfinance and microloans, which serve as lifelines for underserved communities, are likely to be the biggest beneficiaries of these advancements.

The Grameen Credit Score: The proposed Grameen Credit Score is a tailored framework designed to enhance financial inclusion in rural areas, particularly for members of self-help groups (SHGs). Unlike generic credit scoring systems, the Grameen Credit Score accounts for the unique financial behaviours and constraints of rural borrowers. By providing a specialized tool for assessing creditworthiness, this initiative aims to improve access to formal credit for farmers, marginalized communities, and other underserved groups.

The Reserve Bank's Role in Fostering Innovation: The RBI has played a central role in creating an enabling regulatory environment for CICs, FinTechs, and other stakeholders in the credit ecosystem. Key initiatives include:

- **Framework for Self-Regulatory Organisations (SROs) in the FinTech Sector:** Introduced in 2024, this framework balances innovation with risk management, ensuring that FinTechs operate within a robust regulatory framework.
- **Reserve Bank Innovation Hub (RBIH):** The RBI's wholly owned subsidiary fosters collaboration among startups, incubators, regulators, and financial institutions through initiatives like Fintech and Startup Acceleration (FAST) and HaRBInger (Annual **global hackathon** launched by the **Reserve Bank Innovation Hub**), which focus on inclusive design and accessibility.
- **Regulatory Sandbox:** The RBI's 'on-tap' and 'theme-neutral' Regulatory Sandbox encourages continuous innovation by providing a controlled environment for testing new financial products and services.

These efforts reflect the RBI's commitment to fostering innovation while maintaining the integrity of the financial system.

Challenges and Opportunities Ahead: While significant progress has been made, challenges remain in the effective deployment of data-driven systems. Key issues include:

- **Accuracy: Inaccurate** or incomplete data can undermine the reliability of credit assessments, leading to poor lending decisions.
- **Data Security:** Robust data security measures are essential to prevent breaches and protect consumer information.



- **Model Risk:** AI/ML models must be rigorously tested and monitored to ensure fairness, transparency, and compliance with regulatory standards.

To address these challenges, CICs and other stakeholders must prioritize two critical enablers:

1. **Enhancing Data Freshness:** Moving towards real-time or near-real-time credit reporting will improve underwriting precision, reflect borrower actions promptly, and enhance consumer experience. This shift requires investments in technology and process reengineering but promises significant rewards in transparency and efficiency.
2. **Improving Data Quality:** The RBI's Data Quality Index incentivizes credit institutions to submit accurate and timely data. CICs must continue to collaborate with lenders to ensure high-quality submissions.

Another key challenge is identity standardization. The absence of a unique borrower identifier increases the risk of duplication and misreporting. The adoption of a secure, verifiable, and consistent identifier across the financial system is essential to address this issue.

Conclusion: The evolution of Credit Information Companies in India represents a remarkable journey towards financial inclusion and the democratization of credit. From their inception in 2000 to their current role as critical enablers of credit access, CICs have transformed India's financial landscape. Supported by regulatory reforms, digital public infrastructure, and emerging technologies, CICs have reduced information asymmetry, empowered lenders to make informed decisions, and extended credit to underserved populations.

The broader ecosystem, encompassing DPI, FinTechs, and initiatives like ULI, OCEN, and CBDC, has complemented the role of CICs, creating new avenues for financial inclusion. As India stands on the cusp of a transformative financial era, the convergence of technology, policy, and innovation holds immense promise for building a more inclusive, resilient, and sustainable economy.

However, the journey is far from complete. Sustained efforts are needed to enhance data freshness, improve data quality, and address challenges related to data security and model risk. Financial literacy remains a critical component of this journey, requiring a collective commitment from all stakeholders to empower consumers and foster trust in the financial system. As CICs and their partners continue to innovate responsibly, they will play an integral role in realizing the vision of total financial inclusion, ensuring that every Indian has access to the credit they need to thrive.

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Peels, Pomace and Petals: Unlocking the Potential of Horticultural Waste



Mahantesh P. S.¹ and Shruti P. Gondi²

¹ Scientist (Horticulture), ICAR-KVK, Chitradurga, KSNUAHS, Shivamogga

² Assistant professor (Vegetable Science), College of Horticulture, Hiriyr, KSNUAHS, Shivamogga

Abstract

Fruits and vegetables are important sources of vitamins, minerals, dietary fiber and antioxidants. However, large-scale processing generates substantial waste, accounting for nearly 40 per cent of total production, mainly in the form of peels, rinds, pomace, seeds, stones and pulp residues. Improper disposal of these by-products creates serious environmental and sustainability challenges. Despite this, processing wastes are rich in bioactive compounds such as polyphenols, carotenoids, flavonoids and pectins, offering significant opportunities for value addition. Effective utilization of these wastes can reduce environmental impact and support the development of sustainable food systems and value-added products.

Keywords: Value addition, nutraceuticals, bioactive compounds, functional foods and sustainability

1. INTRODUCTION

Fruits and vegetables play a vital role in human nutrition, providing essential vitamins, minerals, antioxidants and phytochemicals. With the expansion of the horticultural processing industry, large volumes of waste are generated during operations such as sorting, peeling, pulping, juicing and trimming. It is estimated that nearly 30–40% of fruits and vegetables are lost globally due to lack of postharvest management and processing activities. These wastes include peels, pomace, seeds, stones, rinds and stalks, which are often discarded without proper treatment.

Improper disposal of horticultural waste causes serious environmental concerns such as water pollution, greenhouse gas emissions, foul odors and microbial contamination. At the same time, these residues are rich sources of valuable compounds that remain underutilized. Scientific evidence suggests that the concentration of bioactive compounds in fruit and vegetable by-products is often higher than in the edible portions. Therefore, converting horticultural waste into value-added products presents a sustainable solution that aligns with the principles of waste minimization, resource recovery and circular bioeconomy.

2. SOURCES AND CHARACTERISTICS OF HORTICULTURAL WASTE

Horticultural waste is generated at various stages of the supply chain, from farm to consumer. The major sources include:

- **Post-Harvest Handling and Storage:** Losses occur due to mechanical damage, physiological disorders, microbial spoilage and improper storage conditions. Sorting, grading and trimming operations produce peels, tops, roots and rejected produce.
- **Processing and Value Addition Units:** Fruit and vegetable processing industries generate large quantities of waste in the form of peels, pomace, pulp residues, seeds, stones, cores, shells and spent flowers. Juice extraction, canning, dehydration, fermentation and essential oil extraction are major contributors.
- **Wholesale Markets and Retail Outlets:** Unsold, overripe, damaged or aesthetically unacceptable fruits, vegetables and flowers are discarded during transportation, wholesale trading and retail marketing.
- **Household and Institutional Sources:** Kitchen waste from domestic consumption, hotels, restaurants, hospitals and food service institutions contributes significantly to

2.2 Characteristics of Horticultural Waste

The characteristics of horticultural waste vary depending on crop type, processing method and stage of generation. In general, horticultural wastes exhibit the following features:

- **High Moisture Content:** Most fruit, vegetable and flower wastes contain 70–90% moisture, making them highly perishable and prone to rapid microbial decomposition.
- **Rich in Organic Matter:** Horticultural waste is composed mainly of carbohydrates, cellulose, hemicellulose, lignin and soluble sugars, contributing to a high biochemical oxygen demand (BOD) if disposed of improperly.
- **Nutrient-Rich Composition:** These wastes are good sources of vitamins, minerals, dietary fiber, proteins, lipids and micronutrients such as potassium, calcium and magnesium.
- **Presence of Bioactive Compounds:** Fruit peels, seeds, vegetable pomace and flower residues contain significant levels of polyphenols, flavonoids, carotenoids, essential oils, alkaloids, tannins and natural pigments.
- **Seasonal and Heterogeneous Nature:** The quantity and composition of horticultural waste vary seasonally and regionally, depending on crop availability, processing scale and consumer demand.
- **Biodegradable and Environment-Friendly:** Most horticultural wastes are biodegradable and suitable for composting, vermicomposting, anaerobic digestion and other biological treatments.
- **Potential Environmental Impact:** If not managed properly, horticultural waste can lead to foul odor, pest infestation, greenhouse gas emissions and contamination of soil and water bodies.

2.3 Significance

Understanding the sources and characteristics of horticultural waste is essential for designing effective waste management strategies and developing value-added products such as functional foods, nutraceuticals, biofertilizers animal feed, bioenergy and biodegradable materials. Efficient utilization of these wastes supports sustainability, resource conservation, and circular bio economy initiatives.

Type 1: Types of waste generated from the fruit processing industry

Type of Fruit	Major Processing Operations	Type of Waste Generated	Approx. Waste (%)
Mango	Pulping, canning, juice extraction	Peel, seed kernel, pomace	35–45
Banana	Pulping, drying, chips	Peel, pseudostem residue	30–40
Citrus fruits (Orange, Lemon)	Juice extraction	Peel, seeds, segment membranes	45–60
Apple	Juice, cider, sauce	Pomace (peel, pulp, seeds)	25–35
Pineapple	Juice, canning	Peel, core, crown	35–50
Grapes	Juice, wine	Pomace (skin, seeds, stems)	20–30
Pomegranate	Juice processing	Peel, seeds	50–60
Papaya	Pulping	Peel, seeds	25–35
Cashew apple	Juice, fermentation	Pomace, peel	60–70
Tomato	Sauce, ketchup	Skin, seeds	20–30
Guava	Pulp extraction	Seeds, peel	30–40

Table 2: Types of waste generated from vegetable and flower processing industries

Commodity	Major Processing Operations	Type of Waste Generated	Approx. Waste (%)
Potato	Peeling, slicing, frying	Peels, rejected tubers	15–40
Tomato	Sauce, paste, ketchup	Skins, seeds	20–30
Onion	Peeling, dehydration	Dry outer peels, roots	20–25
Carrot	Juicing, cutting	Pomace, peels	20–30
Cabbage	Cutting, fermentation	Outer leaves, cores	25–35
Cauliflower	Floret separation	Leaves, stalks	40–50
Beetroot	Juicing	Pomace, peels	20–30
Rose	Essential oil extraction, garland making	Spent petals, stems	60–70
Marigold	Pigment extraction	Spent flowers	50–65
Jasmine	Perfume extraction	Spent flowers	40–60
Chrysanthemum	Decoration, extraction	Discarded flowers	50–60
Tuberose	Garland, fragrance extraction	Spent florets	40–55
Lotus	Food and religious use	Petals, stalks	35–45
Lavender	Essential oil extraction	Spent biomass	50–60

Conclusion

Horticultural wastes from fruits, vegetables and flowers are valuable yet underutilized resources rich in bioactive compounds and nutrients. Their conversion into functional foods, nutraceuticals, biofertilizers, bioenergy and biodegradable materials can reduce environmental pollution and post-harvest losses while improving economic returns. Adoption of waste-to-wealth technologies and circular bioeconomy approaches is essential for sustainable horticultural waste management.

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Revolutionizing Fruit Safety: Ozone's Advanced Disinfection Power



Priyadharshini L M¹ and Dr. C. Ravindran²

¹PG Scholar, Department of Postharvest Technology, HC & RI (TNAU), Periyakulam.

²Associate Professor (Hort.) and Head, Horticultural and Forestry Research Station, Kodaikanal.

Introduction

In a world where fresh produce can be enjoyed without concern for invisible microorganisms, ozone is proving to be a safe, effective alternative to chemical-based disinfection methods for fruit washing. Ozone is a naturally occurring gas that is highly effective at destroying bacteria, mold spores and viruses. As such, ozone-based washing and disinfecting are becoming standard practice among growers, packers and retailers due to the increased awareness of food safety and a growing incidence of pathogen-related outbreaks (e.g. Salmonella in berries). This study will provide an overview of all of the relevant aspects regarding ozone's ability to disinfect and preserve the quality of fresh fruits and vegetables.

Principle of ozone disinfection: The oxidative magic

Ozone functions as a powerful disinfectant through its ability to generate reactive oxygen species (ROS), such as hydroxyl radicals ($\bullet\text{OH}$), which disrupt microbial cell membranes, DNA, and enzymes. Unlike stable molecules, ozone decomposes into oxygen (O_2) after reacting, making it self-neutralizing and residue-free. The process typically involves generating ozone from oxygen or air using electrical discharge or ultraviolet light, then dissolving it into water to create ozonated water or applying it as a gas. For fruits, the principle relies on contact time, ozone concentration (typically 0.5–5 ppm), and pH levels, which influence the disinfection efficacy. This oxidative mechanism targets pathogens like *Escherichia coli*, Salmonella, and molds, while being selective enough to minimize damage to the fruit's surface.

Application in fruit washing and disinfection

Ozone is a versatile option for many fruit processing plants, which use marketable fruit by treating them with ozone in several ways. In one example, strawberries can be cultivated within a controlled climate and processed through an ozonated gas (by direct injection, into the climate-controlled environment). In another case, freshly harvested apples can be placed into a batch of ozonated water (with bubbling action) for treatment.

Common methods include:



Fig.1: Common methods of Ozone treatment

1. Immersive washing using ozonated water – ozonated water can be utilized most effectively as a way to wash fruit in batches. Fruit is submersed in a recirculating low ozone concentration (1-3 mg/L) of ozonated water tanks; tanks continuously receive inputs as they contain ozone gas. After approximately 5-15 minutes of submersion, venturi-style injectors will remove contaminants, including dirt, pesticides, microorganisms, and gas from the fruit.

2. Fumigation of fruit using ozonated gas – fruit is treated using ozone gas at concentrations of 5 to 20 parts per million in a sealed chamber or tunnel for thousands of hours. Both methods provide an advantage over submersion in water because fruit will sustain less injury from handling.

3. Application of ozonated mist using spray/rinse systems – in conveyor-based processing lines, ozonated mist can be applied using high-pressure nozzles, allowing for the cleaning and sanitation of fruit in a single operation.

Advantages of Ozone technology

- Helps to reduce CO₂ emissions and chemical runoff due to their breakdown into oxygen. The use of the eco-warrior will protect wildlife and waterways and reduces disinfectant by-products (by up to 90%) when comparing to chlorine.
- The broad-spectrum slayer will kill a wide variety of microorganisms (including viruses such as norovirus), as well as antibiotic-resistant superbugs, without creating resistance to the product.
- Ozone can extend the shelf life of foods by 20% to 50% through preventing their decay and helping to lessen food waste, which is estimated to cost the world \$1 trillion annually, while also preserving vitamins and minerals, like Vitamin C.
- The eco-warrior also helps with the development of “clean label” claims for organic produce to capture the health-conscious consumer.

Disadvantages of Ozone technology

- Ozone damage on produce: Fruits such as peaches and kiwis may show signs of damage (e.g., pitting, browning, texture loss) due to oxidative stress caused by high concentrations (over 5 ppm) of ozone. These problems are similar to the effects of "ozone burn."
- High set-up costs (generators can run \$10,000-\$50,000) and high electricity demand may prevent small farms from purchasing ozone generators, although new modular units are currently being developed.
- Surface Skimming: Ozone is only effective at treating surface contamination of fruit. Ozone does not treat internal fruit diseases, such as the internal contamination of melons; therefore, additional techniques will be required.
- Human Health Risks: Ozone gas can irritate the eyes and lungs. According to OSHA guidelines, the maximum allowable ozone concentration in an eight-hour workweek is 0.1 ppm; therefore, it is important that there be adequate ventilation and that appropriate PPE is available for workers exposed to ozone.
- Condition Dependent: The effectiveness of ozonation is dependent on water pre-treatment, as alkaline water or turbidity of the water can potentially affect the efficiency of ozonation.

Case studies

Apples proved effective: According to USDA studies, ozonated water (2 mg/L for 10 minutes) was able to reduce *E. coli* in Red Delicious apples by 4.5 logs. This is much greater than the 2-log reduction of *E. coli* achieved with chlorine. Farmers were able to generate 15% more from their orchard due to a 14-day increase in the shelf-life of their apples without compromising on quality.

Strawberries are sensational: A study conducted in Portugal found that by exposing strawberries to 10 ppm ozone gas for 30 minutes, the level of Salmonella found on strawberries was reduced by 3.2 logs, and the amount of antioxidants increased by 20%. As a result, a traditionally perishable product was transformed into a premium export, as farmers noted that their crop had 25% less fungal rot.

Grapes were great: Through ozonating water (3 mg/L for 15 minutes), *Botrytis cinerea* on Thompson seedless grapes (2.8 logs) was eliminated. Four vineyards in Chile reported that through using ozone therapy, they reduced their use of fungicides by 40%, thus making their grape crops more sustainable and producing no difference in taste from traditional methods.

Disinfection rates for various fruits:

Fruit	Pathogen targeted	Ozone method	Log reduction	Key findings
Apples	<i>E. coli</i> O15:H7	Ozonated water (2 mg/L, 10 min)	4.5	Superior to chlorine; no residue
Strawberries	<i>Salmonella spp.</i>	Gaseous ozone (10 ppm, 30 min)	3.2	Preserves antioxidants; reduces decay
Grapes	<i>Botrytis cineria</i>	Ozonated water (3 mg/L, 15 min)	2.8	Eco-friendly mold control
Oranges	<i>Penicillium digitatum</i>	Gaseous ozone (5 ppm, 20 min)	3.0	Extends shelf life
Tomatoes	<i>Salmonella typhimurium</i>	Gaseous ozone (5 ppm, 20 min)	2.5	Effective on cut surfaces
Blueberries	<i>Listeria monocytogenes</i>	Ozonated water (1.5 mg/L, 5 min)	2.9	Minimal quality loss
Mangoes	<i>Colletotrichum gloeosporioides</i>	Ozonated water (2 mg/L, 15 min)	3.1	Controls anthracnose in tropics

Conclusion

Not only is ozone an effective disinfectant but it is also a remarkable innovation successfully merging sustainability with science for better safety of fruits. By using the power of oxidation without the use of any chemical additives, ozone significantly lowers the many hazards associated with growing, harvesting, transporting, handling and selling fresh fruits while simultaneously extending their shelf life. Even though ozone will need continual improvements over time to achieve perfect results, there is no question that it performs better than its competition in both effectiveness and ethical ways. The use of this innovative technology makes produce safer, brighter and fresher than ever before - a winning combination for the earth's environmental ecosystem, the wellbeing of our population and the enjoyment of the flavor of what they consume.

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Vertical farming - Smart urban agriculture for enhancing resilience and sustainability in food security



Chirag Kumar

B.Sc. (Hons.) Agriculture, College of Agriculture, CCSHAU, Hisar, Haryana

Vertical farming is the process of growing crops in a controlled environment, in vertically stacked layers. This is a smart farming technology of the twenty-first century for the sustainability of food to meet the increasing demand for food. It includes hydroponics, aquaponics, and aeroponics as soilless farming techniques and controlled environment agriculture (CEA) technology for good quality produce under optimum light, water, temperature, humidity, nutrients, and proper supervision.

Advantages of vertical farming:

- The main advantage of vertical farming is that fewer farming spaces are required.
- As a result, proper supervision or management of the farm is easy.
- Negligible impact of external environmental factors like drought, frost, high rain, high wind velocity, heat waves, etc.
- There is high water use efficiency, as drip irrigation systems are mainly used here.
- Less water is required as compared to conventional farming.
- Negligible loss of resources; they are used to the point.
- Good quality produce with good nutritional properties.
- It also provides employment.
- There is no use of soil, so there are no pests or diseases, and any type of contamination is negligible.
- High productivity per unit area.
- The produce has negligible amounts of pesticides and other chemical residues in the food, which is harmful for consumption.
- It is an eco-friendly practice of crop cultivation.

Vertical farming includes techniques as follows:

1. Hydroponics is a soilless technique to grow plants in water-based mineral nutrient solutions like nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients like iron, boron, zinc, copper, manganese, molybdenum, and chlorine. These nutrients are pumped through a nutrient pump, and to support roots, gravel, sand, and perlite are used as soil substitutes. This practice is done under a greenhouse or under a controlled environment. Plants usually grown through these techniques are tomatoes, peppers, cucumbers, strawberries, lettuce, cannabis, etc.

System requirements (Royston et al., 2018)

1	PH control	5-7 or slightly acidic
2	Electrical conductivity	1.2-3.5 mho
3	Horticulture lighting	Direct sunlight or extra light for 8-10 hrs. Per day
4	Temperature	50°–70° F for fall plants and 60°–80° F for spring plants.
5	Supplements	Nitrogen-phosphorous-potassium rich formula
6	Oxygen	Supplement oxygen supply is required for optimal nutrient uptake
7	Structure and support	Stakes and strings are usually needed to support plants as they grow

2. Aquaponics is also a soilless technique to grow plants; it is the combination of aquaculture and hydroponics where plants use carbon dioxide, water, and heat, and fishes get purified water and detoxed nutrients. The fish, plants, and microbes are the important components of aquaponics, where microbes make food for plants by converting fish waste into plant nutrients. The fish that mainly grow in aquaponics are goldfish, carp, catfish, barramundi, and tilapia, and the plants mainly grown in aquaponics are tomatoes, lettuce, Pak choi, kale, basil, mint, watercress, peppers, cucumbers, broccoli, beans, peas, squash, cauliflower, and cabbage.
3. Aeroponics is a soilless technique to grow plants; it does not require any type of medium for plants to grow, and there is less requirement of water as compared to hydroponics and aquaponics. The nutrients are sprayed over the plants in atomized or sprayed form. Sometimes it is combined with hydroponics to save the plants' lives when they become sensitive, especially the root system. The hydroponics provide nutrients and water to save the crops when they face sensitivity.

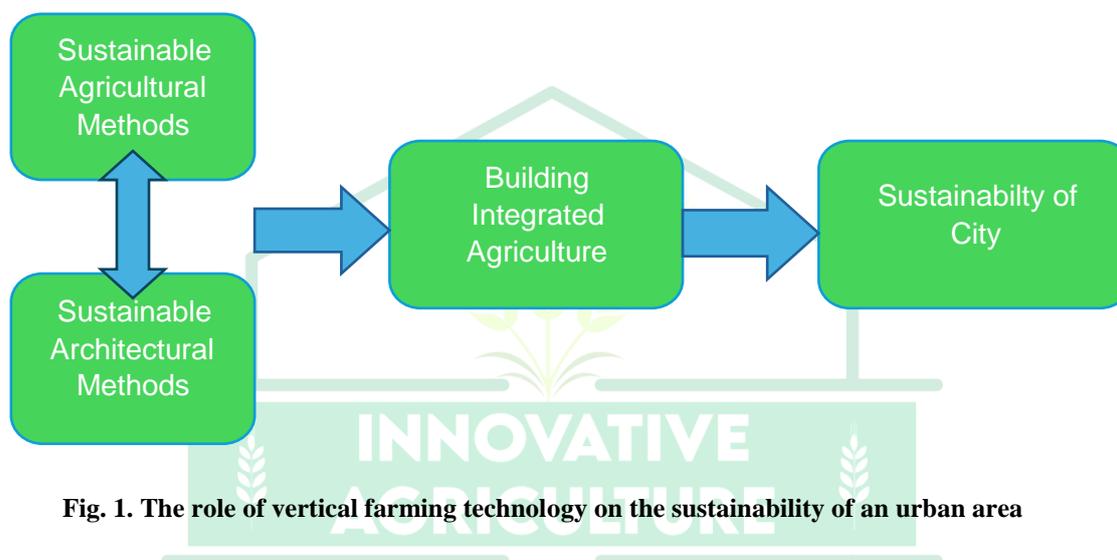


Fig. 1. The role of vertical farming technology on the sustainability of an urban area

Conclusion:

Vertical farming played a very important role in meeting food demand, mainly in densely populated cities where land is limited for cultivation, and this technique takes to the new methods of farming, like rooftop farming, and have a revolutionary effect on the greenhouse industry with great potential. The conclusion is that a basic understanding of vertical farming can enhance food security significantly.

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Microplastics: The Invisible Threat Reshaping Aquatic and Agro-Ecosystems



Priyanka Acharya and Niranjan Sarang

Fisheries Polytechnic College, Rajpur, Chattisgarh

Abstract

Microplastics, defined as plastic particles smaller than 5 mm, have become pervasive contaminants in aquatic, terrestrial, and agro-ecosystems worldwide. Originating from the fragmentation of larger plastic debris and from primary industrial sources, microplastics persist in the environment due to their resistance to degradation and complex chemical composition. Their small size and large surface area facilitate interactions with biotic and abiotic components, enabling widespread distribution across water bodies, sediments, soils, and living organisms. In aquatic ecosystems, microplastic ingestion by fish and invertebrates leads to reduced feeding efficiency, growth inhibition, physiological stress, and impaired reproductive performance, particularly in early developmental stages. Additionally, microplastics act as vectors for toxic chemicals and persistent organic pollutants, enhancing bioaccumulation and biomagnification within food chains. The increasing presence of microplastics in agroecosystems disrupts soil structure, microbial activity, nutrient cycling, and plant growth, thereby threatening agricultural productivity and food security. Human exposure through contaminated food and water has raised concerns regarding inflammation, endocrine disruption, and long-term health risks. This review critically examines the sources, environmental distribution, ecological and socio-economic impacts of microplastic pollution, and discusses emerging mitigation strategies, including biodegradable alternatives, regenerative agricultural practices, improved waste management, and policy interventions. An integrated and multidisciplinary approach is essential to mitigate microplastic pollution and ensure the sustainability of ecosystems and food systems.

Keywords: Microplastics, biomagnification, sustainability

1. Introduction

For generations, oceans and coastal ecosystems have supported human livelihoods by providing food, employment, and ecological stability. However, in recent decades, the increasing accumulation of plastic waste has emerged as a silent yet pervasive threat. Among plastic pollutants, microplastics are the plastic particles smaller than 5 mm which have gained global attention due to their ubiquity, persistence, and biological impacts. Often described as the “dust of the sea,” microplastics now contaminate marine, freshwater, and agroecosystems, altering food chains and posing risks to ecosystem integrity and human health.

It is estimated that 8 million metric tons of plastic debris enter the oceans annually, where they fragment into micro and nanoplastics. These particles are no longer confined to ocean surfaces but are distributed throughout water columns, sediments, organisms, and even agricultural soils.

2. Sources and Characteristics of Microplastics

Microplastics originate from both primary and secondary sources. Primary microplastics are intentionally manufactured at small sizes, such as microbeads used in cosmetics and industrial abrasives. Secondary microplastics result from the breakdown of larger plastic items including bags, bottles, fishing gear, and synthetic textiles.

Microplastics vary widely in size, shape, polymer type, and chemical composition, which influences their environmental behavior and toxicity. Their small size, large surface area, and hydrophobic nature enable them to persist in ecosystems and interact with both biotic and abiotic components. Globally, 1.15–2.41 million tons of plastic waste are estimated to enter agroecosystems each year, largely through irrigation water, sewage sludge, plastic mulching, and atmospheric deposition.

3. Microplastics in Aquatic Ecosystems and Fisheries

3.1 *The Invisible Harvest*

In aquatic ecosystems, microplastics have infiltrated every trophic level. Studies have reported that a significant proportion of coastal and marine fish now ingest microplastic particles, mistaking them for food. For fisheries, this represents a dual challenge: declining fish health and compromised seafood quality.

Microplastics ingested by fish can reduce feeding efficiency, growth, and survival, directly affecting fish stocks and fisheries productivity. This issue is particularly critical for coastal fisheries, where pollution levels are highest and small-scale fishers depend heavily on nearshore resources.

3.2 *Biological Impacts on Fish and Larvae*

One of the most critical biological effects of microplastics is **false satiation**. Larval and juvenile fish often ingest microplastics that visually resemble zooplankton. Because plastics are indigestible, they accumulate in the digestive tract, leading to reduced appetite, energy deficiency, and eventual starvation.

Research has demonstrated that microplastic exposure results in:

- Reduced growth rates
- Delayed development
- Increased mortality in early life stages
- Impaired reproductive potential due to hormonal disruption

Such impacts weaken population resilience and threaten commercially important species, ultimately destabilizing aquatic food webs.

4. Microplastics as Vectors of Toxic Chemicals

Microplastics act as **chemical carriers**, adsorbing persistent organic pollutants (POPs) such as DDT, PCBs, and polycyclic aromatic hydrocarbons from surrounding environments. When ingested, these contaminants are released into organism tissues, leading to bioaccumulation and biomagnification along the food chain.

This “Trojan horse” effect amplifies the toxic impact of microplastics beyond their physical presence, increasing physiological stress, oxidative damage, and immune suppression in aquatic organisms.

5. From Ecosystems to Humans: Food Chain and Health Implications

Microplastic contamination does not end within aquatic organisms; it extends directly to humans through seafood consumption. The discovery of microplastics in human blood, placentas, and tissues highlights the growing concern regarding long-term health effects.

Current evidence links microplastic exposure to:

- Inflammatory responses and vascular disorders
- Endocrine disruption due to plastic additives such as BPA
- Potential reproductive and developmental effects

Thus, microplastic pollution represents a direct interface between environmental degradation and public health, emphasizing the inseparability of ecosystem and human well-being.

6. Microplastics in Agroecosystems and Terrestrial Food Chains

Beyond aquatic systems, microplastics are increasingly detected in soils and agricultural landscapes. Their presence alters soil structure, affects water retention, interferes with root development, and disrupts microbial activity essential for nutrient cycling.

Microplastics may:

- Obstruct plant root systems
- Alter growth and physiological processes in crops
- Act as vectors for toxic compounds and pathogens
- Interfere with decomposers and soil fertility

As a result, agricultural productivity, food security, and soil health are increasingly at risk.

7. Socio-Economic Impacts on Small-Scale Communities

Microplastic pollution disproportionately affects **small-scale fishers and coastal communities**, who lack the capacity to shift fishing grounds or adopt advanced technologies. Polluted coastal waters reduce fish quality and market value, damage fishing gear, and threaten livelihoods.

In some regions, declining fish availability has forced communities to seek alternative income sources, including waste collection and recycling, highlighting the social cost of plastic pollution.

8. Mitigation Strategies and Future Perspectives

Complete eradication of microplastics is currently unrealistic due to their persistence and resistance to degradation. However, several mitigation strategies offer hope:

- **Regenerative agriculture** to reduce plastic inputs into food systems
- **Bio-based and biodegradable plastics** as alternatives to conventional polymers
- **Improved wastewater treatment technologies** to capture microfibers
- **Clean remedial biotechnologies** for environmental restoration
- **Policy interventions** to restrict single-use plastics and enforce producer responsibility

Global initiatives, including international plastic treaties, are increasingly focusing on lifecycle management of plastics to curb future pollution.

9. Conclusion

Microplastics represent one of the most pervasive anthropogenic pollutants of the modern era. Due to their widespread presence, small size, chemical complexity, and interactions with biotic and abiotic components, they exert profound direct and indirect effects on aquatic and terrestrial food chains. Addressing microplastic pollution requires an integrated approach combining scientific innovation, sustainable practices, and strong legislative frameworks. Without decisive action, microplastics will continue to reshape ecosystems and threaten food security and human health for generations to come.

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Digital Soil Mapping for Sustainable Agronomic Planning



Puspa Parameswari¹, Lalit Mohan Garnayak², Sohan Singh Walia³

¹PhD Research Scholar, Division of Agronomy, Punjab Agricultural University, Ludhiana-141004

²Directorate Of Research, Central Agricultural University, Imphal- 795004

³Director-cum-Principal Agronomist, School of Organic Farming, Punjab Agricultural University, Ludhiana-141004

Abstract

Digital Soil Mapping (DSM) integrates soil science with geospatial technologies, remote sensing, and machine-learning techniques to generate spatially explicit soil information for sustainable agronomic planning. Unlike conventional soil surveys, DSM provides continuous predictions of soil properties along with uncertainty estimates, enabling precise, site-specific management decisions. Recent advancements in environmental data availability and modelling approaches have enhanced the applicability of DSM in precision nutrient management, irrigation planning, crop suitability assessment, and climate-smart agriculture (McBratney *et al.*, 2003; Minasny & McBratney, 2016). This article reviews the principles, methods, and applications of DSM in agronomy and highlights its growing role in promoting resource-use efficiency and environmental sustainability.

Introduction

Soil is a vital natural resource that directly influences agricultural productivity, food security, and ecosystem sustainability. Effective agronomic planning depends on accurate information on soil properties such as texture, nutrient availability, organic carbon content, and water-holding capacity. Traditional soil surveys, though scientifically robust, are often limited by coarse spatial resolution, high cost, and infrequent updating, particularly under rapidly changing land-use and climatic conditions.

Digital Soil Mapping (DSM) has emerged as a modern approach to overcome these limitations by quantitatively predicting soil properties across landscapes using environmental covariates and computational models (McBratney *et al.*, 2003). Advances in geographic information systems (GIS), remote sensing, and machine learning have accelerated the adoption of DSM, enabling high-resolution soil information to support precision agriculture and sustainable land management (Hengl *et al.*, 2017). As the demand for sustainable intensification of agriculture increases, DSM has become an essential decision-support tool for agronomists and policymakers.

Concept and Principles of Digital Soil Mapping

Digital Soil Mapping is based on the premise that soil variation can be explained as a function of soil-forming factors such as climate, organisms, relief, parent material, time, and spatial position. This concept is formally expressed through the soil-environment relationship framework proposed by McBratney *et al.* (2003), which forms the theoretical foundation of DSM.

Unlike traditional soil maps that delineate discrete soil units, DSM produces continuous spatial predictions of soil attributes, such as soil organic carbon, nutrient content, and pH, along with associated uncertainty estimates (Minasny & McBratney, 2016). This quantitative nature makes DSM particularly suitable for agronomic planning, where fine-scale variability in soil properties strongly influences crop response and management efficiency.

Data Sources and Modelling Approaches

DSM relies on the integration of multiple data sources, including field-based soil observations, legacy soil databases, environmental covariates, and remote sensing data. Terrain attributes derived from digital elevation models, climate variables, land-use information, and vegetation indices are commonly used predictors in DSM models (Hengl *et al.*, 2017).

A wide range of modelling techniques are employed in DSM, including geostatistical methods, regression-based models, and machine-learning algorithms. In recent years, machine-learning approaches such as random

forest and support vector machines have gained prominence due to their ability to model complex, non-linear relationships between soil properties and environmental predictors (Minasny *et al.*, 2017). Recent studies have demonstrated improved prediction accuracy for soil nutrients and organic carbon using these advanced techniques (Migheli *et al.*, 2024; Kalambukattu *et al.*, 2025).

Figure 1: Workflow of Digital Soil Mapping for Sustainable Agronomic Planning

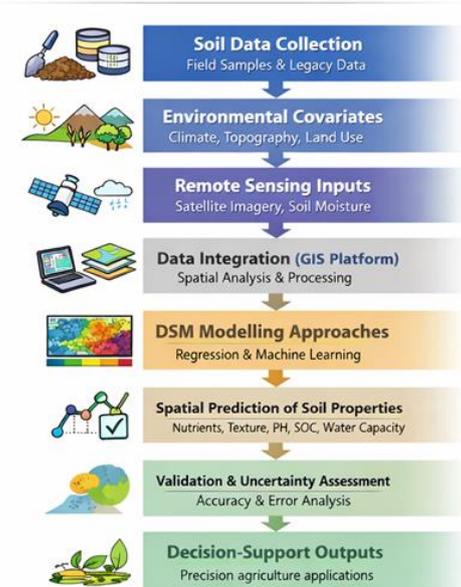
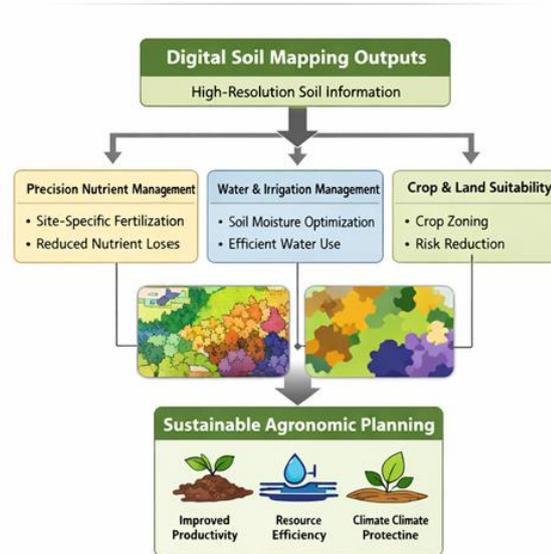


Figure 2: Role of Digital Soil Mapping in Sustainable Agronomic Planning



Applications of DSM in Sustainable Agronomic Planning

Precision Nutrient Management

DSM plays a crucial role in precision nutrient management by mapping spatial variability in soil fertility parameters such as nitrogen, phosphorus, potassium, and organic carbon. These maps enable site-specific fertilizer recommendations, improving nutrient-use efficiency and reducing environmental losses through leaching and runoff (Migheli *et al.*, 2024). Such targeted nutrient management supports both economic and environmental sustainability in agricultural systems.

Crop Suitability and Land-Use Planning

Spatial prediction of soil constraints, including salinity, acidity, shallow depth, and poor drainage, allows DSM to support crop suitability analysis and land-use optimization. By aligning crop requirements with soil capability, DSM reduces production risks and enhances land-use efficiency (Hengl *et al.*, 2017; Sindhushree *et al.*, 2025).

Water and Irrigation Management

DSM-derived maps of soil texture, moisture retention, and hydraulic properties assist in efficient irrigation scheduling and water resource planning. These applications are particularly important in water-scarce and climate-vulnerable regions, where efficient water use is critical for sustainable agronomic planning.

Soil Health and Climate-Smart Agriculture

DSM supports climate-smart agriculture by enabling spatial assessment of soil organic carbon stocks and identifying areas with high carbon sequestration potential or degradation risk (Minasny *et al.*, 2017; Kalambukattu *et al.*, 2025). Such information is essential for designing soil conservation strategies and monitoring long-term soil health.

Role of DSM in Decision Support

The DSM workflow integrates soil observations, environmental covariates, and remote sensing data within a geospatial modelling framework to generate spatial soil predictions for agronomic decision-making (McBratney *et al.*, 2003; Hengl *et al.*, 2017). These outputs directly support sustainable agronomic planning by informing

precision nutrient management, irrigation scheduling, crop zoning, and soil health monitoring (Minasny & McBratney, 2016; Hussain *et al.*, 2024).

Challenges and Future Perspectives

Despite its advantages, DSM faces challenges related to limited availability of high-quality soil data, technical complexity, and uncertainty in model predictions. Addressing these challenges requires capacity building, improved soil data infrastructure, and integration of DSM outputs into user-friendly decision-support systems. Future developments in artificial intelligence, high-resolution remote sensing, and open soil databases are expected to further enhance the role of DSM in sustainable agronomic planning (Minasny *et al.*, 2017).

Conclusion

Digital Soil Mapping represents a transformative approach to soil information generation and application in sustainable agronomic planning. By providing high-resolution, spatially explicit soil data, DSM enables efficient resource management, enhances crop productivity, and supports environmentally responsible farming systems. Continued technological advancement and institutional support will further strengthen DSM as a cornerstone of sustainable agriculture.

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Low-Salinity Farming of Pacific White Shrimp (*Litopenaeus vannamei*)



V. Vijayalakshmi, Mahadevi, Yuvarajan, Mohammed Faizullah

Department of Aquaculture, TNJFU- Dr. M.G.R Fisheries College and Research Institute,
Thalainayeru – 614712

Abstract

Low-salinity shrimp farming enables the culture of marine shrimp in inland areas using low-salinity water resources. The Pacific white shrimp, *Litopenaeus vannamei*, is well suited for this system due to its wide salinity tolerance and strong osmoregulatory ability. However, successful culture depends largely on maintaining proper ionic composition, particularly potassium, magnesium, and calcium, which are often deficient in inland waters. This review highlights the importance of mineral management, osmoregulation, and nutritional supplementation in improving shrimp growth, survival, and production under low-salinity conditions, while also addressing environmental concerns and sustainable management practices.

Introduction:

The euryhaline white shrimp *Penaeus vannamei* inhabits both coastal and oceanic environments and can tolerate a wide range of salinities. However, there remains uncertainty regarding its osmoregulatory mechanisms and its varying levels of tolerance to low-salinity conditions.

Inland shrimp aquaculture in low-salinity waters is widely practiced across many regions of the world. Due to its ability to grow and thrive in such environments, the Pacific white shrimp (*Litopenaeus vannamei*) has emerged as the preferred species for low-salinity culture.

The culture of Pacific white shrimp (*Litopenaeus vannamei*) away from coastal areas whether in inland ponds using low-salinity well water (2–5 g/L), indoor recirculating aquaculture systems (RAS), or indoor biofloc systems with salinity below 15 g/L is a well-established and documented practice in various parts of the world.

The culture of shrimp and marine fish in low-salinity water is a common practice in many countries around the world, including China, Thailand, Vietnam, Ecuador, Brazil, Mexico, and the United States.



Low-salinity, inland shrimp culture in Brazil and Ecuador

Exposure to a wide range of salinities triggers adaptive responses in organisms, leading to changes in physiological functions that can ultimately impact growth and survival (Young et al., 1989). Consequently, physiological adaptation to salinity plays a vital role in the natural recruitment of shrimp (Ferraris et al., 1987) and significantly influences their growth, survival, and feed intake under culture conditions (Jory, 1995).

Wide range of salinity tolerances is being presented by penaeids, although the ideal growth conditions are fulfilled within a limited range. For a penaeid species, *Penaeus monodon*, 15 to 25 ppt salinity (Chen et al., 1995) is considered ideal whereas *Fenneropenaeus chinensis* shows superior growth in the range of 20 to 25 ppt (Chen et al., 1995; Zhang et al., 1999). The Pacific white shrimp, *Penaeus vannamei*, can tolerate a wide salinity range from 1 to 50 ppt, making it a model species for studying osmoregulation mechanisms and salt tolerance (Pante, 1990).

Recently, *Penaeus vannamei* has emerged as a highly promising culture species globally, owing to its capacity to thrive in inland low-salinity waters and its potential to deliver significant economic returns (Davis et al., 2002).

Inland shrimp farming in low-salinity water is a significant practice in Thailand, contributing approximately 30 percent of the country's total shrimp production (Fast and Menasveta, 2000). Shrimp are raised in ponds with salinity levels of 2 to 5 ppt, achieved by mixing brine from coastal seawater evaporation ponds with freshwater.

Due to the success of inland shrimp farming in Thailand, this practice is now being adopted in countries such as Ecuador, Brazil, the United States, and others (Scarpa, 1998; Samocha et al., 2001; Nunes and Lopez, 2001), where low-salinity water is often sourced from saline groundwater wells (Boyd, 2001). In some cases, producers also create low-salinity water by mixing freshwater with granular salt from mines or evaporation ponds.



Inland shrimp culture

Ionic Composition:

The ionic composition of water typically influences shrimp health more significantly than overall salinity (Davis et al. 2004). While sodium (Na) and potassium (K) are essential for osmoregulation, calcium (Ca) and magnesium (Mg) play a critical role in moulting and the formation of new shells (Samocha et al. 2017).

The culture of Pacific white shrimp (*Penaeus vannamei*) in low-salinity inland waters presents several challenges, primarily due to deficiencies in essential minerals such as potassium (K⁺) and magnesium (Mg²⁺). To ensure optimal survival, growth, and production, the magnesium-to-calcium (Mg: Ca) ratio should be maintained at 3:1 (Aruna 2017).

In general, the mineral concentrations in low-salinity pond water should closely match the ionic levels and ratios found in seawater. Essential minerals may be lost through bottom soil adsorption, leaching, pond drainage, or dilution from heavy rainfall. Therefore, it is crucial to regularly analyze the ionic profile both before stocking and throughout the culture period. Maintaining seawater-like ionic composition and ratios is vital for supporting normal physiological functions in penaeid shrimp (Suguna 2020).

A study in Thailand found that magnesium is rapidly removed from pond water by bottom soils when brine is added. Regular application of magnesium chloride to maintain levels above 100 mg/L in ponds with 1–6 g/L salinity significantly improved shrimp survival and production (Idsariya Wuditisin, pers. Comm. 2010). Total alkalinity should be at least 75 mg/L (equivalent to 90 mg/L bicarbonate at pH < 8.3) for adequate buffering (Boyd & Tucker 1998). While low levels of other ions may affect shrimp growth, adding potassium alone has proven effective in correcting ionic imbalances in many groundwater-fed ponds.

While the ratio of major ions in low-salinity water is important, minimum concentrations are also critical. For instance, shrimp struggle to molt when total alkalinity drops below 50 mg/L (equivalent to 61 mg/L bicarbonate).

Shrimp can survive in salinities as low as 1 ppt or less (Jory 1999; Samocha et al. 2001), but acclimation is challenging. In Thailand, farmers typically raise initial pond salinity to 5–6 ppt using brine, which may decline to 1–2 ppt by harvest. Brine or salt is added if salinity falls too low.

Potassium and magnesium fertilizers:

The most commonly used material to raise potassium levels in pond water is fertilizer-grade potassium chloride (KCl), also known as muriate of potash. This compound contains approximately 50% potassium, meaning that

applying 2g/m^3 increases the potassium concentration by 1g/m^3 (1mg/L). Another fertilizer, sulfate of potash magnesia ($\text{K}_2\text{SO}_4 \cdot \text{MgSO}_4$), marketed under the trade name K-Mag, is also used as a source of both potassium and magnesium for treating inland shrimp ponds (Boyd 2003). This product contains 10.5% magnesium, 17.8% potassium and 63.6% sulfate. A treatment rate of 5.6 gm^{-3} is necessary to cause a 1mg L^{-1} increase in potassium; the resulting increases in magnesium and sulfate would be 0.59mg L^{-1} and 3.5mg L^{-1} respectively.

Osmoregulation of Shrimp in low salinity waters:

Penaeid shrimp are a diverse group of decapod crustaceans found in environments from full-strength seawater to brackish water. Although they are strong hypo- and hyperosmoregulators that maintain stable haemolymph osmolality (Pequeux 1995), not all species are fully euryhaline.

Hyperosmoregulation in euryhaline crustaceans like *L. vannamei* involves gill processes that support adaptation to low-salinity marine waters. However, inland low-salinity waters often lack the proper ionic balance, particularly potassium and magnesium. This imbalance increases Na^+/K^+ -ATPase (NKA) activity, leading to poor growth and higher mortality. While *L. vannamei* can tolerate low salinity if calcium hardness is adequate, some waters remain unsuitable due to ionic deficiencies. A proposed, untested theory suggests that in low-salinity conditions, potassium exits cells through stretch-activated channels to reduce cytosol osmolality and water influx. Combined with potassium loss through gills and body surfaces, this lowers haemolymph potassium and disturbs the K^+/Na^+ ratio, impairing NKA and Na-K-2Cl function. Since magnesium is essential for NKA, its deficiency further disrupts ion transport and osmoregulation by affecting mitochondrial-rich cells (MRCs).

Minerals:

Shrimp, like other crustaceans, need specific minerals for metabolism, growth, and osmoregulation, as these minerals support hard and soft tissues, enzymes, and proteins (Davis & Lawrence 1997). Dietary supplementation of essential ions has been proposed to compensate for deficiencies at the gill-water interface. In *L. vannamei* cultured in low-salinity waters in Arizona, adding NaCl, magnesium chloride, potassium chloride, cholesterol, and lecithin to the diet improved osmoregulatory capacity (Gong et al. 2004).

Other Nutritional Supplements

Carbohydrate levels in diets have been shown to affect *L. vannamei* growth in low salinity water. In a 5-week study, Wang et al. (2004) found that higher dietary carbohydrate levels improved specific growth rates at lower salinities, likely by offsetting the increased energy cost of osmoregulation.

Astaxanthin, a carotenoid pigment, has also been tested as a dietary supplement to reduce stress and improve performance in low salinity. Flores et al. (2007) reported that shrimp fed 80 mg/kg astaxanthin in 3 g/L salinity water showed higher levels of glucose, lactate, haemocyanin, and total haemocyte count. While growth improved, survival did not significantly differ from other doses ($0, 40, 150\text{ mg/kg}$).

Additionally, the prebiotic GroBiotic® was shown to enhance survival in *L. vannamei* cultured at 2 g/L salinity (Li et al., 2010).

Environmental regulations and control:

The use of saline water has enabled inland expansion of shrimp farming, but raises concerns about introducing high total dissolved solids (TDS) into freshwater ecosystems (Boyd 2006; Boyd et al. 2006; Pine 2008). While salinization is often linked to arid regions, studies show that inland low-salinity aquaculture can also cause stream salinization in humid areas. To address this, farms should be located away from freshwater sources, ponds should be properly lined to prevent seepage, and water should be recycled to minimize discharge (Boyd 2001, 2002; Boyd et al. 2006; Pine & Boyd 2010b).

Case studies:

The super-intensive culture of *Penaeus vannamei* in low salinity water: A comparative study among recirculating aquaculture system, biofloc, and synbiotic systems (Pimentel, O.A.L.F., et al.2025).

This study found that the synbiotic system is suitable for super-intensive culture of *Penaeus vannamei* in low-salinity water. It provided better control of nitrogenous compounds throughout the experiment compared to BFT and supported a higher abundance of ciliates and amoebae than both RAS and BFT. As a result, shrimp in the synbiotic system showed higher survival rates, greater yield, and lower feed conversion ratio (FCR) than those in the RAS and BFT systems.

Conclusions:

Inland farming of marine shrimp is expected to grow globally, especially in areas with suitable low-salinity water sources. As remediation techniques improve, shrimp survival, growth, and production are likely to increase.

Researchers and farmers have explored both water and dietary modification strategies to enhance the growth and survival of marine shrimp in low-salinity waters. Among these, modifying the rearing water with potassium and magnesium fertilizers has proven more effective than dietary supplementation in improving shrimp growth, survival, and osmoregulatory capacity.

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Kodai Orange: The Jewel of Thandigudi Hills



Dr. M. Kabilan

Regional Coffee Research Station, Coffee Board, Thandigudi, Tamil Nadu, India

Introduction

Nestled in the cool, mist-laden slopes of the Palani Hills, Thandigudi stands apart as a unique horticultural landscape of Tamil Nadu. Among the crops that define this region, none carries as much cultural, economic, and emotional value as the Kodai orange. Revered for its refreshing flavour, bright colour, and seasonal charm, Kodai orange is more than a citrus fruit it is a symbol of hill agriculture, farmer resilience, and regional pride. Often associated with the broader Kodaikanal region, Kodai orange has a particularly strong identity in Thandigudi, where elevation, climate, and traditional farming practices come together to produce a fruit unlike any other. For decades, Kodai orange has supported livelihoods, shaped local markets, and earned a loyal consumer base that eagerly awaits its seasonal arrival. This article explores the journey of Kodai orange from the hills of Thandigudi to household tables, examining its origin, cultivation ecology, quality attributes, nutritional value, socio-economic role, challenges, and future prospects. In doing so, it highlights why Kodai orange truly deserves to be called the jewel of the Thandigudi hills.

Thandigudi: A Natural Home for Hill Citrus

Thandigudi is situated in the lower Palani hill range, forming a transitional zone between the plains of Dindigul district and the upper elevations of Kodaikanal. This location gives the region a distinctive agro-climatic advantage. Moderate temperatures, cool nights, gentle sunlight, and well-distributed rainfall create ideal conditions for citrus cultivation. The soils of Thandigudi are predominantly loamy to sandy loam, rich in organic matter due to continuous leaf litter from shade trees and surrounding vegetation. Good drainage prevents waterlogging, while sufficient moisture retention supports sustained fruit development. These natural features collectively contribute to the superior eating quality of Kodai orange. Unlike citrus grown in hot plains, hill-grown oranges develop slowly. This extended growth period allows for better accumulation of sugars, organic acids, and aromatic compounds, resulting in a balanced sweet-tangy flavour that consumers strongly associate with Kodai orange.

Kodai Orange: A Fruit Shaped by Hills and Climate

Kodai orange is not defined by a single improved variety but rather by a regional type shaped over time by local selection, climate, and farming practices. Farmers traditionally propagate planting material from trees that exhibit desirable traits such as better sweetness, thin rind, good juice content, and attractive colour. The cool hill climate plays a decisive role in fruit quality. Lower day temperatures and cooler nights slow respiration rates, helping retain sugars and acids. The result is an orange that is neither overly sweet nor sharply acidic, but refreshingly balanced. Fruit colour development is another hallmark. Kodai oranges develop a bright orange to deep orange hue, especially during cooler months. This visual appeal, combined with natural aroma and juiciness, sets Kodai orange apart from many commercially grown citrus fruits.

Traditional Cultivation Practices in Thandigudi

Kodai orange cultivation in Thandigudi is deeply rooted in traditional knowledge passed down through generations. Orchards are often small to medium in size and maintained as mixed farming systems rather than monocultures. Orange trees are commonly intercropped with coffee, pepper, vegetables, or shade trees, creating a diversified and resilient production system. Farmers rely heavily on organic manures such as farmyard manure and compost, which improve soil structure and microbial activity. Chemical fertilizer use is generally moderate, partly due to cost constraints and partly due to the recognition that excessive inputs can affect fruit quality. Pruning is carried out selectively to maintain tree health and improve sunlight penetration. Flowering usually occurs in response to seasonal climatic cues, and fruit development follows a natural rhythm dictated by temperature and rainfall. Harvesting is done manually, with fruits picked at physiological maturity rather than full

ripeness to ensure better shelf life and transportability. This careful handling preserves fruit quality and minimizes post-harvest losses.

Seasonality and Market Arrival

One of the most anticipated aspects of Kodai orange is its seasonality. The fruit typically reaches markets during specific months, creating a sense of excitement among consumers. Unlike year-round citrus supplied through intensive commercial systems, Kodai orange remains a seasonal delicacy. This limited availability enhances its value and reputation. Consumers associate Kodai orange with freshness, authenticity, and hill origin, often preferring it over imported or off-season citrus. Local markets in Tamil Nadu see a surge in demand during the Kodai orange season, with traders sourcing fruit directly from hill farmers. Seasonality also reflects the fruit's natural production cycle, reinforcing the idea that quality is closely tied to respecting ecological rhythms rather than forcing continuous output.

Nutritional Value and Health Appeal

Kodai orange is valued not only for taste but also for nutrition. Like other citrus fruits, it is an excellent source of vitamin C, which supports immune function, skin health, and antioxidant protection. The fruit also provides dietary fiber, contributing to digestive health and satiety. Hill-grown citrus is often perceived as more “natural” and wholesome, free from excessive chemical residues. While scientific comparisons vary, consumer trust in Kodai orange stems from traditional cultivation practices and minimal processing. The refreshing nature of Kodai orange makes it particularly popular during warmer months. Its juice is hydrating, mildly energizing, and easy to digest, making it suitable for all age groups.

Cultural and Social Significance

In Thandigudi, Kodai orange is woven into everyday life. It is not merely a crop but a seasonal marker that shapes local routines and economic activity. Harvest periods bring increased labour demand, market interactions, and social exchange. For many farming families, orange trees planted by earlier generations continue to provide income and identity. Orchards are often associated with family heritage, and knowledge related to tree care and harvesting is shared within households and communities. Kodai orange has also become part of the cultural image of the Palani Hills, often mentioned alongside other hill produce. For visitors, purchasing Kodai orange is seen as taking home a piece of the hills.

Economic Importance for Hill Farmers

Kodai orange plays a crucial role in the hill economy of Thandigudi. For small and marginal farmers, it provides a dependable source of seasonal income. Even modest orchards can generate meaningful returns when fruit quality is high and market demand is strong. Because Kodai orange is recognized for its unique taste, it often commands a premium price compared to ordinary oranges. This price advantage helps offset the higher costs associated with hill farming, including transport and labour. Beyond direct income, orange cultivation supports ancillary activities such as packing, transport, and local trade. The crop thus contributes to a broader rural value chain that sustains livelihoods across the region.

Challenges Facing Kodai Orange Cultivation

Despite its strengths, Kodai orange cultivation faces several challenges. Aging orchards are a major concern, as many trees are beyond their peak productive years. Replanting is often delayed due to high establishment costs and the time required for new trees to bear fruit. Pest and disease pressures, including citrus decline and insect infestations, pose serious threats. Limited access to quality planting material and scientific advisory services further complicates management. Climate variability is another growing challenge. Changes in rainfall patterns, rising temperatures, and unexpected dry spells affect flowering, fruit set, and quality. Hill ecosystems are particularly sensitive to such changes, making adaptation essential. Market-related challenges also exist. Price fluctuations, dependence on middlemen, and lack of organized branding can reduce farmer profitability despite strong consumer demand.

Kodai Orange and the Question of Identity

As citrus from various regions enters markets under generic labels, preserving the identity of Kodai orange has become increasingly important. Consumers often seek Kodai orange specifically, valuing its hill origin and distinctive taste. There is growing discussion around the need to formally recognize Kodai orange as a

geographically unique product. Such recognition could help protect its reputation, ensure fair prices for farmers, and prevent mislabeling. Strengthening this identity requires coordinated efforts involving farmers, researchers, and policymakers. Documentation of traditional practices, quality traits, and regional characteristics is a crucial step in this direction.

Sustainability and the Hill Ecosystem

Kodai orange cultivation in Thandigudi is closely linked to the health of the hill ecosystem. Mixed cropping, shade trees, and organic matter recycling contribute to ecological balance. These practices reduce erosion, improve soil fertility, and support biodiversity. Sustainable management is not just an environmental concern but an economic necessity. The long-term viability of Kodai orange depends on conserving soil, water, and climate stability. Encouraging eco-friendly practices, efficient water use, and integrated pest management can help safeguard both fruit quality and environmental health.

Scope for Improvement and Revival

There is significant scope to revive and strengthen Kodai orange cultivation in Thandigudi. Rejuvenation of old orchards through pruning or replanting, introduction of improved yet locally adapted planting material, and better nutrient management can enhance productivity. Post-harvest handling and marketing also offer opportunities. Improved grading, packaging, and direct marketing can increase returns and reduce losses. Promoting Kodai orange through farmers' markets, branding initiatives, and agri-tourism can further enhance visibility. Extension support and farmer training are essential to bridge the gap between traditional knowledge and modern horticultural science, ensuring that improvements respect local context.

Kodai Orange in the Future

The future of Kodai orange lies in balancing tradition with innovation. Preserving the qualities that make the fruit special taste, aroma, and hill identity must go hand in hand with addressing modern challenges. With rising consumer interest in regional, authentic, and sustainably produced foods, Kodai orange is well positioned to gain renewed attention. Strengthening farmer collectives, improving market access, and highlighting the fruit's unique story can help secure its place in evolving food systems.

Conclusion

Kodai orange is not just a citrus fruit grown in the hills; it is a living expression of Thandigudi's landscape, climate, and farming culture. Its distinctive flavour, seasonal charm, and economic value make it a jewel in the truest sense rare, cherished, and deeply rooted in place. As agriculture faces the pressures of climate change, market volatility, and changing consumer expectations, Kodai orange reminds us of the value of region-specific crops nurtured through generations of experience. Protecting and promoting this hill fruit is not only about preserving a commodity, but about sustaining livelihoods, ecosystems, and cultural heritage. In celebrating Kodai orange as the jewel of the Thandigudi hills, we affirm the importance of local agriculture in shaping resilient and meaningful food systems for the future.

Application of Omics Approaches for Seed Health and Disease Management



Dr. M. Madhavi, Mr. Shaik Shareef, Dr. V. Anitha and Dr. B. Pushpavathi

Agricultural College, Palem, Professor Jayashankar Telangana Agricultural University,
Hyderabad- 500 030

Introduction

Seed-borne diseases play a critical role in the dissemination of plant pathogens across geographical regions and growing seasons. Infected seeds not only reduce germination and vigour but also act as carriers of fungal, bacterial, viral and nematode pathogens that initiate disease epidemics in the field. Traditional seed health testing methods such as visual inspection, blotter tests and culturing techniques are time-consuming and often ineffective in detecting dormant or low-level infections. Moreover, chemical seed treatments provide limited protection and raise environmental concerns. In this context, omics technologies have emerged as advanced molecular tools that enable a detailed understanding of seed-borne pathogens and host responses, thereby supporting effective and sustainable disease management strategies.

Genomics in Seed-Borne Disease Management

Genomics involves the comprehensive analysis of an organism's genome and has become a cornerstone in plant disease research. Whole-genome sequencing of seed-borne pathogens allows precise identification and differentiation of closely related species and strains. Genomic studies facilitate the identification of genes associated with pathogenicity, virulence, toxin production, and survival within seeds. In crop plants, genomics aids in the discovery of resistance genes and quantitative trait loci linked to resistance against seed-borne diseases. These genetic markers are extensively used in marker-assisted selection and genomic selection programs, accelerating the development of resistant crop varieties and reducing reliance on chemical control measures.

Transcriptomics and Host-Pathogen Interactions

Transcriptomics focuses on the analysis of gene expression patterns by studying messenger RNA under specific biological conditions. In seed-borne disease research, transcriptomic analysis provides insights into molecular interactions between host seeds and invading pathogens. This approach identifies genes that are differentially expressed during seed infection, dormancy, and germination. It reveals activation of plant defense pathways such as salicylic acid, jasmonic acid, and ethylene signaling. Additionally, transcriptomics helps identify pathogen genes that are actively expressed during seed colonization, offering potential targets for early detection and disease intervention.

Proteomics and Functional Insights

Proteomics is the large-scale study of proteins, which are the functional molecules driving biological processes. In seed-borne disease management, proteomic approaches enable the detection of pathogen-derived proteins even when pathogen populations are low or inactive. This technique helps identify virulence factors, including enzymes, toxins, and effector proteins involved in infection and seed deterioration. Proteomics also facilitates the identification of host defense proteins such as pathogenesis-related proteins and antimicrobial peptides that contribute to resistance. By linking gene expression to functional outcomes, proteomics enhances understanding of disease mechanisms at the cellular level.

Metabolomics and Disease Biomarkers

Metabolomics involves the analysis of small molecular metabolites produced during metabolic processes. Infected seeds exhibit distinct metabolic changes compared to healthy seeds, making metabolomics a valuable tool for disease diagnosis. This approach enables detection of mycotoxins such as aflatoxins, ochratoxins, and fumonisins produced by seed-borne fungal pathogens, which pose serious risks to food and feed safety. Metabolomic studies also help elucidate resistance mechanisms by identifying defensive compounds such as phenolics, phytoalexins, and antioxidants that inhibit pathogen growth and enhance seed protection.

Metagenomics and Seed Microbiome

Metagenomics is a culture-independent approach that analyzes the collective genetic material of microbial communities associated with seeds. This technique allows simultaneous detection of pathogenic, beneficial, and neutral microorganisms present in or on seeds. Metagenomic analysis is particularly useful for identifying unculturable and latent pathogens that escape conventional detection methods. Furthermore, it helps identify beneficial microbes that suppress seed-borne pathogens through competition, antibiosis, or induced resistance. Such insights support the development of microbiome-based seed treatments and biological control strategies.

Epigenomics and Durable Resistance

Epigenomics focuses on heritable changes in gene expression that occur without alterations in the DNA sequence. Epigenetic mechanisms such as DNA methylation and histone modification regulate plant defense responses against seed-borne pathogens. Studies suggest that plants can develop stress memory, where exposure to pathogens induces epigenetic changes that enhance resistance in subsequent generations. Understanding epigenetic regulation of defense genes provides new opportunities for developing durable and long-lasting resistance in crop plants.

Integrated Multi-Omics Approaches

Integration of multiple omics approaches, referred to as multi-omics, provides a holistic understanding of seed-borne diseases by linking genomic information with gene expression, protein function, and metabolic changes. Multi-omics strategies improve diagnostic accuracy, enhance understanding of pathogen biology, and accelerate resistance breeding. Although challenges such as high cost, data complexity, and the need for bioinformatics expertise remain, continuous technological advancements are facilitating broader adoption of multi-omics approaches in seed health management.

Conclusion

Omics technologies have significantly advanced the management of seed-borne diseases by enabling early detection, precise pathogen identification, and comprehensive analysis of host-pathogen interactions. The application of genomics, transcriptomics, proteomics, metabolomics, metagenomics and epigenomics supports resistance breeding, biological control and sustainable disease management practices. Integration of these approaches into seed health testing and crop improvement programs holds great potential for reducing crop losses, improving seed quality and ensuring global food security.

Soil Health Cards: Helping Farmers Grow Smarter and Sustain their Soils



Dr. S.R. Padma

Assistant Professor (Agricultural Extension)
Tamil Nadu Agricultural University, Coimbatore

Introduction

Healthy soil is the foundation of successful farming. To help farmers understand their soil better and use fertilizers wisely, the Government of India introduced the Soil Health Card (SHC) scheme. The card provides farmers with information about the nutrient status of their fields along with simple recommendations for crop-wise fertilizer use. This popular article explains what Soil Health Cards are, why they matter, how farmers benefit from them, and how the scheme supports sustainable agriculture and income security.

Understanding the Importance of Soil Health

Soil is more than just land—it is a living system that supports crops, microbes, and nutrients essential for plant growth. Over the years, continuous cultivation, excessive use of chemical fertilizers, and limited organic inputs have reduced soil fertility in many regions. As a result, farmers often face declining yields, higher input costs, and poor crop response. Maintaining soil health has therefore become a major concern for sustainable agriculture.

What Is a Soil Health Card?

A Soil Health Card is a simple report given to farmers after testing soil samples from their fields. It shows the status of key nutrients such as nitrogen, phosphorus, potassium, organic carbon, and micronutrients. Based on these results, the card provides crop-specific recommendations on the type and quantity of fertilizers and soil amendments required. In easy terms, it acts as a “health report” for the soil, guiding farmers on how to nourish their fields properly.

Why the Soil Health Card Matters

Many farmers traditionally apply fertilizers based on guesswork or past experience. While this may sometimes work, it often leads to overuse or underuse of nutrients. Soil Health Cards help replace this uncertainty with scientific guidance. By following SHC recommendations, farmers can avoid unnecessary fertilizer expenses, prevent soil degradation, and improve crop productivity. Balanced nutrient application also reduces environmental pollution and protects groundwater from chemical contamination.

Benefits Experienced by Farmers

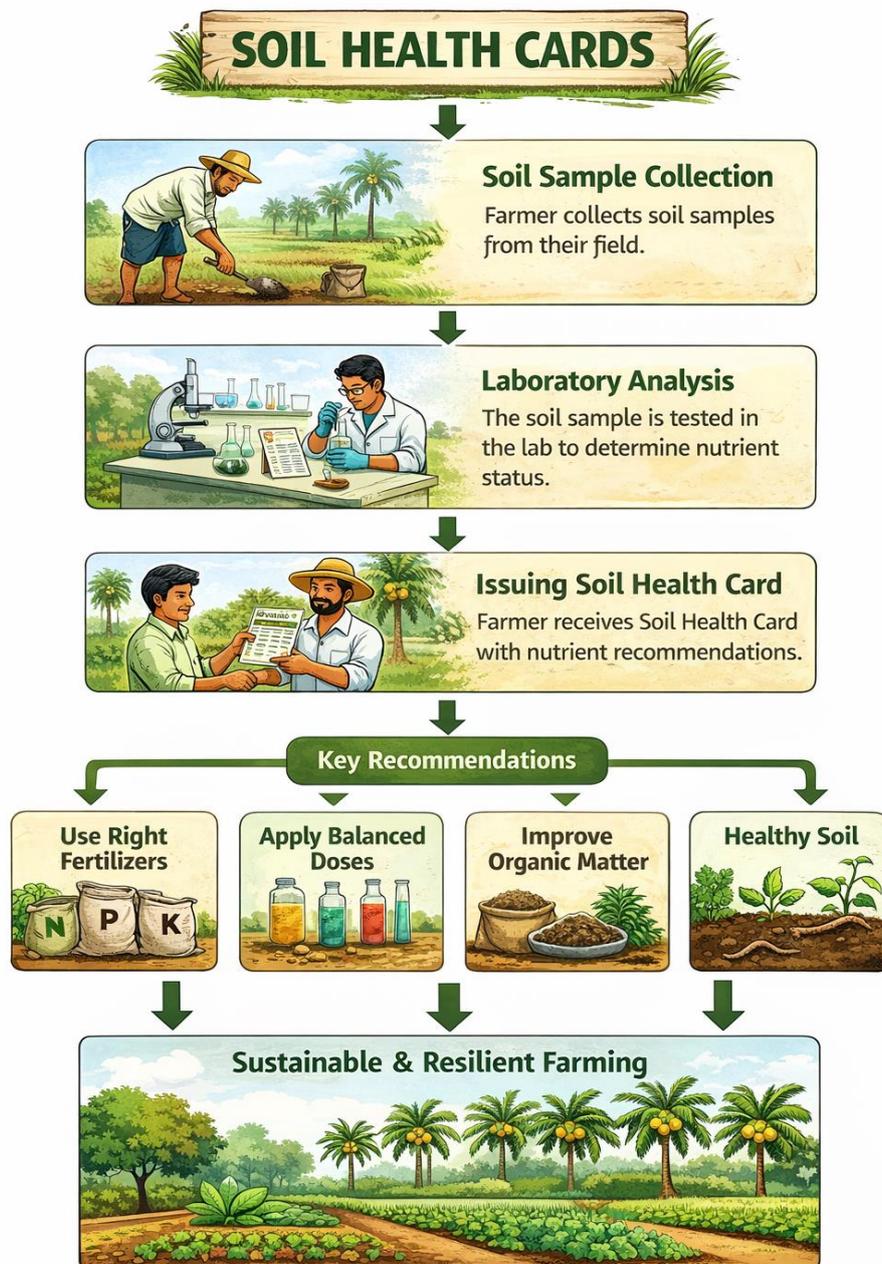
Farmers using Soil Health Cards often report better crop growth and more efficient input use. With clear guidance on nutrient requirements, they are able to reduce excess fertilizer application and adopt more balanced practices. This leads to lower cultivation costs and improved net income. Many farmers also observe gradual improvement in soil structure and fertility when SHC recommendations are combined with organic manures and crop residues. Over time, this contributes to stable yields and healthier farms.

Encouraging Sustainable Farming Practices

The Soil Health Card scheme promotes sustainable agriculture by encouraging integrated nutrient management. Farmers are guided to combine chemical fertilizers with organic inputs such as farmyard manure, compost, green manure, and biofertilizers. This approach not only improves soil fertility but also enhances microbial activity and water-holding capacity. By understanding their soil better, farmers become more conscious of conserving natural resources while producing food.

Role of Extension Services

Agricultural extension officers play a key role in helping farmers interpret Soil Health Cards and apply recommendations effectively. Through training programs, demonstrations, and village meetings, they explain soil test results in simple language and guide farmers on fertilizer scheduling. Farmer awareness programs also encourage peer learning, where experienced users of SHCs share their success stories with others.



Challenges and the Way Forward

Despite its benefits, some farmers face difficulties in fully adopting Soil Health Card recommendations. Limited awareness, delayed card distribution, lack of follow-up guidance, and access to recommended inputs remain challenges. Strengthening extension support, ensuring timely soil testing, and improving availability of fertilizers and organic inputs can help overcome these barriers. Digital tools and mobile-based advisories can further enhance the reach of soil health information.

Conclusion

Soil Health Cards empower farmers with knowledge about their most valuable resource—the soil. By promoting balanced nutrient use and sustainable practices, the scheme helps improve crop productivity, reduce costs, and protect the environment. When combined with continuous guidance and farmer participation, Soil Health Cards can play a vital role in building resilient and profitable farming systems for the future.

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Hidden Engineers of Soil: How Insects Shape Soil Fertility



M.C. Narendran, Teresa Mary Agastian, R. Jebisha, P. Kavin, S. Muthu mari,
B.S.M. Narmada, O.M. Ramiashree

Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, UT of
Puducherry

Abstract

Soil fertility emerges from complex and dynamic interactions among the physical, chemical, and biological components that collectively determine soil productivity. While microorganisms such as bacteria and fungi are well known for their pivotal role in nutrient cycling and organic matter decomposition, soil insects and arthropods form an equally crucial but often underappreciated biological group. These organisms function as ecosystem engineers, actively modifying soil structure, regulating soil porosity, and enhancing the distribution of organic matter through their feeding, burrowing, tunneling, and nesting behaviors. By breaking down complex organic residues and enhancing microbial access to substrates, soil insects accelerate organic matter decomposition and improve nutrient availability for plants. Species such as ants, termites, beetles, collembolans, and mites significantly contribute to soil aggregation, aeration, mineralization, and stabilization of soil organic carbon. This review synthesizes and expands upon existing knowledge about the ecological and functional roles of soil insects in improving soil fertility. Additionally, it highlights the importance of conserving soil fauna in modern sustainable and climate-resilient agricultural strategies.

Keywords: Soil insects, ecosystem engineers, soil fertility, nutrient transformation, soil biodiversity, sustainable agriculture.

1. Introduction (Elaborated)

Soil is not merely a substrate for plant growth but a dynamic living ecosystem composed of mineral particles, organic matter, water, air, and an immense diversity of organisms. Historically, soil fertility research has placed heavy emphasis on chemical and microbial attributes such as nutrient availability, soil pH, electrical conductivity, organic carbon content, and microbial biomass. However, a large and functionally important group—soil insects and arthropods—has often been neglected in soil health assessments.

Soil insects influence soil function both directly and indirectly. Their **feeding activities** break down leaf litter, dead roots, and organic residues into smaller fragments, accelerating decomposition rates. Their **burrowing and tunneling behaviors** create biopores that enhance air circulation, water infiltration, and root penetration. These physical alterations foster a more favorable environment for microorganisms, which in turn sustain nutrient cycling. Furthermore, their **nest-building activities** redistribute mineral and organic particles, affecting nutrient patchiness and microhabitat formation within the soil. Thus, soil insects serve as an essential link between soil structure, nutrient dynamics, and biological functioning.

2. Diversity and Functional Classification of Soil Insects (Elaborated)

Soil insects and arthropods belong to diverse taxonomic groups including ants (Formicidae), termites (Isoptera), beetles (Coleoptera), springtails (Collembola), mites (Acari), and immature stages of multiple insect orders. Their distribution and function vary widely depending on their ecological niches.

• Epigeic Organisms (Surface Dwellers)

Epigeic insects inhabit the litter layer on the soil surface. Examples include springtails, litter beetles, and various dipteran larvae. They feed on fresh leaf litter, fungi, and decomposing plant residues. Their major contributions include fragmentation of organic matter and initiation of early decomposition processes.

• Endogeic Organisms (Upper Soil Layer Dwellers)

These insects, such as certain mites and beetle larvae, live within the upper mineral soil horizons. They feed on soil organic matter that is already partially decomposed. Their burrowing within these layers results in continuous mixing of organic and mineral particles, improving soil porosity and structure.

- **Anecic Organisms (Deep Burrowers)**

Anecic insects include termites and some ant species that build deep vertical tunnels or elaborate mounds. These insects incorporate organic matter from the surface into deeper layers, influencing vertical nutrient redistribution. Termites, for example, are key decomposers of wood and cellulose, contributing to long-term carbon cycling. Each of these functional groups plays a unique and complementary role in improving soil mixing, residue incorporation, microbial interactions, and nutrient enrichment.

3. Soil Insects as Ecosystem Engineers (Elaborated)

Soil insects are often termed **ecosystem engineers** because of their ability to structurally modify the soil environment. Their engineering activities have far-reaching impacts on soil health.

- **Burrowing and Tunneling**

Insects such as ants and beetle larvae create networks of tunnels and galleries that enhance soil porosity. This improves aeration, gas exchange, microbial activity, and root penetration. The tunnels also act as natural drainage channels that facilitate downward water movement, reducing waterlogging in heavy soils.

- **Aggregation and Soil Mixing**

As insects move through soil layers, they mix organic matter with mineral particles, creating microaggregates. Ants and termites often transport fine clay particles to the surface or into their nests, altering soil texture and structure over time.

- **Nest-Building and Soil Redistribution**

Termite mounds and ant anthills are hotspots of biochemical activity. They accumulate organic matter, nutrients, and microbial biomass, forming fertile patches within the landscape. These nests also stabilize soil surfaces and can significantly improve resistance against erosion.

- **Reduction in Bulk Density**

The creation of biopores reduces soil compaction, making the soil more friable. This enhances root growth, nutrient uptake, and overall plant productivity.

Through these activities, soil insects significantly modify the micro- and macro-structure of soils, leading to enhanced soil fertility.

4. Contribution to Nutrient Cycling (Elaborated)

Soil insects are integral to nutrient cycling processes due to their role in decomposition and organic matter turnover.

- **Fragmentation of Organic Residues**

By breaking down coarse plant residues into smaller particles, insects increase the surface area available for microbial attack and speed up decomposition.

- **Production of Nutrient-Rich Excreta (Frass)**

Insect frass is rich in readily available nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients. These nutrients can be directly absorbed by plant roots or further transformed by microbes.

- **Mineralization and Humus Formation**

Gut microorganisms within insects—especially termites—produce enzymes that break down cellulose, lignin, and hemicellulose. This contributes to the mineralization of nutrients and long-term humus formation, improving soil organic carbon.

- **Nutrient Redistribution**

Anecic species transport organic residues deep into the soil profile, contributing to vertical nutrient cycling. Ants often carry seeds and organic debris into their nests, enriching subsoil layers.

Overall, soil insects enhance the rate and efficiency of nutrient cycling, making essential nutrients more available to plants.

5. Interaction with Soil Microorganisms (Elaborated)

Soil insects and microorganisms share a symbiotic relationship, benefiting each other in multiple ways.

- **Enhancement of Microbial Habitats**

Burrows created by insects serve as microhabitats with stable temperatures, moisture levels, and aeration—ideal for microbial colonization. These hotspots often exhibit high enzymatic activity and rapid nutrient turnover.

• Gut Microbial Symbiosis

Termites, in particular, rely on symbiotic microorganisms such as protozoa and bacteria to digest cellulose. These microbes produce enzymes that insects cannot synthesize themselves, facilitating decomposition of tough plant materials.

• Microbial Dispersion

As insects move through the soil, they inadvertently transport microbial cells, spores, and enzymes across different soil microhabitats. This promotes microbial diversity and functional redundancy.

• Enzyme Enhancement

The presence of soil insects increases the activity of soil enzymes such as dehydrogenases, ureases, cellulases, and phosphatases, which facilitate decomposition and nutrient release.

Through these interactions, insects enhance microbial community structure and activity, thereby improving overall soil fertility.

6. Soil Aggregation and Structural Stability (Elaborated)

Soil insects contribute directly to building and stabilizing soil aggregates, which are essential for soil quality.

• Organic Secretions as Binding Agents

Insects produce saliva, mucus, and other organic adhesives that bind soil particles together. These secretions act as natural “glues,” forming stable microaggregates.

• Incorporation of Organic Matter

Insects integrate plant residues into soil aggregates, contributing to long-term carbon sequestration and improved soil structure.

• Termite-Modulated Soil Structure

Termite activity often creates soils with higher clay content, better aggregate stability, and improved resistance to erosion. These soils exhibit enhanced infiltration and reduced susceptibility to crusting.

• Enhanced Soil Porosity

The micro- and macro-pores created by insects allow better water movement, reduce compaction, and increase soil aeration—all critical for plant growth.

These structural improvements enhance soil health and make the soil more resilient to environmental stress.

7. Role in Sustainable and Climate-Resilient Agriculture (Elaborated)

Soil insects provide ecological services that align closely with the principles of sustainable and climate-resilient agriculture.

• Improved Water-Holding Capacity

By improving soil aggregation and pore structure, insects enhance the soil’s ability to retain water—critical in drought-prone areas.

• Reduction of Soil Erosion

Insect-modified soils exhibit improved aggregate stability and reduced surface runoff, helping prevent topsoil loss.

• Soil Organic Carbon Sequestration

Through decomposition, humification, and bioturbation, insects contribute to the long-term storage of carbon in soil. This helps mitigate climate change by lowering atmospheric CO₂.

• Enhanced Nutrient-Use Efficiency

Nutrient hotspots created by insects enable plants to access nutrients more efficiently, reducing dependence on synthetic fertilizers.

• Promotion of Biodiversity

Healthy insect populations support diverse microbial communities and enhance soil ecosystem resilience against climatic fluctuations.

Thus, integrating soil fauna conservation into agricultural systems strengthens ecological stability and improves crop productivity.

8. Conclusion

Soil insects serve as vital yet often overlooked components of soil ecosystems. Their roles go far beyond simple decomposition—they alter physical soil properties, enhance nutrient dynamics, and support microbial communities. Their collective actions significantly improve soil fertility, structural stability, and ecological resilience. Recognizing their importance and incorporating soil fauna management into agricultural practices can enhance soil health, minimize degradation, and promote sustainable and climate-resilient farming systems. Protecting and encouraging soil insect biodiversity therefore represents a crucial step toward building productive and ecologically stable agricultural landscapes.



The Silent War Beneath Our Crops: Plants vs. Pathogens



¹Meh Run Nisa, ²Ranbir Singh and ³Laxmi Devi

¹Ph.D. Scholar, Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu-180009

²Professor, Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu-180009

³Ph.D. Scholar, Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu-180009

Abstract

Every crop field at any given moment is a battlefield. Beneath the calm of green leaves, plants are continuously defending themselves against pathogens such as fungi, bacteria, viruses and nematodes that have co-evolved with them for hundreds of millions of years. This communication examines how plants perceive pathogen invasion, mount layered immune responses from PAMP-Triggered Immunity (PTI) to Effector-Triggered Immunity (ETI) and develop systemic memory through Systemic Acquired Resistance (SAR). Understanding this molecular warfare is not merely academic with plant diseases costing global agriculture over \$200 billion annually and climate change expanding pathogen ranges decoding plant immunity is central to food security.

Keywords: Plant immunity, Pathogens, PTI, ETI, Systemic Acquired Resistance, Crop disease

Introduction

Plant pathogens are responsible for 20 to 40 per cent of global crop losses each year, a figure that translates directly into food insecurity for millions of people. The Irish Famine of the 1840s, driven by the oomycete *Phytophthora infestans* killed over a million people and displaced a million that reminds us that plant disease is not a peripheral agricultural concern but a civilizational one. Today, with *Fusarium oxysporum* Tropical Race 4 threatening global banana production and new rust races menacing wheat the stakes remain as high as ever. Yet plants are far from passive victims. They possess a sophisticated and multi-tiered immune system that has been refined over evolutionary time. This communication provides an overview of that system and its significance for modern crop protection.

The First Line: Physical and Molecular Barriers

A plant's defenses begin at its surface. The waxy cuticle, lignified cell walls and stomata which can close within minutes of detecting pathogen-associated signals constitute the first physical barrier against invasion. When these are breached, the plant's molecular surveillance system activates. Pattern Recognition Receptors (PRRs) on plant cell surfaces detect conserved microbial signatures called PAMPs (Pathogen-Associated Molecular Patterns) such as fungal chitin or bacterial flagellin. This recognition triggers PAMP-Triggered Immunity (PTI) a rapid cascade involving calcium influx, reactive oxygen species bursts, cell wall reinforcement with callose and a systemic hormonal alarm carried by salicylic acid, jasmonic acid and ethylene (Jones and Dangl, 2006). PTI is broad-spectrum, fast and effective against a wide range of invaders.

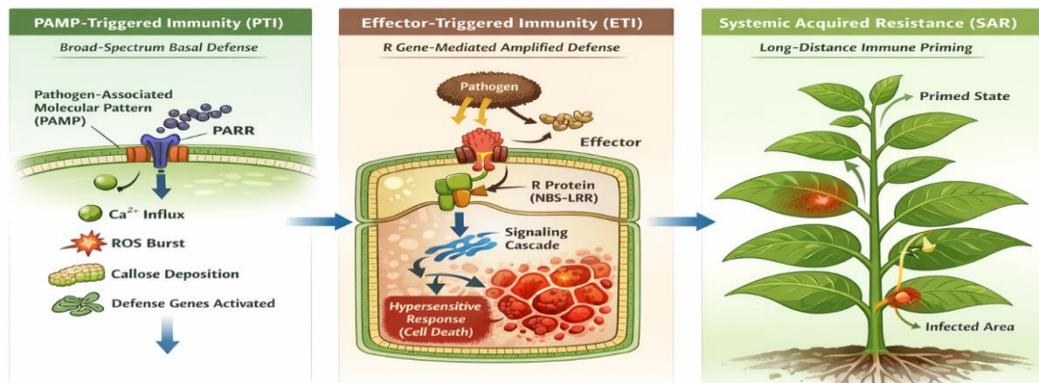
The Molecular Arms Race: Effectors and ETI

Pathogens have countered PTI by evolving effector proteins molecular saboteurs delivered directly into plant cells to disable immune signaling. Some effectors mimic host proteins while others chemically modify immune components. Plants in turn have evolved a second immune tier that is Effector-Triggered Immunity (ETI) mediated by intracellular NBS-LRR resistance (R) proteins encoded by R genes. These proteins act as intracellular sentinels that detect specific effectors and trigger an amplified immune response often culminating in the Hypersensitive Response (HR) a programmed death of infected cells that starves the pathogen of living tissue (Kourelis *et al.*, 2018). This co-evolutionary dynamic formalized as the gene-for-gene hypothesis by Harold Flor in the 1940s, remains a cornerstone of plant pathology and breeding.

Systemic Acquired Resistance: The Plant Remembers

One of the most remarkable features of plant immunity is its capacity for systemic priming. Following a localized infection, plants enter Systemic Acquired Resistance (SAR) a whole-plant state of heightened alertness mediated by salicylic acid. SAR induces Pathogenesis-Related (PR) proteins throughout the plant, including chitinases and glucanases that attack pathogen cell walls. Importantly, primed plants respond faster and more strongly to subsequent infections, a response linked to epigenetic remodeling of chromatin around defense genes (Luna *et al.*, 2012). This immune memory, structurally analogous to vertebrate immunological memory offers a biological basis for resistance that breeders and agronomists are increasingly seeking to exploit.

The Multi-Layered Plant Immune System



Why Plants Still Lose: The Monoculture Problem

Despite this sophisticated immunity, pathogens regularly overcome plant defenses most often where genetic diversity is absent. Agricultural monocultures by planting millions of acres of genetically identical varieties create landscapes in which a single successful pathogen mutation can spread unchecked. The Lumper potato's lack of *P. infestans* resistance genes caused the Irish Famine the near-total monoculture of the Cavendish banana today presents a parallel vulnerability to Tropical Race 4. Wild relatives of crop plants, by contrast, harbor extensive R gene diversity shaped by millions of years of co-evolution with local pathogen populations. Mining this diversity through conventional breeding, marker-assisted selection and gene editing is one of the central priorities of modern plant pathology.

Conclusion

The interaction between plants and pathogens is one of the most dynamic and consequential evolutionary relationships in nature. From PRR-mediated PAMP recognition to the gene-for-gene hypothesis of R genes and effectors, plants have evolved an immune system that is layered, adaptive and capable of systemic memory. Yet agricultural practices that sacrifice genetic diversity for yield uniformity leave this system chronically undermined. As climate change expands pathogen ranges and accelerates their evolution, understanding and harnessing plant immunity has never been more urgent. Integrating knowledge of these molecular mechanisms with modern tools such as CRISPR-based resistance editing, effectoromics, and microbiome-mediated ISR represents the most promising path toward durable crop protection and food security.

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RNA REVOLUTION: NON-CODING RNAs IN AQUACULTURE



Shasti Risha K¹, Rujan J², Kavimathy K R³

¹Fisheries Research Station, Andhra Pradesh Fisheries University, Undi

²Central Institute of Fisheries Education, Mumbai

³Central Marine Fisheries Research Institute, Kochi

Non-coding RNA (ncRNAs) are a critical regulatory component of the transcriptome, they regulate gene expression without the generation of protein products, but perform an important role in Gene expression. Each aquaculture species is becoming increasingly aware of the significance that ncRNA's play in the regulation of growth, immunity, stress tolerance, reproduction and adaptation to their environment as reported recently in the scientific literature; this can be attributed to a recent Paradigm shift whereby the use of Next Generation Sequencing (NGS) coupled with Long-read sequencing technologies has led to the improved characterisation of microRNA's (miRNA), long non-coding RNAs (lncRNA) & circular RNAs (circRNA). Indeed, the application of bioinformatic tools and network approaches has allowed researchers to comprehend the functional pathways and complex regulatory modes of machinery mediated via ncRNA's, to better understand traits of economic significance.

Introduction

Aquaculture has emerged as one of the fastest-growing food production sectors, contributing significantly to global food and nutritional security. However, intensification of aquaculture practices has led to increased susceptibility to disease outbreaks, environmental stress, and inconsistent growth performance (Yanez et al., 2023). Addressing these challenges requires a deeper understanding of molecular regulatory mechanisms that control physiological responses and adaptive traits in cultured species. Although early genetic studies largely focused on protein-coding genes, it is now evident that a substantial portion of the genome is transcribed into non-coding RNAs (Wang et al., 2018). These transcripts regulate gene expression at transcriptional, post-transcriptional, and epigenetic levels. In fish, ncRNAs exhibit dynamic, tissue-specific, and condition-dependent expression patterns, making them highly relevant for studies related to growth regulation, immune competence, stress adaptation, and environmental resilience in aquaculture systems (Hu et al., 2022).

Classification of Non-Coding RNAs in Fish

Non-coding RNAs are broadly classified based on their length and molecular function. Small ncRNAs, including miRNAs, small interfering RNAs (siRNAs), and piwi-interacting RNAs (piRNAs), are generally less than 200 nucleotides long and primarily regulate gene expression at the post-transcriptional level (Hu et al., 2022). Among these, miRNAs are the most extensively studied in aquaculture species due to their evolutionary conservation and regulatory efficiency. Long non-coding RNAs are transcripts longer than 200 nucleotides and exhibit substantial structural and functional diversity. They are involved in transcriptional regulation, chromatin modification, and post-transcriptional control through interactions with DNA, RNA, and proteins. Circular RNAs, generated through back-splicing events, form covalently closed loops that confer high stability and resistance to exonuclease degradation. Increasing evidence suggests that long non-coding RNAs (lncRNAs) and circular RNAs (circRNAs) interact with microRNAs (miRNAs) and messenger RNAs (mRNAs) through competing endogenous RNA (ceRNA) networks, adding complexity to gene regulatory systems in fish (Amin et al., 2019).

Functions of ncRNAs in fish biology

Regulation of Growth and Development

Growth is a critical economic trait in aquaculture, and ncRNAs have been implicated in the regulation of muscle development, metabolism, and cell proliferation. Recent transcriptomic studies comparing fast- and slow-growing fish strains have identified differentially expressed miRNAs and lncRNAs associated with growth-related pathways, including the growth hormone–insulin-like growth factor and mTOR signaling pathways (Cao et al., 2024). These ncRNAs influence myogenesis, protein synthesis, and energy metabolism, contributing to variation

in growth performance. Long non-coding RNAs also exhibit dynamic expression patterns during embryonic development and tissue differentiation, suggesting regulatory roles in early developmental processes and organ formation (Deng et al., 2022).

Immune Response and Disease Resistance

NcRNAs play a central role in regulating immune responses in fish. Upon pathogen exposure, specific miRNAs and lncRNAs are differentially expressed and modulate immune-related signaling pathways such as Toll-like receptor, NF- κ B, and cytokine-mediated pathways (Zhao et al., 2023). Recent studies employing long-read sequencing and integrated transcriptomic approaches have demonstrated that ncRNAs regulate key immune genes during bacterial and viral infections, influencing host defense mechanisms and disease susceptibility (Wang et al., 2018). These findings highlight the potential of immune-responsive ncRNAs as molecular markers for disease resistance and health monitoring in aquaculture.

Role of ncRNAs in Stress and Environmental Adaptation

Aquatic organisms are frequently exposed to environmental stressors, including temperature fluctuations, salinity changes, hypoxia, and ocean acidification. NcRNAs act as molecular regulators that mediate stress-responsive gene expression. Recent investigations have revealed widespread changes in miRNA, lncRNA, and circRNA expression profiles in fish subjected to environmental stress, implicating ncRNAs in oxidative stress management, metabolic reprogramming, neural signaling, and cellular homeostasis (Yang et al., 2023). Such regulatory flexibility underscores the role of ncRNAs in phenotypic plasticity and adaptive capacity, which are essential for sustaining productivity under changing environmental conditions.

Recent Analytical Methods for Fish ncRNA Research

Technological advances have significantly accelerated ncRNA research in aquaculture species. High-throughput RNA sequencing remains the primary approach for discovering and profiling non-coding RNA (ncRNA). The adoption of long-read sequencing platforms, such as Single Molecule Real-Time sequencing, has enhanced transcript annotation by resolving full-length long non-coding RNAs (lncRNAs) and accurately distinguishing them from protein-coding transcripts (Micheel et al., 2021). Bioinformatic tools essential for identification and analysis of non-coding RNAs were enlisted along with their biological functions were summarized in Table.1. Experimental validation using quantitative real-time PCR remains essential for confirming transcriptomic results.

Applications of ncRNAs in Aquaculture

Biomarkers and Selective Breeding

NcRNAs with stable expression differences correlated with desirable traits (e.g., growth rate, disease tolerance) can function as molecular biomarkers (Wang et al., 2017; Hu et al., 2022). Integrating ncRNA profiles into selective breeding programs enhances precision and accelerates genetic improvements (Yin et al., 2023; Yáñez et al., 2023).

Nutrigenomics and Feed Optimization

Diet composition influences ncRNA expression, suggesting opportunities for nutrigenomic strategies to modulate gene expression for better feed efficiency and stress tolerance (Hu et al., 2022; Alhoshy et al., 2022). These approaches target miRNAs and lncRNAs in liver, muscle, and adipose tissues to optimize nutrient utilization in aquaculture species (Hu et al., 2022).

Therapeutic Potential

MiRNA mimics or inhibitors act as RNA interference agents to suppress viral replication, like WSSV in shrimp, by targeting pathogen genes (Wang et al., 2017; Sangchai et al., 2025). lncRNA-miRNA-mRNA networks offer targets for vaccines or feed additives enhancing resistance in integrated systems (Huo et al., 2020). These strategies align with biotechnology advances for sustainable aquaculture (Sangchai et al., 2025).

Environmental Monitoring

NcRNA expression signatures may serve as sensitive indicators of environmental stress or water quality impacts on cultured fish, supporting timely management interventions (Huo et al., 2020; Cai et al., 2022). lncRNAs like lncMPEG1 respond to heat, hypoxia, and shell damage in species such as sea cucumbers, aiding biomineralization and stress detection (Cai et al., 2022).

Table.1. Major Non-Coding RNA Types, Bioinformatic Approaches, and Functional Roles in Aquaculture

Type of ncRNA	Primary Analytical Tools / Methods	Purpose of Tools	Major Biological Functions in Fish and Aquaculture
MicroRNAs (miRNAs)	Small RNA-Seq, miRDeep2, miRBase, Bowtie, DESeq2, edgeR	Identification, annotation, quantification, and differential expression analysis	Post-transcriptional regulation of gene expression; regulation of growth hormone-IGF axis, muscle differentiation, immune signaling, antiviral defense, stress response, and metabolism
Long Non-Coding RNAs (lncRNAs)	RNA-Seq, StringTie, FEELnc, CPC2, CNCI, CPAT, BLASTn	Transcript assembly, coding potential prediction, classification of lncRNAs	Transcriptional and epigenetic regulation; modulation of growth, immune response, reproduction, development, stress tolerance, and chromatin remodeling
Circular RNAs (circRNAs)	RNA-Seq, CIRI, find_circ, circExplorer2, STAR	Detection of back-splicing events and circRNA identification	miRNA sponging, regulation of parental gene expression, immune modulation, developmental regulation, and stress adaptation
Small Interfering RNAs (siRNAs)	RNA-Seq, ShortStack, Bowtie	Identification and mapping of siRNA loci	RNA interference-mediated gene silencing; antiviral defense and genome stability
Piwi-interacting RNAs (piRNAs)	RNA-Seq, proTRAC, piRBase	Detection and annotation of piRNA clusters	Germline development, transposon silencing, reproductive regulation
Competing Endogenous RNA Networks (ceRNA)	miRanda, TargetScan, RNAhybrid, StarBase, Cytoscape	Prediction and visualization of lncRNA-miRNA-mRNA and circRNA-miRNA-mRNA networks	Integrated regulation of gene expression influencing growth, immunity, stress tolerance, and development
Differential Expression Analysis (All ncRNAs)	DESeq2, edgeR, limma	Statistical identification of differentially expressed ncRNAs	Identification of condition-specific ncRNA signatures related to disease, stress, nutrition, and growth
Co-expression and Network Analysis	WGCNA, Cytoscape	Construction of gene-ncRNA interaction modules	Functional prediction of ncRNAs and identification of trait-associated regulatory modules

Conclusion

Non-coding RNAs (ncRNAs) are at the forefront of innovation for aquaculture as a crossover between molecular biology and functional application (disease control, breeding and sustainability). Recent studies are determining the functions of each ncRNA and functionally validating them through the use of CRISPR-based editing and high-throughput screening in commercially exploited species (e.g., shrimp and salmon) to speed up the process of moving research from the laboratory to the farm.

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BENEFITS OF ARTIFICIAL INTELLIGENCE IN AGRICULTURE



T. Tarun Kshatriya

Department of Soil Science & Agricultural Chemistry, Tamil Nadu Agricultural University,
Coimbatore – 641003

Abstract

Artificial Intelligence (AI) is rapidly transforming the agricultural sector by enabling data-driven decision-making, improving resource efficiency, and enhancing productivity. With increasing pressure on global food systems due to population growth, climate variability, and limited natural resources, modern agriculture requires innovative technological solutions. AI technologies such as machine learning, computer vision, robotics, and predictive analytics help farmers monitor crops, assess soil conditions, optimize irrigation, detect diseases, and forecast yields. These intelligent systems integrate data from sensors, drones, satellites, and farm machinery to provide accurate insights for farm management. The adoption of AI not only increases agricultural productivity but also promotes sustainable practices by reducing chemical inputs, conserving water, and minimizing environmental impact. This article discusses the major benefits of AI in agriculture, including precision farming, crop monitoring, pest and disease management, irrigation optimization, soil health analysis, yield prediction, automation, supply chain efficiency, climate change adaptation, and digital advisory services. The discussion highlights how AI-driven technologies can support resilient and sustainable farming systems while improving economic outcomes for farmers.

Keywords: Artificial Intelligence, Precision Agriculture, Smart Farming, Sustainable Agriculture

Introduction

Agriculture is undergoing a major transformation as digital technologies become more integrated into farming practices. Traditional agriculture has relied heavily on manual observations and experience-based decisions. While these approaches remain valuable, they are often insufficient to handle modern challenges such as climate change, soil degradation, water scarcity, and increasing demand for food. Artificial Intelligence (AI) has emerged as a powerful solution that can help farmers manage these challenges through automation, data analysis, and predictive decision-making.

AI refers to computer systems capable of learning from data, recognizing patterns, and making intelligent decisions with minimal human intervention. In agriculture, AI systems collect information from various sources, including weather stations, soil sensors, satellite imagery, drones, and agricultural machinery. This data is analyzed to provide recommendations that help farmers optimize crop management practices.

The benefits of AI in agriculture go beyond increasing crop yield. AI helps reduce production costs, minimize environmental impact, and improve resilience against climate-related risks. As farming becomes more complex, AI-based technologies are enabling farmers to adopt precision agriculture, improve sustainability, and ensure long-term food security. The following sections explore the key benefits of AI and its growing role in modern agricultural systems.

1. Precision Farming and Efficient Resource Use

Precision farming is one of the most significant advantages of AI in agriculture. It involves applying the right amount of inputs such as fertilizers, pesticides, and water at the right time and location. AI algorithms analyze spatial data from sensors and satellite imagery to identify variations within fields. This helps farmers understand differences in soil fertility, moisture levels, and crop growth patterns.

By using AI-based recommendations, farmers can reduce unnecessary input usage and focus resources on areas that need attention. This targeted approach improves productivity while lowering operational costs. Precision farming also helps reduce environmental pollution by preventing excessive chemical application, which can harm soil health and nearby ecosystems.

2. Advanced Crop Monitoring and Growth Analysis

Monitoring crop health over large agricultural areas can be challenging using traditional methods. AI-powered crop monitoring systems use drone imagery and satellite data to provide real-time insights into plant growth. Computer vision models analyze plant characteristics such as leaf color, canopy density, and growth patterns.

These technologies allow farmers to identify issues such as nutrient deficiencies or water stress at an early stage. Continuous monitoring also helps track crop development throughout the growing season, enabling better planning and management. By detecting problems early, farmers can take timely action, reducing crop losses and improving yield quality.

3. Intelligent Pest and Disease Detection

Pests and diseases are among the leading causes of crop damage worldwide. AI-based image recognition systems can quickly identify signs of infection or pest attacks by analyzing plant images. Farmers can upload pictures through mobile applications, and AI algorithms provide instant diagnosis along with treatment recommendations.

Early detection reduces the need for widespread pesticide spraying, allowing farmers to apply treatments only where necessary. This targeted approach protects beneficial organisms and promotes eco-friendly farming practices. AI models can also predict disease outbreaks by analyzing environmental conditions such as humidity, temperature, and rainfall patterns.

4. Smart Irrigation and Water Conservation

Efficient water management is essential for sustainable agriculture, especially in regions facing water scarcity. AI-driven irrigation systems analyze weather forecasts, soil moisture data, and crop water requirements to optimize irrigation schedules. These systems automatically adjust watering patterns based on real-time conditions.

Smart irrigation reduces water wastage and ensures that crops receive the correct amount of moisture for optimal growth. This not only conserves water resources but also lowers energy costs associated with pumping and irrigation infrastructure. By improving water-use efficiency, AI contributes to sustainable agricultural practices and long-term environmental conservation.

5. Soil Health Monitoring and Nutrient Optimization

Soil quality plays a critical role in determining agricultural productivity. AI helps farmers analyze soil properties such as nutrient levels, organic matter content, and pH through advanced data analysis techniques. Machine learning models process soil testing data and generate recommendations for balanced fertilization.

AI-driven soil mapping allows farmers to visualize variations in soil health across their fields. This information helps in planning crop rotation, selecting suitable crops, and preventing soil degradation. By improving nutrient management strategies, AI enhances soil fertility and supports sustainable farming systems.

6. Yield Prediction and Farm Decision Support

Accurate yield prediction is essential for farm planning, financial management, and market strategy. AI models analyze historical yield data, climate patterns, and crop growth indicators to forecast production outcomes. These predictions help farmers decide when to harvest, how much storage is needed, and where to sell their produce.

Decision support systems powered by AI provide practical recommendations on planting dates, fertilizer application, and risk management strategies. Farmers can receive alerts about potential weather risks or market fluctuations, enabling them to make informed decisions. Such predictive tools reduce uncertainty and improve overall farm profitability.

7. Automation, Robotics, and Labor Efficiency

Labor shortages are becoming a significant concern in agriculture, particularly during peak seasons such as planting and harvesting. AI-powered robots and autonomous machinery are helping farmers perform repetitive and labor-intensive tasks. Examples include robotic weeders, automated harvesters, and self-driving tractors.

These technologies increase operational efficiency and reduce dependence on manual labor. Robots can perform tasks with high precision, minimizing crop damage and improving product quality. Automation also allows farmers to focus on strategic decision-making rather than routine activities.

8. Improving Agricultural Supply Chains

AI enhances not only farm-level activities but also the agricultural supply chain. Predictive analytics helps optimize storage, transportation, and distribution processes by analysing demand trends and logistics data. This

reduces post-harvest losses and ensures timely delivery of agricultural products to markets. AI-driven market analysis tools provide farmers with price forecasts and consumer demand insights. With better information, farmers can plan their sales strategies and reduce financial risks. Improved supply chain efficiency benefits both producers and consumers by increasing transparency and reducing food waste.

9. Climate Change Adaptation and Risk Reduction

Climate change presents serious challenges to agricultural productivity through unpredictable rainfall, heat stress, and extreme weather events. AI helps farmers adapt to these challenges by analyzing climate data and suggesting resilient farming strategies. Predictive models can forecast drought conditions, flood risks, and temperature fluctuations.

Farmers can use AI-generated insights to select climate-resilient crop varieties, adjust planting schedules, and manage resources effectively. Early warning systems based on AI provide timely alerts, helping farmers protect crops and reduce economic losses. These technologies play a crucial role in building climate-smart agriculture.

10. Digital Advisory Services and Farmer Empowerment

AI-powered digital platforms are transforming agricultural extension services by providing personalized recommendations to farmers. Mobile-based applications offer advice on crop management, pest control, fertilizer use, and irrigation scheduling. These tools make scientific knowledge more accessible, especially for smallholder farmers.

Digital advisory systems also bridge the gap between research institutions and farmers by delivering localized information. By empowering farmers with data-driven insights, AI encourages better decision-making and supports inclusive agricultural development.

11. Enhancing Sustainability and Environmental Protection

Another important benefit of AI in agriculture is its contribution to environmental sustainability. By optimizing resource use and reducing chemical inputs, AI helps minimize pollution and greenhouse gas emissions. Precision farming techniques reduce fertilizer runoff into water bodies, protecting ecosystems.

AI also supports regenerative agriculture practices by monitoring soil carbon levels and promoting conservation strategies. Sustainable farming not only preserves natural resources but also ensures long-term productivity and resilience.

Conclusion

Artificial Intelligence is reshaping agriculture by introducing innovative solutions that improve productivity, efficiency, and sustainability. From precision farming and smart irrigation to automation and climate adaptation, AI technologies are helping farmers address the complex challenges of modern agriculture. By analyzing large datasets and providing actionable insights, AI enables informed decision-making that enhances both economic and environmental outcomes.

While the benefits of AI are significant, successful implementation requires proper infrastructure, digital literacy, and supportive policies. Training programs and accessible technologies are essential to ensure that smallholder farmers can also benefit from AI-driven solutions. As agriculture continues to evolve in the digital era, AI has the potential to create a smarter and more resilient farming system capable of meeting global food demands while protecting natural resources.

Statistical Approaches in Fish Stock Assessment for Sustainable Fisheries Management



Reema Thakur¹, Shashank Sharma², Anjali Verma³

^{1,2}Teaching Associate, LSPN College of Fisheries, Kawardha, Dau Shri Vasudev Chandrakar
Kamdhenu Vishwavidyalaya, Durg

³Assistant Professor, SVB College of Agriculture & Research Station, Durg, Indira Gandhi Krishi
Vishwavidyalaya, Durg

1. Introduction

Fish stock assessment is a scientific process used to evaluate the status of fish populations and to determine appropriate management strategies for sustainable exploitation. Fisheries are renewable natural resources; however, excessive fishing pressure, environmental variability, and anthropogenic disturbances can lead to stock depletion. Therefore, quantitative and statistical approaches are essential for estimating stock size, growth potential, mortality rates, and sustainable harvest levels. Stock assessment combines biological theory, mathematical modelling, and statistical inference. The primary objective is to provide reliable estimates of population parameters that support rational fisheries management decisions.

2. Fish Population Dynamics

Fish populations are dynamic systems influenced by: Recruitment (addition of new individuals), Growth (increase in size and biomass), Natural mortality, Fishing mortality. The theoretical framework of stock assessment is based on population dynamics, particularly the concept that population change over time is governed by biological growth and removals due to fishing. The classical logistic growth theory suggests that population growth is density-dependent. At low population levels, growth is rapid, while at higher densities, growth slows due to environmental limitations (carrying capacity). This biological principle forms the foundation for many stock assessment models.

3. Concepts of Biomass and Maximum Sustainable Yield (MSY)

A central theoretical concept in fisheries science is Maximum Sustainable Yield (MSY). MSY refers to the largest average catch that can be continuously taken from a stock under prevailing environmental conditions. Although simple, MSY remains a cornerstone of fisheries management policies worldwide and is promoted by agencies such as the Food and Agriculture Organization. The MSY concept is grounded in population growth theory, particularly the logistic growth model, which assumes that fish populations increase rapidly at intermediate biomass levels. At this point, the growth rate of the stock is maximized, allowing for the highest sustainable harvest without causing long-term depletion. Estimation of MSY requires reliable data on biomass, growth rates, recruitment and fishing mortality and it serves as a biological reference point for setting catch limits and preventing overfishing.

4. Surplus Production Theory

Surplus production models are biomass-based models that treat the stock as a single homogeneous unit. These models rely on the theory that the fish population produces a biological surplus, which can be harvested without affecting long-term sustainability. These models are particularly useful when only catch and effort data are available, which is common in data-limited fisheries. Classical surplus production models, such as the Schaefer and Fox models, are derived from the logistic growth framework and estimate parameters like intrinsic growth rate and carrying capacity. By relating catch per unit effort (CPUE) to stock biomass, these models allow estimation of Maximum Sustainable Yield (MSY) and optimal fishing effort. Despite their simplicity, surplus production models provide valuable management guidance in situations where age-structured or length-based data are unavailable.

5. Age-Structured Population Theory

Unlike surplus production models, age-structured models recognize that fish populations consist of multiple age classes with varying survival and reproductive capacities. Such approaches require detailed biological sampling and are widely applied by research institutions such as ICAR-Central Marine Fisheries Research Institute. These models incorporate age-specific growth, natural mortality, fishing mortality, and recruitment to provide a more realistic representation of population dynamics. By tracking cohorts over time, age-structured frameworks such as Virtual Population Analysis (VPA) and statistical catch-at-age models enable estimation of spawning stock biomass and fishing pressure with greater precision. Although data-intensive, age-structured models are considered more robust for long-term management planning and evaluation of harvest control rules.

6. Length-Based Theoretical Approaches

In tropical fisheries, age determination is often difficult. Therefore, length-based theory is applied using growth functions such as the Von Bertalanffy Growth Model. The theoretical foundation assumes: growth follows a predictable asymptotic pattern; length distribution reflects population structure and mortality can be estimated from size composition. Length-based approaches are practical in multi-species fisheries where age data are limited. These methods utilize length–frequency data to estimate growth parameters, total mortality and exploitation rates without the need for direct age readings. Techniques such as length-converted catch curves and length-based spawning potential ratio (LB-SPR) models provide valuable indicators of stock status. Because of their lower data requirements and operational feasibility, length-based models are widely applied in tropical and small-scale fisheries management.

7. Mortality and Exploitation Concepts

Stock assessment theory distinguishes between:

Natural mortality (M), Fishing mortality (F)

Total mortality ($Z = M + F$)

The exploitation rate (E) is defined as the proportion of total mortality caused by fishing. Sustainable fisheries management aims to maintain fishing mortality at or below biologically acceptable limits. Understanding mortality structure is fundamental to determining whether a stock is overfished or sustainably harvested.

8. Recruitment Theory

Recruitment refers to the number of young fish entering the exploitable stock. Recruitment variability is influenced by environmental conditions, spawning stock biomass and ecological interactions. Stock–recruitment relationships, such as: Beverton-Holt model, Ricker model are based on density-dependent survival theory. These theoretical relationships help predict future stock levels.

9. Uncertainty and Statistical Inference

All stock assessment models involve uncertainty due to: Sampling errors, Environmental variability, Model assumptions, Incomplete data. Statistical inference is used to estimate parameters and quantify uncertainty through confidence intervals and probability distributions. Modern theory increasingly emphasizes: Bayesian inference, Likelihood-based estimation, Risk-based management, incorporating uncertainty ensures precautionary management decisions.

10. Sustainable Fisheries Management Framework

Stock assessment supports management measures such as: Total Allowable Catch (TAC), effort regulation, seasonal closures and mesh size control. The theoretical principle underlying sustainable management is that harvest should not exceed the biological surplus produced by the stock. International fisheries governance frameworks emphasize science-based decision-making and ecosystem-based management approaches. Reference points such as Maximum Sustainable Yield (MSY), fishing mortality at MSY (F_{msy}) and biomass at MSY (B_{msy}) serve as quantitative benchmarks for implementing these regulatory measures. Precautionary approaches are increasingly adopted to account for uncertainty in stock estimates and environmental variability. Effective implementation of management strategies requires continuous monitoring, periodic reassessment and adaptive governance to ensure long-term sustainability of fishery resources.

11. Emerging Theoretical Developments

Recent advancements in stock assessment theory include ecosystem-based models, multi-species interaction models, climate-linked population models and integrated assessment frameworks. These approaches move beyond single-species models to consider broader ecological and environmental dynamics. By incorporating trophic relationships, habitat variability and predator–prey interactions, ecosystem-based models provide a more holistic understanding of fisheries systems. Climate-linked models integrate environmental drivers such as sea surface temperature, ocean productivity and circulation patterns to improve recruitment and distribution forecasts under changing climate scenarios. Integrated assessment frameworks combine biological, economic and social indicators, enabling management decisions that balance conservation objectives with livelihood sustainability and ecosystem health.

12. Conclusion

Statistical approaches in fish stock assessment are grounded in population dynamics theory, growth modelling, mortality estimation and uncertainty analysis. From surplus production theory to age-structured frameworks, these methods provide the scientific foundation for sustainable fisheries management. Effective stock assessment ensures that exploitation levels remain within biologically sustainable limits, thereby securing food security, livelihoods and ecological balance for future generations. Quantitative models enable estimation of key biological reference points, allowing managers to evaluate the status of stocks and implement timely corrective measures when overfishing is detected. Incorporation of probabilistic techniques and confidence intervals improves transparency in decision-making by explicitly accounting for uncertainty in data and model assumptions. Continuous refinement of statistical methodologies, coupled with improved data collection and monitoring systems, strengthens the reliability of stock assessments and supports adaptive, science-based fisheries governance in an increasingly dynamic marine environment.



Strategies for Yield Maximization in Nutri Cereals



Sajjan. G¹, D. Hemanth², Rangaswamy. S³, Karthikgowda. R⁴

¹PhD scholar Department of Agronomy, College of Agriculture, Dharwad

²PhD scholar Department of Agronomy, S.V. Agricultural College, Tirupati

³Young professional AICRP on Maize, College of Agriculture, Dharwad

⁴M.Sc. (Agri.), Department of Agronomy, College of Agriculture, Dharwad

Introduction:

Millets or nutri-cereals are high-energy foods that were domesticated and cultivated as early as 10,000 years ago. Millet cultivation is taken up usually in degraded and marginal lands that receive very less rainfall and are poor in soil nutrient content. Overdependence on cereals after the Green Revolution and the present-day sedentary lifestyle of people has proliferated health-related disorders like obesity, diabetes, coronary diseases, etc. The only way to fight back is through the introduction of nutritionally rich millets in our daily diets. India is known to be the leading producer of both large and small millets. Considering their climate resilience, and role in nutritional and health security, the Government of India has declared the year 2018 as the “National Year of Millets” and the year 2023 by as the “International Year of Millets” by the United Nations. Research activities under agronomy to support the beneficial farming of small millets are Sowing window, Nutrient management, cropping system, Weed management, etc.

Why Millets Considered as ‘Nutri-Cereals’?

Gluten-free: Millets are naturally gluten-free, making them suitable for people with celiac disease or gluten intolerance

Sustainable: Millets are often grown using traditional farming methods, which are more sustainable and environmentally friendly than modern, industrial farming practices.

Rich in nutrients: Millets are a good source of fiber, protein, vitamins, and minerals.

Climate Resilient Staple Food Crops: Millets are drought-resistant, require less water, and can grow in poor soil conditions.

Strategies for Yield Maximization in Nutri Cereals

- Short to medium term strategies
- Long term strategies

Short to medium-term strategies:

- Create awareness among farmers
- Introduce millet to the public distribution system
- A remunerative price for farmers through a proper buy-back arrangement
- Proper systematic channel for timely distribution of improved agronomic practices.
- Development and distribution of HYV
- Procurement of millet through MSP
- Inclusion of millet under the mid-day meal scheme

Long term strategies

- ✓ Promotion of Farmers Producer Organization (FPO)
- ✓ Create farm gate processing and warehouse facilities
- ✓ Inclusive policy support for small millets
- ✓ Research and development

Agro Techniques:

1. Date of sowing

- Increases yield due to suitable environment
- Flowering is induced after sufficient vegetative growth
- Moisture stress avoided at critical stages

Ex: For kharif crops: June or July

Temperate crops: last week of Oct to 1st of Nov

Summer crops: First fortnight of Jan

- But time of sowing depends on cropping system, variety, receipt of rainfall and others

2. Maintenance of optimum plant population

- Yield of crop is result of final plant population
- In dry land population should not be more
- If all the resources in optimum condition, then higher population is advantageous

3. Plant population and yield are related each other

Crop	Spacing
Bajra	45 cm × 10 cm
Barnyard millet	25 cm × 10 cm
Finger millet	30 cm × 10 cm
Foxtail millet	20cm × 10 cm

4. Methods of sowing

- Broadcasting
- Nursery transplanting
- Sowing behind the plough
- Seed drilling

5. Weed control methods

- Hand weeding
- Intercultivation
- Cover crops
- Herbicides

6. Intercropping systems

Growing two or more crops simultaneously on the same piece of land with a definite row pattern, thus cropping intensity in space dimension is achieved.

Objectives:

- ❖ Insurance against total crop failure
- ❖ Increase in total productivity per unit land area
- ❖ Judicious utilization of resources

Successful intercropping:

- ✓ Peak nutrient demands of component crops should not overlap
- ✓ Competition for light should be minimum among the component crops
- ✓ Complementary should exist between the component crops
- ✓ Differences in maturity of component crops should be at least 30 days

Conclusion:

Millets are known as superfoods because of the numerous health benefits they offer, which have been backed by recent research. Our ancestors, who made millet a staple food, were less susceptible to diseases and had longer life expectancies. Finger millet is a good source of calcium and potassium, pearl millet is rich in iron and beta-carotene, and little millet is an excellent source of energy. Unfortunately, due to a lack of awareness and availability, millet has not been widely consumed in modern times. However, we are now witnessing an increase in awareness and demand for millets among urban and semi-urban societies. Additionally, the market is now being flooded with "ready to cook" and "ready to eat" processed foods made from millet.

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Digital Couture: How AI is Designing the Future of Fashion



Reema Thakur¹, Shashank Sharma², Anjali Verma³

¹Research Scholar, ³Associate Professor and Head
Department of Apparel and Textile Science,
Maharana Pratap University of Agriculture and Technology, Udaipur.
²Founder, Swizuka Recyweave Textiles LLP, Jaipur

Abstract

The fashion industry has often been criticized for its lagging integration of digital advancements. There has been a significant shift toward digitalization, with digital fashion, apparel that cannot be physically worn, gaining prominence. Numerous high-end labels are embracing this trend, and digital fashion is emerging as an influential factor that is altering the realm of fashion. For fashion designers, digital couture introduces them a whole new universe of opportunities. If digital fashion gains momentum, there are numerous advantages, particularly in terms of societal influence and sustainability. Instead of traditional pen-and-paper fashion design, enterprises might experiment with computerized fashion design, which allows for the creation of precise digital samples, shortens production times, and reduces waste, all of which contribute to more environmentally friendly and responsible fashion manufacturing.

Keywords: Digital Couture, Digital Fashion, Virtual fashion,

Introduction

The fashion industry has always been a hub of creativity and innovation, constantly evolving to reflect cultural shifts and technological advancements. In recent years, affordable fashion has seen countless revolutions, from the rise of sustainable materials to gender-neutral lines but none as transformative as the integration of artificial intelligence.

In the vast and intricate universe of fashion, **digital innovations** are spreading in an increasingly pervasive way, transforming the industry in ways that would have seemed impossible just a few decades ago. **Digital fashion** is the outcome of this fusion, where technology and fashion converge **to create what has not existed before**. The introduction of digital technology has significantly changed the way fashion is designed, produced and consumed.

A new wave of designers and tech innovators are shaping *Digital Couture*, where creativity meets code to redefine how fashion is imagined, made and worn. Digital fashion, also known as **e-fashion**, **digital couture**, or **virtual fashion**, represents a branch of the fashion industry that revolves around creating clothing using software, artificial intelligence (AI) and **3D technology**. This sector appears destined to revolutionize the way of working and creating fashion, potentially in an irreversible manner. From virtual fashion shows to AI-driven designs, the fusion of fashion and technology is shaping the future of couture in ways never seen before.



The Evolution of Digital Couture

Digital couture refers to the creation of high-fashion garments in a purely virtual space. Unlike traditional fashion, which relies on physical textiles and tailoring, digital couture leverages software to create digital garments that can be worn in virtual environments or showcased in stunning digital presentations. This innovation is a means of expressing one's own identity in non-physical space. Digital couture sounds like something that only exists in those sci-fi movies from the 90s. However, the concept came alive in 2018.

This shift towards digital design was catalyzed by advancements in technology, including 3D modeling, animation and augmented reality. Fashion designers are now embracing digital tools to create stunning collections without using traditional materials. Digital fashion design software allows for the development of highly detailed 3D garments that can be visualized before production. This not only speeds up the design process but also reduces waste, making the industry more sustainable.

Advanced programs like CLO 3D and Marvelous Designer enable designers to experiment with patterns, textures and silhouettes in a virtual environment, minimizing the need for physical samples. Instead of utilizing actual cloth and materials, digital outfits are created using 3D computer software and then either worn by your online avatars or augmented onto your body. As a method for creating prototypes of garments in an ethical and ecological way before producing final goods, virtual fashion is quickly becoming the industry standard.

Pioneers of the Digital Fashion Movement

1. Dapper Labs and Digital Collectibles

Among the pioneers of digital fashion is Dapper Labs, known for its pioneering work in blockchain technology and digital collectibles. Their blockchain-based platform enables designers to create unique digital garments that exist as NFTs (non-fungible tokens). This innovative approach not only gives designers a way to monetize their creations but also allows wearers to have rare, verifiable pieces that stand out in the crowded digital landscape.

2. The Fabricant and the Future of Fashion

Founded in 2018, The Fabricant is a leading name in digital fashion, known for its bold designs and emphasis on sustainability. The team at The Fabricant is dedicated to rethinking the fashion lifecycle, advocating for the reduction of fabric waste by creating garments that exist solely in the digital realm. With pieces that have appeared on virtual runways and in digital campaigns for brands like Adidas, The Fabricant is shaping the future of fashion by proving that garments can be stunning, unique and ethical—all without a physical component.

3. Diana Wang and Virtual Dressing Rooms

Diana Wang, a creative director and leader in fashion technology, has pioneered the concept of virtual dressing rooms. By combining augmented reality with fashion design, she allows consumers to "try on" digital garments in real-time. Wang's work emphasizes the merging of physical and virtual identities, illustrating how digital couture can create personalized experiences for users and transform the shopping experience.

4. Neha Celly

Neha Celly, the Bengaluru-based founder of sustainable denim label Nece Gene, worked with Paris-based creative studio Scotoma Lab to create an entirely digital collection for her showcase at Helsinki Fashion Week.

5. Sidharth Sinha

Sidharth Sinha, the Delhi-based founder and creative director of N&S GAIA—had begun dabbling in digital designs. He presented a collection at Global Talents Digital, a hybrid fashion event as part of the Mercedes Benz Fashion Week Russia (MBFWR).

The Role of Technology

1. 3D Modelling and Animation

At the heart of digital couture is sophisticated 3D modelling software, such as Clo3D and Blender. These tools enable designers to create intricate garments with life-like textures and movements. Animation further enhances the experience, allowing designers to visualize how fabrics move and react in a digital world.

2. Virtual Reality and Augmented Reality

Virtual reality and augmented reality are changing the way people experience fashion. Virtual fitting rooms allow customers to try on clothes without physically wearing them, reducing the need for returns and enhancing the online shopping experience. Brands like Gucci and Balenciaga have introduced AR filters that let users see how

accessories or clothing would look on them through their smartphones. With platforms like Oculus and ARKit, designers can showcase their creations in captivating environments, pushing the limits of how garments are presented. These tools offer consumers a chance to interact with fashion in an entirely new way, breaking down the barriers of traditional fashion shows. Virtual fashion shows have also gained popularity, with designers creating fully digital presentations that showcase their collections in immersive 3D environments.

3. AI: The New Design Assistant

Artificial intelligence is transforming the fashion industry by streamlining the creative process and predicting future trends. AI-powered platforms analyze vast amounts of data from social media, runway shows and customer preferences to provide insights into upcoming styles. Designers and brands use these insights to create collections that align with consumer demands. AI also assists in automating tasks like pattern making, fabric selection and color combinations, helping designers focus on creativity rather than repetitive work.

AI tools like neural networks and generative design platforms are now helping designers create unique patterns, silhouettes and even full collections. Unlike traditional methods that depend heavily on manual sketching and prototyping, AI can generate thousands of concepts in seconds based on trends, customer data, or even historical fashion archives. The result? Faster innovation cycles and hyper-personalized fashion.

Companies like **The Fabricant** and **DressX** have pioneered digital-only garments, selling fashion that exists purely in virtual spaces. These clothes are worn in photos, games and virtual meetings, allowing consumers to enjoy fashion without the environmental cost of physical production.

4. Virtual Try-Ons and AI Stylists

Retailers are increasingly turning to AI for virtual try-ons, where customers can see how clothes fit on their bodies through augmented reality. This tech not only enhances online shopping but reduces returns an expensive and wasteful problem for many brands.

AI is also changing how people shop. Personal stylist apps now use machine learning to understand individual tastes, body types and even moods. They curate wardrobes, suggest outfits and predict what users might like next blurring the line between fashion and tech-driven lifestyle management.

5. Fashion in the Metaverse

The rise of the metaverse has opened a new frontier for digital fashion. Major labels like Gucci, Balenciaga and Nike are investing heavily in virtual collections, creating limited-edition items for avatars in games like Fortnite and platforms like Roblox. These aren't just gimmicks, they represent new revenue streams and branding opportunities.

Showcasing Digital Couture: Virtual Fashion Shows and Exhibitions

The presentation of haute couture is also being transformed by digital technologies. Virtual fashion shows and exhibitions are becoming increasingly popular, enabling designers to showcase their creations to a global audience in new and innovative ways.

Virtual fashion shows are being used to present haute couture collections to a global audience, reducing the need for physical runway shows and minimizing the environmental impact of fashion events. These events are often streamed online, enabling viewers to experience the show from anywhere in the world.

The benefits of virtual fashion shows include:

- Increased global reach and audience engagement
- Reduced costs and environmental impact
- Enhanced creativity and innovation in presentation and storytelling
- Improved accessibility for viewers with disabilities

The digital future of fashion

Artificial intelligence, from ChatGPT to TikTok filters, has become an integral part of our daily lives. This transformational technology has also significantly impacted the fashion world, giving rise to digital fashion.

Through virtual **avatars and digital models**, digital fashion enables individuals to experience **wearing clothing that cannot be physically touched**, yet they can interact with it within a virtual environment. Virtual garments and accessories have already become **an integral part of the fashion industry**, holding significant

value, both economically and creatively. Furthermore, the potential for growth and expansion in this domain is boundless.

The potential benefits of digital fashion

Digital fashion can satisfy consumers who are constantly changing their aesthetic or want to keep their wardrobe up to date with each new trend. It also allows for more creativity in fashion; since digital fashion has no physical form, garments that go against the Laws of Physics can be designed. From basic clothes to bubbles, metal and unique shapes, the possibilities are endless.

One of the most significant benefits of digital couture is its contribution to sustainability. Digital fashion can be a very sustainable alternative to fast fashion, which places a significant burden on the environment due to massive overproduction and consumption. Virtual garments require no physical resources, making them an eco-friendly alternative. Additionally, 3D printing technology allows for on-demand clothing production, reducing overproduction and minimizing textile waste. Sustainable fashion brands are increasingly adopting these methods to create a more responsible industry.

Final Thoughts

Fashion has always been about self-expression and innovation and digital couture is pushing these boundaries even further. In this era of digital transformation, *Digital Couture* is not just a trend, it's a movement. As technology continues to evolve, it is clear that the future of fashion will become more inclusive, sustainable, imaginative than ever before as well as deeply intertwined with digital advancements. Whether through AI-driven designs, sustainable virtual clothing, or blockchain-based ownership, digital couture is redefining what it means to be stylish in the modern world.

Digital couture represents a radical shift in the fashion industry, led by a new generation of innovative thinkers and creators. As technology continues to evolve, these creative minds are paving the way for a future where fashion is redefined, highlighting individuality, sustainability and artistic expression. Personalized digital wardrobes, AI-powered personal stylists and fully virtual fashion ecosystems may soon become a reality.

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Mastitis: A Silent Enemy of Milk Production and Tests Used for Its Detection



Mukesh Gangwar, Sadhana Ojha, and Abhishek Kumar

Department of Livestock Products Technology, College of Veterinary and Animal Sciences
(BASU), Kishanganj, Bihar-855107

Department of Veterinary Gynaecology and Obstetrics, College of Veterinary and Animal
Sciences (BASU), Kishanganj, Bihar-855107

Mastitis is one of the most common and economically important diseases affecting dairy animals across the world. It is an inflammatory condition of the mammary gland and udder tissue that leads to reduced milk production, poor milk quality, and significant economic losses to dairy farmers. In many cases, mastitis develops silently without obvious symptoms, especially in its subclinical form, making it difficult to detect at an early stage. The disease affects cows, buffaloes, goats, and sheep and remains a major concern for the dairy industry due to its impact on animal health, milk safety, and farm profitability. The term mastitis is derived from the Greek words “mastos,” meaning breast, and “itis,” meaning inflammation. Thus, mastitis refers to inflammation of the mammary gland. This inflammation usually results from bacterial infection, although physical injury, chemical irritation, or stress may also contribute to the condition. Mastitis causes damage to the milk-secreting cells of the udder, leading to alterations in the quantity and quality of milk produced by the affected animal.

Causes and Risk Factors of Mastitis

Mastitis is primarily caused by microorganisms that gain entry into the udder through the teat canal. Bacteria such as *Staphylococcus aureus*, *Streptococcus agalactiae*, *Streptococcus uberis*, *Escherichia coli*, and *Klebsiella species* are commonly associated with mastitis in dairy animals. Several management and environmental factors increase the risk of infection, including poor housing hygiene, dirty bedding materials, improper milking techniques, injuries to teats, malfunctioning milking machines, and weakened immunity due to nutritional deficiencies or stress. Overcrowding and inadequate sanitation further aggravate the problem, especially in large dairy herds.

Types of Mastitis

Based on the presence or absence of visible signs, mastitis is classified into clinical and subclinical forms. Clinical mastitis is characterized by noticeable changes in the udder and milk. The affected quarter may become swollen, hot, painful, and red, while the milk may appear watery and contain flakes, clots, pus, or blood. Animals suffering from severe clinical mastitis may also show systemic signs such as fever, reduced feed intake, and depression. Subclinical mastitis, on the other hand, does not show visible symptoms in the udder or milk, but it leads to a gradual reduction in milk yield and deterioration of milk quality due to an increase in somatic cell count. Subclinical mastitis is more widespread and economically damaging because it often remains undetected for long periods.

Economic and Public Health Importance of Mastitis

Mastitis causes substantial economic losses to dairy farmers by reducing milk production and increasing treatment costs. Milk from mastitis-affected animals often has poor processing qualities and reduced shelf life, making it unsuitable for the manufacture of milk products. The disease also leads to increased labor, veterinary expenses, and loss of income due to discarded milk during antibiotic treatment. In chronic cases, permanent damage to the udder may necessitate culling of animals. From a public health perspective, mastitis poses a risk because contaminated milk may harbor pathogenic bacteria and antibiotic residues, which can adversely affect human health if consumed without proper processing.

Importance of Early Detection of Mastitis

Early detection of mastitis is essential for effective treatment and control of the disease. Timely identification of infected animals helps in reducing the severity of infection, preventing its spread to healthy animals, and

minimizing economic losses. While clinical mastitis can be detected by observing changes in the udder and milk, subclinical mastitis requires the use of specific diagnostic tests. Regular screening of dairy animals using simple and reliable tests is therefore crucial for maintaining udder health and ensuring the production of safe and high-quality milk.

Physical Examination of Udder and Milk

Physical examination of the udder and milk is the first step in the detection of mastitis. Palpation of the udder helps in identifying swelling, hardness, heat, and pain in the affected quarters. Visual examination of milk during milking may reveal abnormalities such as clots, flakes, watery appearance, or blood, which are indicative of clinical mastitis. Although this method is simple and cost-effective, it is useful mainly for detecting clinical cases and is not effective in identifying subclinical mastitis.

Strip Cup Test for Mastitis Detection

The strip cup test, also known as the foremilk test, is a simple on-farm method used to detect clinical mastitis. In this test, the first few streams of milk are stripped onto a dark-colored cup or plate. The presence of clots, flakes, or abnormal milk particles indicates mastitis. This test is easy to perform and helps in early detection of clinical cases, but it cannot be used to detect subclinical mastitis.

California Mastitis Test

The California Mastitis Test is one of the most widely used field tests for detecting subclinical mastitis. This test is based on the principle that the reagent reacts with the DNA of somatic cells present in milk, leading to gel formation when the somatic cell count is high. Milk samples from individual quarters are mixed with an equal amount of CMT reagent in a paddle and gently rotated. The degree of gel formation indicates the severity of infection. The California Mastitis Test is quick, inexpensive, and suitable for routine use at the farm level, making it a valuable tool for mastitis control programs.

Somatic Cell Count as an Indicator of Mastitis

Somatic cell count is a widely accepted indicator of udder health and milk quality. Somatic cells mainly consist of white blood cells that increase in number during inflammation of the mammary gland. In healthy milk, the somatic cell count is generally below two lakh cells per milliliter, whereas in mastitis-affected milk, it rises significantly. Somatic cell count can be determined through microscopic examination or electronic cell counters in laboratories. Although this method is reliable, it requires specialized equipment and is not always feasible for small-scale farmers.

Electrical Conductivity and pH Tests of Milk

Electrical conductivity of milk increases during mastitis due to elevated levels of sodium and chloride ions resulting from damage to mammary tissue. This method is commonly used in automated milking systems for monitoring udder health. Similarly, mastitis causes an increase in milk pH, making it more alkaline compared to normal milk. The pH of milk can be measured using pH paper or digital pH meters. While both tests are useful as supportive diagnostic tools, their results may be influenced by factors such as stage of lactation and breed, limiting their accuracy when used alone.

White Side Test and Other Screening Methods

The White Side Test is a simple screening method in which milk is mixed with an alkaline solution, leading to the formation of flakes in mastitis-positive samples. Although this test is quick and easy to perform, it is less sensitive than the California Mastitis Test and is therefore used mainly for preliminary screening. Other simple tests are often combined with clinical observation to improve detection efficiency at the farm level.

Bacteriological Examination of Milk

Bacteriological examination of milk is considered the confirmatory test for mastitis diagnosis. In this method, milk samples are cultured on suitable media to identify the causative organism. This test is essential for determining the appropriate antibiotic for treatment and for understanding the epidemiology of mastitis in a herd. However, bacteriological examination requires laboratory facilities, trained personnel, and time, which limits its routine use under field conditions.

Prevention and Control of Mastitis

Effective prevention and control of mastitis depend on good management practices and regular monitoring of udder health. Maintaining clean housing conditions, practicing proper milking hygiene, washing and drying teats before milking, using post-milking teat dips, and ensuring correct functioning of milking machines are essential preventive measures. Regular screening of animals using simple tests such as the California Mastitis Test, along with balanced nutrition and timely veterinary intervention, helps in reducing the incidence of mastitis and improving overall dairy productivity.

Conclusion

Mastitis is a major constraint to profitable dairy farming and quality milk production. While clinical mastitis can be easily detected through observation, subclinical mastitis requires the use of specific diagnostic tests for early identification. Adoption of simple, cost-effective detection methods and good management practices can significantly reduce the incidence and impact of mastitis. Increasing awareness among dairy farmers about mastitis and its detection is essential for ensuring healthy animals, safe milk, and a sustainable dairy industry.



Carbon Sequestration in Aquatic Farming Systems



Rohit M. Bange¹,¹Ediga Arun Goud, ¹Shivam V. Bhor, ¹Sushmita G. Gaonkar, ¹Aishwarya S. Bhalekar, ¹Suyog C. Mhanere, ¹Sudhir N. Dhale, ¹Rohit B. Tonape

¹College of Fisheries, (Dr. B. S. K. K.V, Dapoli). Shirgaon, Ratnagiri, Maharashtra- 415629, India

One of the most potent greenhouse gases, carbon dioxide (CO₂), accounts for over 60% of the heat that is trapped in the earth's atmosphere. Over the past century, the concentration of CO₂ in the atmosphere has steadily climbed by about 0.50% annually to 405 parts per million in 2017, surpassing pre-industrial levels by roughly 40%. In 2005, global agriculture was projected to have contributed 5.1–6.1 Pg CO₂ equivalents annually, or 10–12% of all human greenhouse gas emissions. Methane (CH₄) has a 72-fold greater potential for global warming than CO₂, although being second only to CO₂ in volume. Together, CH₄ and CO₂ account for around 80% of the total radiative forcing of the atmosphere brought on by human activity. Because of the rising levels of these gases, the Earth's average temperature has already increased by about 1°C compared to pre-industrial times, and the years from 2015 to 2018 were the warmest on record. Scientists warn that by the end of this century, CO₂ levels could reach 570 ppm, which may raise global temperatures by nearly 2°C. These changes are expected to cause more extreme weather, longer droughts and floods, changes in climate zones, irregular rainfall, and a rise in sea levels by about 0.19 to 0.58 meters.

Carbon Sequestration in Aquaculture

Aquaculture is generally divided into three types extensive, semi-intensive, and intensive depending on how much management and human effort is involved. In extensive systems, fish fry or fingerlings are released into ponds or water bodies with very little human intervention. In contrast, semi-intensive and intensive systems involve more active management, such as drying and plowing pond bottoms, adding lime, stocking fish at high densities, and providing regular feed, manure and fertilization. These systems mainly rely on feeding nutrient-rich feed to increase fish production. However, only a small part of the feed is actually converted into fish growth, with feed efficiency ranging from about 4% to 27%. Most of the unused feed either settles within the pond or is released into nearby water bodies.

As a result, aquaculture ponds accumulate large amounts of organic matter from leftover feed and fish waste. Over time, this organic carbon can either break down into carbon dioxide (CO₂) or methane (CH₄), or become stored in pond sediments as soil organic carbon, where it can remain for long periods. Practices such as manuring and fertilization further add organic carbon to pond soils and help convert easily degradable carbon into more stable forms. Feeding and manuring not only increase carbon in sediments but also release nutrients like nitrate (NO₃) and phosphate (PO₄) during decomposition. These nutrients promote the growth of algae, which absorb CO₂ from the water through photosynthesis. This controlled increase in nutrients, known as eutrophication, can help reduce CO₂ levels because higher algal productivity leads to greater carbon uptake.

However, excessive feeding, manuring, and algal blooms can also have negative effects by increasing methane emissions and reducing water quality. The functioning of aquaculture ponds largely depends on daily feeding practices and the photosynthetic activity of phytoplankton. When considering all sources of carbon in ponds such as dead plankton, unused fertilizers, uneaten feed, and fish waste in freshwater aquaculture ponds, worldwide it is estimated to have the potential to store about 13.1 million tons of carbon per year. In India, aquaculture ponds cover around 0.79 million hectares and have a strong capacity to store carbon in their sediments. Carbon storage in pond sediments varies by culture type, ranging from about 1,460 to 1,530 kg per hectare per year in polyculture systems, around 860 kg per hectare per year in shrimp ponds, and about 1,100 kg per hectare per year in scampi culture ponds.

Carbon Sequestration by Microalgae

Microalgae are mostly self-feeding organisms that use sunlight to grow, and they are among the main producers of oxygen on Earth. They play a major role in capturing carbon, accounting for nearly half of the global carbon

dioxide (CO₂) fixed through photosynthesis. An important feature of microalgae is that they can also grow using organic carbon or a mix of sunlight and organic sources. This ability allows them to absorb organic carbon found in wastewater, which would otherwise be broken down by bacteria and released into the atmosphere as CO₂. Algae form a large part of the living biomass in both freshwater and marine environments and are the most important CO₂ absorbers in aquatic ecosystems. Because they grow very quickly and can survive under a wide range of environmental conditions, algae are able to capture more CO₂ per unit area than land plants. During photosynthesis, chlorophyll in algae absorbs light energy and uses it to convert carbon dioxide and water into sugars and starch, releasing oxygen in the process. The captured carbon becomes part of the algal biomass, and the type of biomass formed can influence how much CO₂ is absorbed. Studies have shown that algae absorb CO₂ at a much higher rate than most land plants. While many researchers have linked higher CO₂ absorption in plants to their lignin content, algae were once believed to lack lignin. However, later studies confirmed that algae do contain small amounts of lignin. For example, a low lignin content was found in certain red algae species, yet these algae still showed very high CO₂ uptake rates. This shows that even with less lignin, algae are extremely efficient at capturing carbon. Although forests absorb more CO₂, their CO₂ uptake is still much lower than that of algae.



Conclusion

Microalgae rapidly sequester CO₂ through photosynthesis and improve water quality, while fish ponds store this fixed carbon in biomass and sediments, together enhancing carbon sequestration and sustainability in aquaculture systems.

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Hybrid Onion Seeds: A Boon for Farmers and Seed Traders



Mala Dasari Pavan¹ and *G Prameela²

¹Department of Vegetable Science, IGKV, Raipur, Chattisgarh-492012

²Department of Agronomy, OUAT, Bhubaneswar, Odisha-751003

Corresponding Author's email: drvgp126@gmail.com

Introduction

Onion (*Allium cepa* L.), a high-volume and high-value vegetable crop from the Alliaceae family with a chromosome number of $2n = 16$, positions India as the world's second-largest producer after China, yielding 22.81 million tonnes from 1.22 million hectares (Singh and Khar, 2021). It provides various health benefits, such as lipid-lowering, antidiabetic, antihypertensive, antimicrobial, immune-protective, and anti-obesity properties (Galavi *et al.*, 2020). India's productivity falls short of countries like the USA, Japan, and China mainly due to the use of open-pollinated varieties (OPVs), unregulated local seeds lacking quality control, and limited hybrid options (Khar and Singh, 2020). As a highly cross-pollinated crop susceptible to severe inbreeding depression, onion benefits significantly from heterosis, which stems from genetic interactions creating developmental superiority in hybrids over their parents (Singh and Khar, 2021). Onion hybrids demonstrate greater yield and agronomic performance than OPVs, making heterosis breeding a viable approach to enhance productivity; these hybrids offer higher yield potential than local varieties but require evaluation for commercial cultivation (Singh and Bhonde, 2011). To fulfil domestic requirements and export needs, identifying suitable hybrids for specific agro-climatic conditions remains essential.

Hybrid Onion Seeds

Hybrid onion seeds result from crossing two genetically diverse, meticulously chosen parental lines to merge beneficial traits like high yields, consistent bulb sizes, excellent quality, strong adaptability, and robust disease resistance. The first-generation (F_1) seeds exhibit hybrid vigor (heterosis), allowing plants to outperform conventional open-pollinated varieties. Production of these seeds relies heavily on cytoplasmic-genetic male sterility (CGMS), which blocks self-pollination and guarantees efficient, genetically uniform hybrid seed output. Through male sterility systems, breeders boost productivity, achieve greater crop uniformity, and create top-performing hybrid varieties ideal for commercial farming. (Chikh *et al.*, 2025)

Advantages of Hybrid Onion Seeds Over Open-Pollinated Varieties:

Hybrid onion seeds surpass open-pollinated varieties (OPVs) in yield, uniformity, quality, and resistance. Research on F_1 hybrids reveals larger bulb diameters, greater fresh and dry bulb weights, and higher per-plot yields than traditional types. This elevated performance stems primarily from heterosis (hybrid vigour), which promotes stronger vegetative growth, bigger bulbs, and superior overall results, addressing OPV drawbacks like inbreeding depression and limited yield capacity. Moreover, some hybrids display lower vulnerability to thrips and enhanced storability, boosting market value and shelf life. Meanwhile, persistent use of OPVs with farmer-saved seeds and poor quality checks contributes to onion productivity gaps. Overall, hybrid seeds deliver key benefits, including increased yields, consistent bulb sizes, better pest resistance, and stronger financial gains for growers. (Ajjappalavara *et al.*, 2022)

Higher Yield and Uniform Bulb Quality

Hybrid onion varieties achieve higher yields and more consistent bulbs when provided with optimal nitrogen fertiliser levels. Proper nitrogen supply boosts robust vegetative development, enhances photosynthesis and optimises nutrient allocation for forming bulbs, of larger sizes, heavier weights and greater marketable output (Brewster, 2008; Muluneh *et al.*, 2019). It also enhances bulb quality and minimises small or non-marketable bulbs (Khan *et al.*, 2021). Thus, integrating advanced hybrid varieties with precise nitrogen management is crucial for maximising productivity and bulb uniformity in onion farming.

Disease Resistance and Climate Adaptability

Hybrid onion seeds are known not only for their higher yield potential but also for better adaptability and resilience under varying environmental conditions. Their vigorous vegetative growth and efficient nutrient utilisation contributed to healthier plants, which can indirectly support better tolerance to environmental stress. In addition, hybrids produced a higher proportion of marketable bulbs and fewer unmarketable ones, reflecting their better overall plant vigour and adaptability. These characteristics make hybrid onion seeds a reliable choice for farmers aiming for stable production under changing climatic conditions and diverse growing environments.

Role of Hybrid Seeds in Increasing Farmers' Income

Hybrid onion seeds significantly increase farmers' earnings through superior yields, enhanced bulb quality, and better storage compared to conventional open-pollinated varieties. A field trial at Ethiopia's Koga Irrigation Scheme found that hybrids like Russet, Red Coach, and Jambar exceeded the popular Bombay Red, with Russet delivering the top marketable yield of 57.84 t ha⁻¹ under 82 kg N ha⁻¹ application. This pairing also yielded the highest net return (12,419.87 USD ha⁻¹) and a marginal rate of return of 3061.09%, highlighting the financial benefits of hybrids alongside optimal nitrogen use. Additionally, hybrids resisted bolting and produced consistent bulbs, cutting post-harvest losses and boosting market appeal. Therefore, using hybrid seeds, especially Russet with precise fertilization, can greatly enhance profitability and food security for smallholder farmers in Ethiopia and comparable agro-ecological areas (Getaneh *et al.*, 2026).

Market Demand and Export Potential

India's onion seed industry is rapidly growing as a key driver for local farming and global commerce. Facing an annual demand of about 13,000 tons, efforts centre on generating premium-quality seeds to guarantee consistent yields and bolster farmers' incomes. When excess seeds are stored properly in cold conditions with controlled moisture, they ensure next-season availability and help keep prices steady. This dependability bolsters India's export prospects, as international buyers in regions like the Middle East, Southeast Asia, and parts of Europe prize Indian onions for their strong pungency, taste, and versatility. By satisfying local requirements and generating surplus for overseas markets, onion seed production enables farmers to earn more and establishes India as a strong contender in the worldwide seed market.

Challenges in Hybrid Onion Seed Production and Trade

Hybrid onion seed production and trade face significant hurdles that limit scalability and profitability. High seed costs deter farmers from adoption, while limited access to quality hybrid seeds stems from poor supply chains, reliance on local markets or NGOs, and shortages of foundation seeds for recommended varieties. Production challenges include maintaining soil fertility, ensuring true-to-type germination amid inbreeding depression, controlling pests and diseases, labour shortages, and environmental risks like rain during maturity or irrigation deficits, often resulting in low yields or crop losses. Trade issues compound this with inadequate storage and processing facilities, leading to post-harvest losses from sprouting and rotting, market linkage gaps, broker interference distorting prices, low farmer awareness of shelf-life extension, and insufficient extension services or training. Additionally, imported seeds raise certification and quality concerns, while high perishability and fluctuating prices during peak harvest undermine economic viability, particularly in regions like India, Ethiopia, and Sri Lanka.

Government Support and Seed Certification Standards

Governments promote hybrid onion seed production through subsidies, research funding, and extension programs to encourage farmer uptake. In India, this includes Odisha's Rs. 18,750 seed subsidy plus post-planting support, Gujarat's up-to-Rs. 20,000 per hectare aid for natural farming inputs, and Jammu & Kashmir's Agriculture Department offering water infrastructure and nursery advice, helping farmers secure high yields and profits from hybrids. Haryana's seed corporation provides breeder and foundation seeds for certified multiplication. Official seed certification, managed by government bodies, verifies quality via strict checks on germination, purity, and field performance; authorities overseas breeding, inspect production sites, approve hybrids to block substandard seeds, and foster market fairness through subsidies and protections like plant breeders' rights.

Future Prospects of Hybrid Onion Seed Industry

India's hybrid onion seed sector holds bright future potential, with hybrids providing superior yields, consistent bulb sizes, enhanced storage life, and stronger adaptability over conventional open-pollinated varieties. As one of the top global onion producers, India has yet to fully leverage hybrid technology, largely because of scarce stable male sterile lines and refined inbred parents. Implementing cytoplasmic male sterility (CMS)-based methods, combined with molecular markers for fertility restoration (Ms locus), promises to speed up hybrid creation. Advanced techniques like doubled haploid production and genomics-guided breeding can cut the onion's lengthy breeding timeline and streamline seed output. Amid growing local needs, export opportunities and climate pressures, targeted research, better facilities, and robust public-private collaborations could elevate the hybrid onion seed industry to drive higher productivity, boost farmer earnings, and strengthen worldwide market standing.

Conclusion

Hybrid onion seeds mark a game-changing progress in onion farming, tackling issues like low yields, inconsistent bulbs and reduced profits from open-pollinated varieties. Leveraging heterosis in carefully bred F_1 hybrids, growers gain boosted production, superior bulb traits, stronger disease resistance, and greater flexibility across varied agro-climatic zones. Paired with optimal nutrition and reliable certification processes, these hybrids sharply raise marketable output and farmer revenues.

In nations like India, where onions underpin food security, exports, and rural economies, bolstering hybrid seed development, quality assurance and research backing is critical. With surging local needs and rising global trade prospects, the hybrid onion seed market holds vast promise for fostering sustainable yields, economic progress, and international edge. Promoting broader use of premium hybrid seeds can fundamentally reshape onion production, rewarding both farmers and seed producers.

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Cage Culture in Chhattisgarh: Opportunities and Technological Interventions



Tripti Tanjay¹ and Saneer Chauhan¹

Ph.D. Scholar FEES, COF (CAU, Imphal), Tripura (W) India

Introduction

Cage culture has emerged as a promising aquaculture method in India, offering potential for sustainable fish production and economic development (David et al., 2015). This intensive farming technique involves fish rearing from fry to fingerling, fingerlings to table size, or table size to marketable size in an enclosed structures submerged in water bodies that allows free water exchange, allowing for efficient use of space and resources (Fan et al., 2023). They can be placed at the water column's base, middle, or top. The floating cages have been prevalent and simple to use. Cages are available in a variety of shape, including square, rectangular, and spherical. Cage culture is suitable for a variety of open freshwater habitats, particularly reservoirs. The cage is surrounded by synthetic mesh netting that can withstand continuous exposure to water. Chhattisgarh state covers 1,35,194 square kilometers, accounting for 4.14% of the country's total size. The state contains around 1.909 lakh hectares of water functional for fish production. The state contains a reservoir covering 0.826 lakh hectares. 45% of the state's water resources are in reservoirs (DOF, 2020). In Chhattisgarh, cage culture is being explored in reservoirs to enhance fish production and provide alternative livelihoods for local communities (Abery et al., 2005; Azevedo-Santos et al., 2011). Additionally, cage culture plays an important role in addressing the increasing worldwide demand for fish protein, promoting food security, rural livelihood development, and economic growth (FAO, 2023).

Geographical and Ecological Context of Chhattisgarh

Fisheries Resources in Chhattisgarh

Chhattisgarh plays a major role in developing fishing as a substantial source of self-employment and nutrition for rural areas. With 91,928 rural ponds (1.094 lakh ha) and 1,770 irrigation reservoirs (0.826 lakh ha), the state has developed 94.38% of its entire 1.920 lakh ha water resources for fishing by 2020-21. This comprises 92.66% of pond areas and 96.97% of reservoir areas, resulting in a total fish production of 5.77 lakh tons, with rural tanks accounting for 95.99%. Advanced procedures, such as balanced feeding, significant fingerling stocking, and skill training, have increased output to 3,682 kg/ha/year in rural tanks. Fish seed production exceeded demand in 2019-20, with 273 crores st. fry produced. The sector has created 2.20 lakh jobs and 318 lakh man-days of employment annually.

Table-1 Fishery Resources of Chhattisgarh

Water bodies	Area
Total inland water bodies (lakh Ha)	1.82
Rivers & canals (Km) 70 number of rivers and canals	3573
Reservoirs (Lakh ha)	0.826
Tanks & ponds (lakh Ha)	0.994
Brackish water (lakh Ha)	0.7
Total Fish culture area	1.714
Fisher population	2.10 lakh

Climatic and Environmental Suitability for Cage Culture

Chhattisgarh has a tropical and subtropical climate that promotes the natural replenishment of reservoirs. With an average annual rainfall of 1200 mm to 1600 mm, Chhattisgarh provides optimal environmental and climatic conditions for cage farming (Singh et al., 2021). The state's moderate temperatures, which range from 8.2°C to 39.5°C, are good for the growth of marketable fish species including pangasius and Indian major carps. (Das & Vass, 2019) Cage aquaculture thrives in reservoirs like Mahanadi and Indravati because of their large surface

areas and steady water flow (Kumar et al., 2022). By enhancing nutrient retention and production, the state's soil type which is primarily reddish-yellow with a modest capacity to retain water increases aquaculture activity (Sharma et al., 2020). These beneficial conditions have established Chhattisgarh as a potential location for cage culture expansion, together with government initiatives under PMMSY that support sustainable aquaculture practices (NFDB, 2023).

Status of Cage Culture in Chhattisgarh

In 2019–20, the Chhattisgarh government's fisheries department constructed 115 new cages under the Blue Revolution Scheme. In 12 state reservoirs, the Chhattisgarh state has set up 912 cage units under the National Mission for Protein Supplement, Rashtriya Krishi Vikas Yojana, Blue Revolution, and National Fisheries Development Board (NFDB) programs. Under these ideas, each unit consists of 48 cages measuring 6 x 4 x 4 meters. Fish that develop quickly, such as tilapia and pangasius (*Pangasianodon hypophthalmus*), are raised in these cages. Each cage contains around 4000 fingerlings, and each cage produces 3000-5000 kg of fish. The manufacturing cost is 65 to 70 rupees per kilogram, and 48 cage units yield Rs. 70,000 in yearly revenue per cage. The previously stated schemes give a 40 to 50 percent subsidy for the installation of cage units in lease reservoirs for Rs. 3.00 lakh per unit.

Table-2 Cage culture in Chhattisgarh Reservoirs (area/m)

S.No.	Reservoirs	No. of Cages	Area (meter)
1	Sarodha Sagar	96	469
2	Chhirpani	96	450
3	Ghongha	48	720
4	Torenga	48	1189
5	Jhumka	96	2820
6	Gondli	48	1100
7	Ghungutta	48	242
8	Bango	48	554.5
9	Dudhawa	96	2907
10	Bhuka	96	112
11	Khutaghat	48	296

(Source: Dept of Fisheries, Govt of CG, 2020)

Technological Interventions for Sustainable Cage Culture

Classification of Cage Culture

Cage culture can be classified into four main types based on their operation: **fixed, floating, submersible, and submerged**. Fixed cages are supported by posts driven into the substrate and are suited for shallow, sheltered sites. Floating cages are the most commonly used and are supported by a buoyant frame that allows flexibility in site selection. Submersible cages are designed to adjust their position within the water column, enabling them to adapt to varying environmental conditions, such as calm or turbulent waters. Submerged cages operate below the surface to avoid wave forces and floating debris, offering better thermal stability and reduced biofouling (Huguenin, 1997). These classifications enable aquaculturists to adapt cage systems to different environments, such as freshwater, brackish, or marine waters (Guo & Wu, 2004).

Design and Construction of Cages

The cage frames in Chhattisgarh's reservoir are generally composed of galvanized iron (GI). The battery can store four 24 m² cages and is 24 m long and 16 m wide. A bamboo frame requires 24 lengths for the top and 24 for the bottom. To provide balanced flotation, high-density polyethylene (HDPE) drums are installed between the two GI frames, particularly at corners and near joints. Catwalks were built locally using bamboo, wooden bars, or plywood to provide comfort for cage workers. The catwalks were connected to a GI frame, with a bamboo frame at the top secured with GI wire. Net cages made of nylon measuring 6 m by 4 m by 4 m were fastened to the frame after it was secured at the cage culture location, creating a battery of four cages. To prevent drooping, nets are securely fastened to the bamboo frame on top using silk fibers. Sinkers were used to secure the net cages' sides and lower bottom corners so they would hang tightly vertically.

Species Selection and Stocking

Due to their strong market demand in C.G., monosex tilapia fingerlings and *Pangasiodon sp.* were utilized for growth. It generally takes them six to eight months to harvest one kilogram of table-sized fish. It also depends on the water body's basic production and the quality of the supplemental feed. Each cage has a stocking density of 5,000 fingerlings (30 g weight).

Feed and Nutrition Management

Supplemental feeding is necessary for raising fingerlings to table-size fish in captivity, as natural food sources in many Indian reservoirs may not be sufficient for growth even in fingerlings. Abis Company's 32 percent protein extruded feed is utilized to develop *Pangasianodon hypophthalmus* and monosex tilapia in Chhattisgarh. Feeding is done at 5% of body weight (pellet size 2 mm) for the first two months, then dropped to 4%, 3%, and 2% of body weight as growth increased. As fish grow in size, pellet size increases. Feeding is done twice per day. Initially, 5-6 kg of feed is given each cage every day. This reduces over time.

Water Quality Management

Water quality plays a crucial role in aquaculture systems, as it directly impacts fish health, growth, and overall production. Poor water quality can lead to stress, diseases, and reduced profitability in freshwater fish culture. Parameters such as temperature, pH, dissolved oxygen (DO), and ammonia are interdependent and influence the aquatic environment in complex ways (Joseph et al., 1993). The maintenance of optimal water conditions is essential for the survival and growth of fish, as their entire life processes depend on the quality of their surroundings (Bolorunduro and Abdullah, 1996). Additionally, nutrient loading from feed and fish waste in cage culture systems can degrade water quality, causing problems such as low dissolved oxygen and increased organic pollution (Yee et al., 2012). Regular assessment and monitoring of water quality parameters are therefore vital to ensuring sustainable aquaculture practices (Thirupathaiah et al., 2012).

Table-3 Water Quality Parameters in Freshwater Fish Culture

Parameter	Abbreviation	Desirable Range	Remarks
Water Temperature	Temp	25–32°C	Optimal for tropical fish; extreme temperatures reduce growth and increase mortality
pH	pH	6.5–9.0	Ideal for fish growth; influenced by organic decomposition and photosynthesis
Dissolved Oxygen	DO	5–15 mg/L	Critical for fish survival; low levels may indicate pollution
Biological Oxygen Demand	BOD	0–6.8 mg/L	Reflects organic matter decomposition; high values signal water pollution
Chemical Oxygen Demand	COD	3.6–17.4 mg/L	Indicates the presence of oxidizable organic and inorganic matter
Alkalinity	Alk	>20 mg/L	Important for buffering and photosynthesis
Hardness	Hard	15–300 ppm	Higher values buffer against pH changes; soft water (<75 ppm) is less stable
Nitrite-N	NO ₂ -N	<0.3 mg/L	Excess can cause hypoxia; produced during ammonia oxidation
Nitrate-N	NO ₃ -N	0.2–10 mg/L	An indicator of organic breakdown; high levels from agricultural runoff
Ammonia-N	NH ₃ -N	<0.1 mg/L	Produced by fish metabolism; toxic levels impair fish health
Phosphate-P	PO ₄ -P	0.005–0.2 mg/L	Key nutrient but excess can lead to eutrophication
Sulfate	SO ₄	5–100 mg/L	Common salt; needed in moderate amounts
Total Dissolved Solids	TDS	166–239 mg/L	Indicates salinity and nutrient levels
Total Suspended Solids	TSS	Varies	High levels reduce light penetration and photosynthesis

Monitoring and Disease Prevention and Control in Cage Culture

Fry weight and length should be measured at regular intervals to track growth. This information is crucial for harvest timing, fish health maintenance, and appropriate feeding. Disease prevention and control are critical for the sustainability and profitability of cage aquaculture systems. Intensive fish culture in cages often creates an environment conducive to disease outbreaks, particularly due to high stocking densities, limited water exchange, and stress factors such as poor handling and water quality issues. Pathogens including bacteria, viruses, and parasites can spread rapidly under these conditions, leading to significant economic losses. Effective management practices such as maintaining optimal water quality, implementing biosecurity measures, and using immunostimulants and vaccines are essential to mitigating disease risks. Moreover, proper site selection, sanitation, and regular health monitoring play a pivotal role in reducing disease prevalence and improving fish welfare.

Table-4 Disease Prevention and Control in Cage Culture

Prevention/Control Measure	Details
Water Quality Management	Maintain dissolved oxygen >5 ppm, appropriate pH, and temperature levels.
Sanitation	Regularly clean cages and disinfect equipment to prevent pathogen buildup.
Stocking Practices	Use genetically resistant and disease-free fingerlings; avoid overstocking.
Nutrition	Provide high-quality feed to meet nutritional requirements of fish.
Monitoring	Regularly observe fish behavior and monitor water quality parameters.
Vaccination and Immunostimulants	Employ vaccines and immunostimulants to boost fish immune responses.
Disease Diagnosis	Conduct immediate diagnosis using live fish and water samples.
Treatment	Use medicated feeds, baths, or cage-specific treatments for disease control.
Emergency Harvesting	Harvest affected fish early to minimize economic losses.
Communication and Training	Facilitate farmer education on disease management and sharing of best practices.

Harvesting

Table-size fish were harvested six to eight months after they were stocked. To harvest, remove the cage's bottom frame and begin raising it from three corners, guiding the fish to a corner close to the cage's entrance.

Economics of cage culture

Cage culture is an economically viable aquaculture practice that utilizes water bodies for high-density fish farming, offering significant profitability while ensuring sustainable resource utilization. The economics of cage culture over an 8–10-month cycle highlights its cost-effectiveness, with manageable fixed and operational expenses balanced against substantial outputs. Key components of expenditure include stocking, feeding, and labor, with species like tilapia and pangasius offering high survival rates and strong market demand. This model demonstrates the potential for generating profits even with minimal initial investments, making it an attractive livelihood option for farmers and entrepreneurs. By optimizing stocking density, feed usage, and operational practices, cage culture proves to be a profitable and scalable solution for enhancing fish production in regions with accessible water resources.

Conclusion

Cage culture in Chhattisgarh has emerged as a sustainable and efficient aquaculture practice, leveraging the state's abundant reservoirs, favorable climate, and government support. It has significantly enhanced fish production while creating economic and livelihood opportunities for rural communities. The adoption of modern technologies, efficient resource utilization, and species like tilapia and pangasius has addressed challenges like disease management and feed efficiency. With continued focus on capacity building, research, and policy support, cage culture in Chhattisgarh holds immense potential to strengthen food security, boost rural incomes, and serve as a model for sustainable aquaculture in India.

Table-5 Economics of Cage Culture (Culture Period: 8–10 Months)

Operational Cost	Particular	Per Unit Cage
1. Fixed Cost	i. Cage Lease Amount (in Rs.)	5,078
	ii. Cage Size	6x4x4 m
2. Operational Cost	i. Stocking Density (in no.)	5,000
	ii. Mortality (10%, in no.)	500
	iii. Survival (90%, in no.)	4,500
	iv. Price of Fingerling (@ Rs. 5 per 100 mm)	25,000/-
	v. Total Feed Required (@ 1.7 kg per fish)	8,500 kg
	vi. Feed Cost (@ Rs. 35 per kg)	2,97,500/-
	vii. Wages (@ Rs. 150 per day)	45,000/- per person per cycle
	Total Operational Cost (in Rs.)	3,72,578/-
3. Total Production (in kg)	4,500	
4. Total Output (@ Rs. 90 per kg fish)	4,05,000/-	
5. Total Profit (Total Income - Total Operational Cost)	32,422/- /per cage	

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Fish Protein Hydrolysate: The Superfood Hiding in Fishery Waste



Shivam V. Bhor¹, Arun Goud², Rohit M. Bange², Rohit B. Tonape³

¹PhD Scholar, Department of Fish Processing Technology, College of Fisheries, Ratnagiri 415 612, Maharashtra, India

²PhD Scholar, Department of Aquaculture, College of Fisheries, Ratnagiri 415 612, Maharashtra, India

³Master's Scholar, Department of Aquaculture, College of Fisheries, Ratnagiri 415 612, Maharashtra, India

Fishery By-product:

As the production and consumption of fish increased, the waste generated from the processing of fish also increased. "By-product" refers to something that is not considered an ordinary saleable product but can be used after treatment and "waste" describes products that cannot be utilized for food or feed and must be composted or destroyed. The inedible portions of seafood processing are referred to by a variety of words, including "by-product," "co-product," "fish waste," "fish offal," "fish visceral mass," "fish discards," and so on.

Around 75% of the total weight of the fish is thought to be made up of waste from fish processing after filleting. Processing of fish generates 35–40% of the edible meat while the remaining tissues, such as bones, skin and scales, swim bladders, intestines, roes, liver, blood, etc., are not. A significant amount of solid byproduct from the original raw material is produced during the processing of fish. By-product production is further increased by the demand for RTE and other value-added products that require skinless, boneless fillets. A significant amount of by-product is produced when numerous species are unintentionally captured during the harvesting of fish and crustaceans and are not prepared for human consumption. When finfish are processed, 10–50% of their weight is produced as inedible portions, such as the head, gut (viscera), skin, bone, and meat that is still attached to the bone and up to 85% of the raw material produced by shellfish, particularly crustaceans, is made up of inedible portions such the head, viscera, carapace, and appendages.

Global utilisation pattern of By-product:

Nowadays, a major portion of discards and low-value catch, mostly pelagic varieties, is used for the production of fish meal and fish oil, which makes up about 30% of the world's total catch. According to FAO projections, by 2025, fish meal derived from fish waste will contribute for 38% of global fish meal production compared with an average of 29% for the 2013 to 2015 average level. A sizeable amount, aside from fishmeal, is used to make fermented products like silage and fish sauce.

Waste generated from different parts of fish:

By-product	Head	Viscera	Skin	Bones	Scales
% of By-product	9-12	12-18	1-3	9-15	4-5

Hydrolysis:

Hydrolysis can be defined as the breakdown of an organic substrate into smaller products that can subsequently be taken up and degraded by bacteria. Hydrolysis of particulate organic matter is likely to be as diverse as the particles and organisms that are involved in the process. Particle sizes range over orders of magnitude, particles are composed of different types of organic matter, and a mixture of different bacteria and also higher organisms are involved in the overall process.

Protein content in major fish waste parts

Sr. No.	Waste part	Protein (%)
1	Head	11-13
2	Backbone/ frame	10-15
3	Cut offs	12-22
4	Skin	8-12
5	Milt	14-27
6	Viscera	9-23

Fish protein hydrolysate:

Fish protein hydrolysate (FPH) is a product prepared from proteins sourced from fish meat/fish processing by-products via an enzymatic or chemical process. Enzymatically produced hydrolysates are widely accepted, which contain a mixture of peptides of varying sizes and free amino acids.

Enzymatic process:

Enzymatic hydrolysis of fishery by-products uses either the autolysis process or by adding exogenous protein. The autolysis process involves incubating ground fishery waste at optimum reaction conditions of endogenous enzymes and also uses the fish visceral waste. The endogenous enzymes trigger the breakdown of biomolecules to smaller peptides through the autolysis process. The autolysis is usually conducted at neutral or slightly alkaline pH, exploiting the presence of serine protease of the intestine in alkaline conditions or the carboxyl protease of gastric juice in acidic conditions.

Proteolysis is the enzymatic hydrolysis of the amide bond in peptides and proteins. The enzymes are exploited to perform desired functions in processing and analysis and to facilitate the conversions of raw materials into high-quality, more desirable foodstuffs. Proteolytic enzymes are economically the most important group of enzymes and their use is well established in the food industry. Use of proteases in the preparation of fish protein hydrolysates has received wide attention among researchers, as it is more economical and easier to process. The process involves homogenization of fish meat or fish waste with the addition of water. The homogenate is brought to the optimum temperature and pH. The hydrolysis is initiated by the addition of the enzyme at the desired concentration. After a particular duration of incubation, the hydrolysis is terminated by applying heat or by adjusting the pH. The soluble fraction after removing the unhydrolyzed portion is concentrated by freeze drying / oven drying / spray drying. The dried protein powder is referred to as protein hydrolysate.

Fish protein hydrolysate (FPH), a value-added product made from fish waste, is regarded as a significant global output. FPH can be utilised as nutraceuticals, functional foods, dietary supplements, and healthy meals. They may also be used to prevent and treat a number of illnesses, including gastrointestinal disorders.

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Easing The Labour Burden: Assessing The Impact Of Farm Mechanization In Smallholder Paddy Systems



Mauchumi Kalita¹, Nishan Bhuyan², Abhigyan Priyadarshan³, Pompei Dutta⁴

^{1,3&4}Department of Agricultural Economics,

²Department of Agricultural Statistics,
Assam Agricultural University, Jorhat, Assam

Abstract

Farm mechanization has emerged as a transformative force in agriculture, particularly in labour-intensive systems such as paddy cultivation. In the context of Assam, where small and marginal farmers dominate and manual labour still constitutes a major production input, mechanization offers the potential to reduce drudgery, improve timeliness, and enhance farm efficiency. This study assesses the labour-saving and economic effects of mechanization in smallholder paddy farms across Assam's Upper and Central Brahmaputra Valley Zones (UBVZ and CBVZ). Data were collected from 780 farm households categorized under three systems—bullock-operated, tractor-operated, and tractor plus thresher-based farms. The findings indicate that mechanized farms achieve 30–40% reduction in labour requirements and up to 42% reduction in labour costs compared to traditional systems. Mechanization also improved the benefit-cost ratio, reflecting higher operational efficiency and productivity. However, regional and social variations persist in adoption, underlining the need for inclusive and context-specific mechanization strategies.

Keywords: Farm Mechanization, Labour productivity, Paddy cultivation, Assam

1. Introduction

Agriculture continues to be the backbone of India's rural economy, employing over half of the country's workforce and supporting nearly 70% of its population. Within this structure, the predominance of small and marginal farmers—accounting for nearly 85% of operational holdings—poses significant challenges to achieving sustainable agricultural growth. Labour scarcity, rising wages, and high physical drudgery have become defining constraints for agricultural productivity, especially in labour-intensive crops such as paddy.

In Assam, the situation is more pronounced due to fragmented landholdings, limited irrigation, and low adoption of technology. Seasonal migration of labourers, unpredictable climatic conditions, and delayed field operations often lead to suboptimal yields and increased production costs. Farm mechanization, therefore, stands out as a viable strategy to enhance productivity, reduce physical hardship, and address the problem of timely operations.

Mechanization not only replaces human and animal power with machines but also acts as a catalyst for structural transformation—enhancing the efficiency of input use, enabling better crop management, and promoting rural employment diversification. However, its adoption among smallholders is influenced by socio-economic factors, access to machinery, and infrastructural support. Against this backdrop, the present study aims to assess the impact of mechanization on labour use, cost, and economic efficiency in smallholder paddy farming systems of Assam.

2. Objectives

To evaluate the extent of labour utilization and cost differentials between traditional and mechanized paddy farming systems, examine regional variations in the impact of mechanization across the Upper and Central Brahmaputra Valley Zones, and propose policy measures to promote inclusive and sustainable mechanization among smallholder farmers.

3. Methodology

The study was conducted in two major agro-climatic regions of Assam — the Upper Brahmaputra Valley Zone (UBVZ) and the Central Brahmaputra Valley Zone (CBVZ). Together, these zones represent a significant share

of Assam's paddy-growing area and reflect variation in resource endowment, infrastructure, and mechanization levels.

3.1 Data Source

Primary data were collected through structured interviews with 780 farm households selected using a stratified random sampling technique. The sample comprised:

- Bullock-operated farms (traditional system)
- Tractor-operated farms
- Tractor plus thresher-based farms

3.2 Analytical Framework

The study employed comparative cost analysis to assess differences in labour inputs, operational costs, and returns across systems. Labour use was measured in man-days per hectare, and costs were computed following the Cost A2 + Family Labour concept. Descriptive statistics and benefit-cost ratio analysis were used to interpret the findings. Regional comparisons were made between UBVZ and CBVZ to identify efficiency gaps.

4. Results and Discussion

4.1 Labour Use Patterns

The results revealed that labour requirements were substantially higher in bullock-operated farms compared to mechanized ones. Bullock-operated systems required approximately 50% more labour per hectare, especially during tillage and transplanting operations, which are the most labour-intensive stages in paddy cultivation. In contrast, farms using tractors and threshers significantly reduced labour demand, particularly for land preparation and post-harvest operations. The overall labour use declined by 30–40% in mechanized systems. Mechanization not only reduced the total man-days required but also redistributed labour towards management and supervisory roles rather than manual fieldwork, reflecting a qualitative transformation of rural labour patterns.

4.2 Labour Cost and Economic Efficiency

Mechanization had a marked impact on reducing labour costs. The study found a 42% reduction in labour cost per hectare in fully mechanized systems compared to traditional ones. Consequently, total production cost declined, and the benefit-cost ratio improved notably.

The cost advantage of mechanized operations was more visible in the UBVZ due to better accessibility to Custom Hiring Centres (CHCs), availability of repair services, and relatively larger average landholdings. The CBVZ showed moderate adoption, limited by smaller plot sizes and weaker infrastructure.

The economic gain from mechanization also stemmed from the timeliness of operations. Mechanized farms could perform tillage and transplanting at the optimum time, leading to uniform crop stands and higher yields.

4.3 Regional Variations

Regional analysis indicated that the Upper Brahmaputra Valley Zone displayed higher levels of mechanization and efficiency. In contrast, the Central Brahmaputra Valley Zone exhibited lower adoption rates due to smaller holdings, higher machine rental costs, and fewer Custom Hiring Centres. This highlights the importance of region-specific policy support to make mechanization accessible to all categories of farmers.

4.4 Social and Environmental Dimensions

Mechanization also had significant social implications. It reduced physical drudgery, particularly for women workers who are primarily engaged in transplanting and harvesting. By saving time and effort, mechanization allows rural women to engage in non-farm or supplementary income activities. However, care must be taken to ensure that mechanization does not exclude low-income or landless labourers. Promotion of group-based machinery sharing models and rental services through CHCs can ensure inclusivity. Environmentally, mechanization facilitates precision operations that can optimize input use, reduce wastage, and improve soil health when used appropriately.

5. Suggestive Measures

Based on the findings, the study recommends the following measures to promote balanced and inclusive mechanization:

1. **Strengthening Custom Hiring Centres (CHCs):** To provide affordable machinery access for smallholders.

2. **Financial and Policy Support:** Increasing subsidy coverage, promoting low-cost implements suited to small plots, and facilitating credit for machinery purchase.
3. **Skill Development:** Training farmers, especially women and youth, in machine operation and maintenance.
4. **Infrastructure Development:** Establishing rural workshops and service centres for repair and maintenance.
5. **Research and Development:** Encouraging location-specific machinery innovation suitable for Assam's topography and soil conditions.

6. Conclusion

The study clearly demonstrates that farm mechanization significantly reduces labour requirements and costs in smallholder paddy systems while improving operational efficiency and productivity. Mechanized farms experienced **up to 42% savings in labour cost** and **30–40% reduction in labour use**, along with enhanced benefit-cost ratios.

However, the benefits of mechanization are not uniformly distributed. Regional disparities in infrastructure, access to machinery, and financial capacity limit the adoption rate among small and marginal farmers. Therefore, future mechanization strategies must focus on **inclusive, affordable, and context-specific approaches** that balance efficiency gains with social equity.

Mechanization, when integrated with proper planning, training, and institutional support, can serve as a powerful instrument for rural transformation—easing the labour burden, improving farm profitability, and paving the way toward sustainable agricultural development in Assam.

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Smart Technology in Horticulture



S. Sashank

B.Sc. Scholar, N.S. College of Horticulture science, Markapur -523316

Introduction

Horticulture, the science and art of cultivating fruits, vegetables, flowers, and ornamental plants, has always been a field that balances tradition with innovation. In recent decades, technological advancements have transformed horticultural practices, making them more efficient, sustainable, and profitable. Smart technologies such as artificial intelligence (AI), robotics, and vertical farming systems are reshaping the way crops are monitored, grown, and harvested. This article explores three major innovations in horticulture: AI-driven crop monitoring, vertical farming beyond urban centers, and robotics in harvesting. Together, these technologies are redefining the future of horticulture and addressing challenges such as labor shortages, resource management, and food security.

AI-Driven Crop Monitoring

Precision Agriculture and AI

Artificial intelligence has become a cornerstone of modern horticulture. By integrating sensors, drones, and machine learning algorithms, farmers can monitor crops with unprecedented accuracy. Precision agriculture relies on data-driven insights to optimize irrigation, fertilization, and pest control.

Sensors and IoT Devices

- **Soil Moisture Sensors:** These devices measure water levels in the soil, enabling farmers to irrigate only when necessary. This reduces water wastage and ensures plants receive optimal hydration.
- **Climate Sensors:** Monitoring temperature, humidity, and light intensity helps in creating microclimates tailored to specific crops.
- **Nutrient Sensors:** These detect nutrient deficiencies in real-time, allowing for targeted fertilization.

Drones and Imaging Technologies

Drones equipped with multispectral and hyperspectral cameras provide aerial views of fields. They can detect early signs of disease, pest infestations, or nutrient deficiencies. This aerial mapping allows farmers to act proactively rather than reactively.

Benefits of AI Crop Monitoring

- **Water Conservation:** Precision irrigation reduces water usage significantly.
- **Reduced Chemical Use:** Targeted pest control minimizes pesticide application.
- **Higher Yields:** Early detection of problems ensures healthier crops and consistent yields.
- **Cost Efficiency:** Automated monitoring reduces the need for manual labor.

Case Study: Smart Greenhouses

In countries like the Netherlands, smart greenhouses use AI-driven monitoring systems to regulate temperature, humidity, and light. These systems ensure optimal growing conditions, leading to higher productivity and reduced resource consumption.

Vertical Farming Innovations

Concept of Vertical Farming

Vertical farming involves growing crops in stacked layers, often in controlled environments such as greenhouses or indoor facilities. This method maximizes space utilization and allows for year-round production.

Expansion Beyond Urban Centers

Initially popular in urban areas due to limited land availability, vertical farming is now expanding into peri-urban and rural regions. This expansion reduces transportation costs and integrates local communities into the food supply chain.

Technological Features

- **Hydroponics:** Plants are grown in nutrient-rich water solutions without soil.
- **Aeroponics:** Roots are suspended in air and misted with nutrient solutions.
- **LED Lighting:** Specialized lights mimic natural sunlight, optimizing growth cycles.
- **AI Algorithms:** These adjust nutrient delivery, lighting, and irrigation based on plant needs.

Benefits of Vertical Farming

- **Year-Round Production:** Controlled environments eliminate seasonal limitations.
- **Efficient Land Use:** Vertical farming requires less land compared to traditional methods.
- **Reduced Transportation Costs:** Locally grown produce reaches consumers faster.
- **Employment Opportunities:** Rural vertical farms create jobs and promote entrepreneurship.

Case Study: Rural Vertical Farms

In Japan, vertical farming has been introduced in rural areas to revitalize communities. These farms provide fresh produce locally, reduce dependency on imports, and create new economic opportunities.

Robotics in Harvesting

Automation in Agriculture

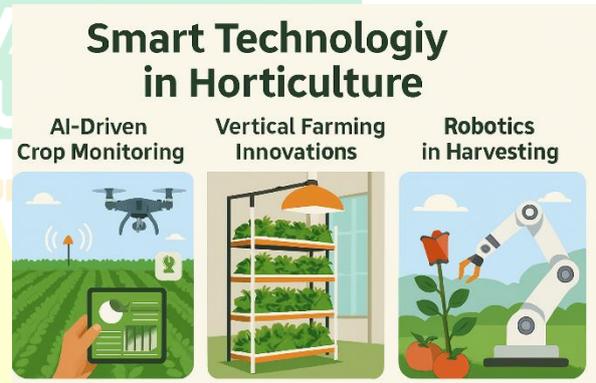
Labor shortages and rising costs have made automation essential in horticulture. Robotics in harvesting ensures efficiency, consistency, and cost reduction.

Types of Harvesting Robots

- **Fruit-Picking Robots:** Equipped with vision systems, these robots identify ripe fruits and harvest them without causing damage.
- **Flower-Cutting Machines:** Used in floriculture, these machines cut flowers with precision.
- **Multi-Crop Harvesters:** Advanced robots can handle different types of crops, increasing versatility.

Benefits of Robotics in Harvesting

- **Reduced Labor Dependency:** Robots operate continuously, reducing reliance on seasonal workers.
- **Consistency:** Automated systems ensure uniform harvesting, improving product quality.
- **Cost Reduction:** Lower labor costs translate into higher profitability.
- **Speed:** Robots can harvest faster than human laborers.



Case Study: Strawberry Picking Robots

In Spain, strawberry-picking robots have been deployed in greenhouses. These robots use AI to identify ripe strawberries and harvest them gently, ensuring minimal damage and maximum efficiency.

Comparative Analysis of Smart Technologies

Technology	Tools & Features	Benefits	Example Use Case
AI Crop Monitoring	Sensors, drones, imaging	Precision irrigation, pest control	Smart greenhouses
Vertical Farming	Hydroponics, LEDs, AI	Year-round yield, land efficiency	Rural vertical farms
Robotics in Harvesting	Vision systems, robotics	Labor cost reduction, consistency	Automated fruit picking

Challenges and Limitations

High Initial Costs

Implementing smart technologies requires significant investment. Small-scale farmers may struggle to afford these systems.

Technical Expertise

Operating AI systems, drones, and robots requires technical knowledge. Training programs are essential to bridge this gap.

Energy Consumption

Vertical farming and robotics consume substantial energy, especially for lighting and automation. Renewable energy integration is necessary to ensure sustainability.

Data Security

With increased reliance on digital systems, data security becomes a concern. Protecting farm data from cyber threats is crucial.

Future Prospects

Integration of Renewable Energy

Solar panels and wind turbines can power vertical farms and robotic systems, reducing carbon footprints.

AI Advancements

Future AI systems will become more sophisticated, capable of predicting crop yields, market demands, and climate impacts.

Global Adoption

As costs decrease and technologies become more accessible, smart horticulture will spread globally, benefiting both developed and developing nations.

Sustainable Development Goals

Smart horticulture aligns with the United Nations' Sustainable Development Goals (SDGs), particularly those related to food security, sustainable agriculture, and economic growth.

Conclusion

Smart technologies are revolutionizing horticulture by making it more efficient, sustainable, and profitable. AI-driven crop monitoring ensures precision in irrigation and pest control, vertical farming expands food production beyond urban centers, and robotics in harvesting addresses labor challenges. While challenges such as high costs and technical expertise remain, the future of horticulture lies in embracing these innovations. By integrating smart technologies, horticulture can meet the growing demands of food security, sustainability, and economic

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Wang, C., & Luo, L. (2024). *Application of Smart Technology and Equipment in Horticulture.* *Horticulturae*, 10(7), 676. <https://doi.org/10.3390/horticulturae10070676> — This peer-reviewed article discusses the integration of AI, robotics, and smart equipment in horticultural systems, with emphasis on sustainability and productivity.

Esnaashariyeh, A., & Gupta, K. (2024). *Integrating Smart Technologies in Horticulture: Drivers, Challenges, and Strategies for Sustainable Management.* — This research outlines how IoT, AI, and robotics are transforming traditional horticulture, with a focus on resource optimization and real-time crop health monitoring.

Smart Horticulture: Its Prospects and Future Scope — This overview highlights innovations like smart irrigation and eco-friendly pest control, emphasizing environmental impact reduction and future scalability.

Remote Sensing: Principles, Types, Importance and Applications



Tara Thakur¹ and Parminder Kaur Baweja²

¹Research Scholar, Department of Environmental Science, Dr. Y S Parmar University of Horticulture and Forestry, Nauni-Solan-173230 (HP), India

²Principal Scientist, Department of Environmental Science, Dr. Y S Parmar University of Horticulture and Forestry, Nauni-Solan-173230 (HP), India

Abstract

Remote sensing is an effective scientific technique for gathering information about the Earth's surface without requiring direct physical contact. It has become an indispensable tool in environmental monitoring, natural resource management, climate change research, agriculture, urban planning, and disaster management. Remote sensing, thanks to advancements in satellite technology, geographic information systems (GIS) and artificial intelligence, now provides accurate, real-time, large-scale data for decision-making. This article examines the concept, definition, significance, types and major applications of remote sensing, with a focus on its role in sustainable development and environmental monitoring. Recent advances in high-resolution satellite imagery, hyperspectral sensing and drone-based remote sensing have significantly improved data accuracy and accessibility, making remote sensing an essential tool for scientific research and policy planning.

Keywords: Remote sensing, satellite imagery, GIS, environmental monitoring, hyperspectral, climate change.

INTRODUCTION

Remote sensing is the science and technology of gathering data about objects, areas, or phenomena without making direct physical contact. It is based on the detection and measurement of electromagnetic radiation reflected or emitted from the Earth's surface via sensors mounted on satellites, aircraft, or unmanned aerial vehicles (UAVs). These sensors record energy in various regions of the electromagnetic spectrum, including visible, infrared, thermal and microwave, allowing scientists to examine the physical, chemical and biological properties of natural and man-made objects. Since the launch of the first Earth observation satellite, remote sensing has evolved rapidly and is now widely used in environmental science, agriculture, forestry, geology, oceanography, hydrology and urban planning (Wong *et al.*, 2021).

The fundamental strength of remote sensing lies in its ability to provide synoptic, repetitive, and multi-temporal observations over large geographic areas. Unlike traditional ground-based methods, it allows for continuous monitoring of remote and inaccessible areas such as polar zones, dense forests, deserts, and mountainous terrain. Remote sensing has become an indispensable tool for studying Earth system processes and environmental changes such as deforestation, glacier retreat, desertification, biodiversity loss, land use/land cover dynamics, and climate variability (Jensen, 2016). Long-term datasets derived from satellites are especially useful for detecting environmental trends, assessing ecosystem health and understanding human impacts on natural systems.

Remote sensing is essential for environmental monitoring and sustainable resource management. In forestry, it is used to map forest cover, calculate biomass and detect forest degradation and wildfires. Remote sensing in agriculture helps to improve precision farming by monitoring crop health, soil moisture, nutrient status and yield prediction using vegetation indices like NDVI (Normalized Difference Vegetation Index). Satellite data are used in hydrology and water resource management to monitor watershed conditions, surface water extent, groundwater potential zones and flood risk levels. Similarly, in oceanography, remote sensing is used to investigate sea surface temperature, chlorophyll concentration, coastal erosion and marine pollution.

Remote sensing has improved in accuracy and versatility as sensor technology advances. High-resolution satellite imagery allows for detailed mapping of urban expansion and infrastructure development, whereas hyperspectral sensors enable precise identification of minerals, vegetation stress and soil contamination. Microwave and radar sensors, such as Synthetic Aperture Radar (SAR), can provide data regardless of cloud

cover or illumination conditions, making them especially useful for flood mapping, soil moisture estimation and terrain analysis. Furthermore, LiDAR (Light Detection and Ranging) technology allows for highly precise three-dimensional mapping of terrain, forest structure and urban landscapes (Richards, 2006).

The integration of Remote Sensing with GIS, GNSS and advanced tools such as AI and Machine Learning has significantly improved spatial data analysis and interpretation. Automated classification, change detection and predictive modeling have improved environmental monitoring and decision-making, transforming remote sensing into an effective geospatial decision-support system.

Remote sensing can help with climate change monitoring, disaster management, urban planning, biodiversity conservation, and pollution assessment. It has become an indispensable tool for environmental management and sustainable development due to its ability to provide precise and timely spatial data.

The term “Remote Sensing” was first introduced in the United States in the 1950s by Evelyn Pruitt, a geographer working with the U.S. Office of Naval Research (ONR). She used this term to describe the science of gathering information about objects, areas, or phenomena from a distance while avoiding physical contact.

Objectives of the Study

The purpose of this study is to investigate how remote sensing improves environmental management and monitoring.

Main goals are:

- 1. Understanding Uses:** Learn how remote sensing is used to monitor deforestation, monitor climate change, and control natural disasters like wildfires and floods.
- 2. Verifying Accuracy:** Examine how accurate and helpful sensors and satellite images are for environmental research.
- 3. Using GIS Together:** Discover how geographic information systems (GIS) aid in the interpretation of data from remote sensing.
- 4. Supporting Sustainability:** Describe how remote sensing helps preserve the environment and make prudent use of natural resources.

IMPORTANCE OF REMOTE SENSING

Remote sensing has become essential in scientific research and environmental management due to the following reasons:

SR.NO.	Area of Study	Key Role of Remote Sensing	Major Applications	Key References
1	Environmental Monitoring	Broad-scale, continuous, non-contact environmental observation	Ecosystem change detection, resource management, environmental assessment	Foody (2020)
2	Climate Change Analysis	High-resolution monitoring of temperature, GHGs, ice sheets	Climate modelling, extreme weather tracking (cyclones, heatwaves), sea surface temperature analysis	Foody (2020)
3	Deforestation & Land Use Change	Satellite imagery comparison (temporal analysis)	Forest loss quantification, illegal logging detection, urban expansion mapping	Hansen et al. (2013)
4	Water Resource Management	Monitoring precipitation, river discharge, groundwater & soil moisture	Irrigation planning, glacier retreat monitoring, wetland loss assessment, water quality evaluation	Vörösmarty et al. (2010)
5	Disaster Management & Mitigation	Real-time hazard tracking using thermal & radar sensors	Flood mapping, wildfire detection, cyclone warning systems, post-disaster damage assessment	Joyce et al. (2009)
6	Land Use & Land Cover (LULC) Monitoring	High-resolution temporal mapping of vegetation & built-up areas	Urban planning, desertification monitoring, sustainable land policy support	Lambin et al. (2003)
7	Biodiversity & Habitat Mapping	Vegetation health & fragmentation analysis	Biodiversity hotspot mapping, wildlife habitat conservation, invasive species detection	Pettorelli et al. (2014)
8	Pollution Detection	Multispectral & hyperspectral pollutant identification	GHG monitoring, oil spill detection, eutrophication mapping, air quality assessment	Kavvada et al. (2020); Yang et al. (2022)

Classification of Remote sensing

Classification	Type	Definition	Key Features	Applications
1. Energy Source	A. Passive Remote Sensing	Detects natural radiation reflected/emitted from Earth	Depends on sunlight, affected by clouds	Vegetation, LULC, water mapping
	B. Active Remote Sensing	Emits its own signal and measures backscatter	Works day/night, cloud penetration	RADAR (floods), LiDAR (topography)
2. Platform	A. Ground-based	Sensors near Earth's surface	High accuracy, small coverage	Field spectrometers
	B. Airborne	Sensors on aircraft/drones	High spatial resolution	Precision agriculture
	C. Satellite	Sensors on orbiting satellites	Large area coverage	Climate & global monitoring
3. Wavelength	A. Optical	Visible & Near Infrared	Vegetation & land cover studies	NDVI analysis
	B. Thermal	Measures emitted heat energy	Surface temperature mapping	Urban heat island studies
	C. Microwave	Long wavelength radar signals	All-weather capability	Flood & soil moisture
	D. Hyperspectral	Hundreds of narrow spectral bands	Detailed material identification	Mineral & pollution detection

Applications of Remote Sensing

Remote sensing has wide applications across various sectors:

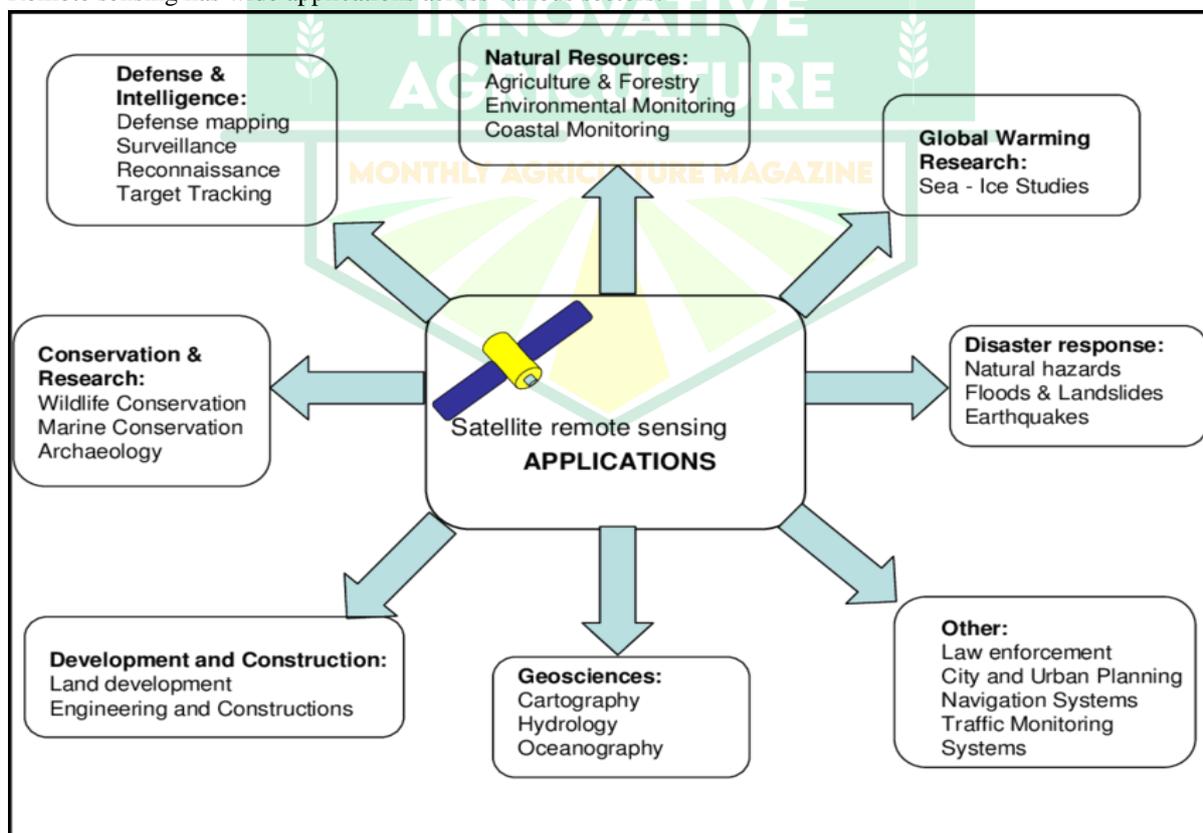


Fig. 1. Showing Application of Remote Sensing (Illie and Vasile, 2011)

Conclusion

Remote sensing has emerged as one of the most powerful and essential scientific tools for environmental monitoring, natural resource management, and sustainable development. It has transformed how scientists observe and understand Earth system processes by allowing them to collect accurate, repetitive, and large-scale data without the need for direct physical contact. Remote sensing provides critical information for evidence-based decision-making and environmental governance, including tracking deforestation and biodiversity loss and monitoring atmospheric pollution and climate change. Its ability to generate near-real-time data has greatly improved disaster preparedness, risk assessment and post-disaster recovery planning, resulting in reduced environmental and socioeconomic losses.

With rapid technological advancements, the scope and effectiveness of remote sensing are constantly expanding. The development of hyperspectral sensors enables the precise identification of materials, pollutants, and vegetation stress at a very fine spectral scale. Unmanned Aerial Vehicles (UAVs or drones) can now perform high-resolution local-scale monitoring in agriculture, forestry, and disaster assessment. Furthermore, the combination of Artificial Intelligence (AI) and Machine Learning (ML) has automated image classification, change detection, and predictive environmental modelling, resulting in significantly faster and more accurate geospatial analysis. The combination of remote sensing, Geographic Information Systems (GIS) and big data analytics has resulted in powerful platforms capable of processing massive, multi-temporal datasets for complex environmental assessments.

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Watershed Programme in India- Present Status, Problems and Policy Issues



Dr. A. Malaisamy

Professor and Head

Department of Agricultural Economics, Tamil Nadu Agricultural University

Introduction

Watershed development is a government-led program under the Pradhan Mantri Krishi Sinchayee Yojana – Watershed Development Component (PMKSY-WDC). It focuses on soil and water conservation, groundwater recharge, erosion control, and improving farm productivity in rain-dependent areas. The Government of India implements it through the Department of Land Resources. Under WDC-PMKSY 2.0 (2021–2026), approximately ₹8,134 crore is allocated at the national level (Central + State share). Recently, about ₹5,576 crore central funds were released to states for watershed implementation.

Historical Evolution of Watershed Policy in India

The key milestones are,

- **1994** - Participatory Watershed Development Program (PWDP) launched the first formal adoption of a community-driven watershed approach across multiple states.
- **2009-10** - Integrated Watershed Management Programme (IWMP) launched by the Department of Land Resources (DoLR), Ministry of Rural Development a landmark consolidation of multiple earlier programmes into one unified framework covering 28 states and 2 UTs.
- **2014-15** - IWMP merged with Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) as WDC-PMKSY — 'Har Khet Ko Pani, More Crop Per Drop.'
- **15 December 2021** - WDC-PMKSY 2.0 approved for 2021–2026 a transformative 'next generation' upgrade with enhanced unit costs, springshed management, GIS-based planning, and higher community focus.
- **February 2025**- 'Watershed Yatra' launched nationally a mass outreach campaign across 805 projects in 26 states and 2 UTs, covering 6,673 Gram Panchayats and 13,587 villages.

WDC-PMKSY 2.0

The Watershed Development Component of Pradhan Mantri Krishi Sinchayee Yojana, Phase 2 (WDC-PMKSY 2.0), is India's primary watershed intervention programme, implemented by the Department of Land Resources (DoLR), Ministry of Rural Development. It is a Centrally Sponsored Scheme (CSS) designed to treat rainfed and degraded land on a saturation basis.

Parameter	Detail
Scheme Name	WDC-PMKSY 2.0 (Next Generation Watershed Development Projects)
Implementing Ministry	Ministry of Rural Development, Dept. of Land Resources (DoLR)
Scheme Period	2021-22 to 2025-26 (5 years)
Physical Target	49.50 Lakh Hectares of rainfed/degraded land
Central Financial Outlay	₹8,134 Crore (indicative Central share)
Funding Pattern (Normal States)	60:40 (Centre:State)
Funding Pattern (NE + Hilly States)	90:10 (Centre:State)

Parameter	Detail
Unit Cost (Plain Areas)	₹22,000/ha (revised from ₹12,000/ha)
Unit Cost (Hilly/Difficult/LWE Areas)	₹28,000/ha (revised from ₹15,000/ha)
Total Projects Sanctioned (2021-22)	1,150 projects; 50 Lakh Ha; ₹12,303 Crore total cost
Number of States/UTs Covered	28 States and 2 UTs
Project Duration (Per Project)	Reduced to 3-5 years (from 4-7 years)
Annual WDC Budget (FY 2026-27)	~₹2,482 Crore (DoLR Demand for Grants, PMKSY head)
New Projects Sanctioned (Jan 2025)	56 new projects; ₹700 Crore; 2.8 Lakh Hectares; 10 best-performing states

Objectives of WDC-PMKSY 2.0

- Improve productive potential of rainfed and degraded land through integrated watershed management.
- Strengthen community-based local institutions for the promotion of livelihoods and watershed sustainability.
- Improve the efficiency of watershed projects through cross-learning and incentive mechanisms.
- Accelerate the economic growth rate of agriculture in less-endowed rainfed areas.
- Rejuvenate Springsheds — a new activity added on NITI Aayog's recommendations to address declining spring water depletion in hilly states.
- Promote GIS and Remote Sensing-based planning for precision targeting of interventions.
- Achieve harmony with ecological principles to ensure sustained transformation of economy and ecology — the 3Es: Economy, Ecology, Equity.

Activities under WDC-PMKSY 2.0

Activity Category	Specific Activities
Ridge Area Treatment	Afforestation, plantation, grassland/pasture development on hilltops
Drainage Line Treatment	Check dams, gabion structures, silt retention dams, rock fill dams
Soil & Moisture Conservation	Contour bunds, trench-cum-bunds, stone bunds, grade stabiliser
Rainwater Harvesting	Farm ponds, percolation tanks, village ponds, groundwater recharge structures
In-Situ Moisture Conservation	Land levelling, field bunding, mulching, cover cropping
Biological Treatment	Agro-forestry, grass planting, biomass conservation
Springshed Management	Springshed area treatment, water source augmentation for springs
Livelihood Support	15% of total project cost reserved for landless/assetless households
Institutional Building	Formation of Watershed Committees, SHGs, FPOs, User Groups
Pasture Development	Fodder production, silvipasture, agropasture systems

Institutional Framework

WDC-PMKSY 2.0 follows a five-tier implementation structure,

- (1) National Level Nodal Agency (NLNA) - DoLR as the apex body
- (2) National Steering Committee chaired by Secretary, DoLR, with members from NITI Aayog and 10 ministries
- (3) State Level Nodal Agency (SLNA)

(4) District Watershed Cell cum Data Centre (DWCDC) and District Watershed Development Team (DWDT) and

(5) Project Implementing Agencies (PIAs) typically NGOs or government departments with Watershed Committees at the village level.

Scope in the Union Budget 2026 for Watershed

The Government of India has allocated an estimated ₹2,16,654 crore for water-related infrastructure and programs (urban and rural), including schemes such as

- Atal Mission for Rejuvenation and Urban Transformation (AMRUT)
- Swachh Bharat Mission
- Jal Jeevan Mission

Atal Mission for Rejuvenation and Urban Transformation (AMRUT)

- Launched: 2015
- Ministry: Ministry of Housing and Urban Affairs

Main Objective

To improve basic urban infrastructure in cities, especially:

- Drinking water supply
- Sewerage and septage management
- Storm water drainage (to reduce flooding)
- Green spaces and parks
- Urban transport (non-motorised transport)

AMRUT ensures every urban household gets:

- Tap water connection
- Proper sewage connection

AMRUT 2.0 (launched in 2021) aims to provide:

- 100% water supply coverage in statutory towns
- Rejuvenation of water bodies
- Reduction of non-revenue water

Challenges and Policy Issues

1. Low Fund Utilisation

- Allocated funds are sometimes not fully used.
- Delays in fund release from Centre to States.
- Projects remain incomplete due to financial bottlenecks.

2. Delay in Project Implementation

- Administrative and approval delays.
- Slow tendering and technical clearances.
- Projects take longer than planned timelines.

3. Weak Community Participation

- Limited involvement of farmers in planning.
- Watershed committees sometimes inactive.
- Lack of local ownership reduces sustainability.

Multiplex CRISPR Gene Editing in Agriculture: A New Era of Smart Crop Improvement



Ragulakollu Sravanthi¹, Dr. Konne Deepika², Azmeera Swetha Sahithi³

¹Ph.D. Scholar, Department of Genetics and Plant Breeding, Tamil Nadu Agricultural University, Coimbatore – 641003

²Teaching associate, Department of Genetics and Plant Breeding, Agriculture College, Polasa Jagityal-505529

³Ph.D. Scholar, Genetics and Plant Breeding, ICAR-Indian Agricultural Research Institute, New Delhi, Off campus, ICAR-Central Research Institute for Dryland Agriculture, Hyderabad- 500059

Abstract

Multiplex CRISPR gene editing is transforming modern agriculture by enabling the simultaneous modification of multiple genes within a single crop genome. Unlike conventional breeding, which is time-consuming and limited by genetic recombination, multiplex CRISPR technology allows precise, targeted, and rapid improvement of complex agronomic traits controlled by multiple genes. This approach uses multiple guide RNAs in combination with CRISPR-associated nucleases to edit several genomic loci at once, facilitating the development of crops with enhanced yield, stress tolerance, disease resistance, and nutritional quality. In agricultural systems facing climate change, emerging pathogens, and growing food demand, multiplex editing offers a strategic advantage by accelerating trait stacking and improving breeding efficiency. It enables the coordinated manipulation of gene networks involved in drought tolerance, salinity resistance, plant architecture, and grain quality, thereby supporting the development of climate-resilient and high-performing crop varieties. Furthermore, multiplex CRISPR reduces breeding cycles, enhances precision, and minimizes linkage drag compared to traditional approaches, this technology holds significant promise for developing resilient, high-performing, and sustainable crop varieties.

Introduction

CRISPR-Cas9 is a molecular tool adapted from a natural defense system found in bacteria. Scientists use it to precisely cut DNA at specific locations and either remove, modify, or insert genetic material.

The CRISPR system has two main components:

- Cas protein (usually Cas9) – acts as molecular scissors that cut DNA.
- Guide RNA (gRNA) – directs Cas9 to a specific DNA sequence.

Once the DNA is cut, the cell repairs the break. During repair, scientists can disrupt a gene, delete it, or introduce desired changes. Traditional CRISPR editing targets one gene at a time. However, most biological traits are not controlled by a single gene. This limitation led to the development of multiplex editing. Multiplex CRISPR gene editing allows scientists to edit multiple genes simultaneously within a single organism. Instead of one guide RNA, researchers design several guide RNAs targeting different genes.

Why Is It Important?

Most important agricultural traits are polygenic, meaning they are controlled by multiple genes working together.

- Drought tolerance in crops involves stress-response genes, hormone signaling genes, and root development genes.
- Disease resistance often requires disabling susceptibility genes and activating defense-related genes.
- Nutritional improvement may involve altering several metabolic pathways.

Editing only one gene often gives limited improvement. Multiplex CRISPR enables coordinated modification of several genes to achieve stronger and stable trait expression. This saves time and increases efficiency dramatically.

1. Yield Improvement in Rice

In *Oryza sativa*, yield is controlled by multiple genes regulating grain size, grain number, and plant architecture.

Scientists have simultaneously edited genes such as:

- **Gn1a** – regulates grain number per panicle
- **DEP1** – controls panicle density
- **GS3** – influences grain size
- **IPA1** – affects plant architecture

By editing multiple yield-related genes together, researchers achieved greater yield improvement than targeting a single gene.

2. Disease Resistance

Some pathogens exploit plant susceptibility genes. Instead of introducing resistance genes, scientists knock out susceptibility genes.

Examples include:

- **MLO gene** – powdery mildew susceptibility
- **SWEET genes** – bacterial blight susceptibility

Multiplex CRISPR allows simultaneous editing of multiple susceptibility genes, providing broader and more durable resistance.

3. Tomato Plant Architecture

In *Solanum lycopersicum*, plant growth and fruit production are regulated by multiple genes.

- **SP (Self-Pruning)** – controls growth habit
- **CLV3** – affects fruit size
- **FAS (Fasciated)** – influences fruit locule number

Compact plants with higher fruit yield and improved productivity.

4. Abiotic Stress Tolerance

Climate change has increased drought, salinity, and heat stress in agricultural fields. Multiplex editing can target genes such as:

- **DREB transcription factors** – drought response
- **HKT genes** – salinity tolerance
- **NCED genes** – ABA biosynthesis under stress

Editing multiple stress-response genes strengthens plant resilience under harsh environmental conditions.

5. Nutritional Enhancement (Biofortification)

Improving crop nutritional quality requires modifying metabolic pathways. In crops like *Triticum aestivum*, and *Zea mays*. Multiplex editing is being explored to increase micronutrient content, reduce anti-nutritional factors and improve protein quality. This contributes to combating hidden hunger and malnutrition.

6. Hybrid Breeding and Male Sterility

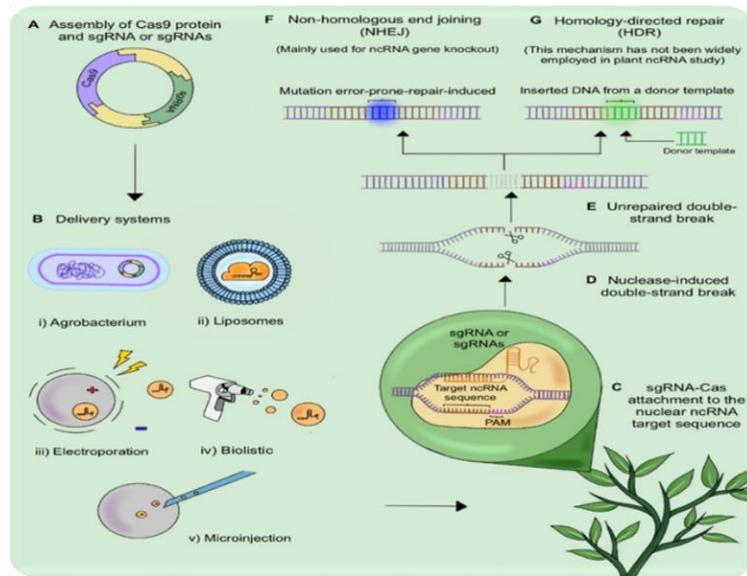
Multiplex CRISPR can generate male sterile lines by editing fertility-related genes. This supports hybrid seed production and improves heterosis exploitation.

How Multiplex CRISPR Works: Step-by-Step

1. **Gene Identification**
Scientists identify multiple target genes linked to a trait.
2. **Guide RNA Design**
Separate guide RNAs are designed for each gene.
3. **Vector Construction**
Multiple guide RNAs are inserted into a single CRISPR vector.
4. **Delivery**
The CRISPR construct is delivered into plant cells, animal cells, or embryos.
5. **Simultaneous Editing**
Cas protein cuts DNA at all targeted sites.
6. **DNA Repair and Mutation Formation**
The cell's natural repair system introduces mutations.

7. Screening

Edited organisms are screened to confirm successful multiplex editing.

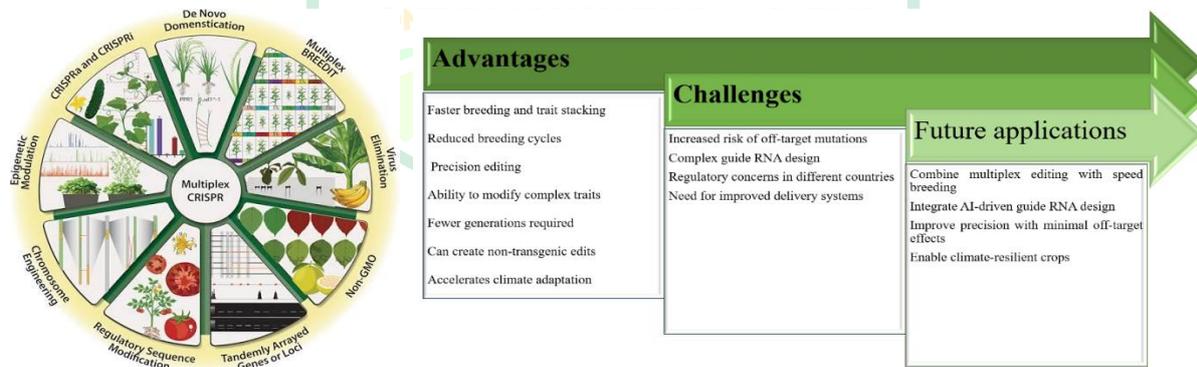


Integration with Modern Breeding Technologies

Multiplex CRISPR can be combined with:

- Speed breeding
- Genomic selection
- Marker-assisted selection
- Automated phenotyping
- AI-based gene prediction

This integration creates a powerful breeding pipeline for next-generation agriculture.



Conclusion

Multiplex CRISPR gene editing represents a major leap forward in biotechnology. By enabling simultaneous modification of multiple genes, it allows scientists to tackle complex traits more effectively. From yield enhancement in *Oryza sativa* to stress tolerance in *Triticum aestivum*, and *Zea mays*, plant architecture in *Solanum lycopersicum*, multiplex CRISPR gene editing is revolutionizing crop improvement.

It is not merely a laboratory technology, it is becoming a practical tool for farmers, breeders, and agricultural scientists. By editing multiple genes simultaneously, agriculture can move toward smarter, faster, and more sustainable crop development.

Multiplex CRISPR is shaping the future of farming—one precise genetic improvement at a time.

Integrated Approaches for the Management of Wheat Aphid in Wheat (*Triticum aestivum*)



Anupam Chaubey¹, Anil Patel^{1*} and Shivanshu², Shivani Tripathi³

¹Department of Entomology

²Department of Agronomy

³Department of Plant Pathology

Acharya Narendra Deva University of Agriculture & Technology Kumarganj,
Ayodhya-224229 (U.P.) India

*Corresponding author email: patelanil81344@gmail.com

INTRODUCTION

Wheat (*Triticum aestivum*) is one of the most significant cereal crops and a staple in the diets of many nations. Maintaining wheat yield is crucial for food security and farmer livelihoods in India and many other wheat-growing nations. The plains states of Punjab, Haryana, and Uttar Pradesh are the main producers of wheat in India. Their contribution to the national wheat pool is significant. The wheat granary is another name for the state of Punjab. The other states that grow wheat include Karnataka, Bihar, Rajasthan, Gujarat, and Maharashtra. Around the world, hundreds of insects have been found on wheat. However, a variety of insect pests that seriously impair grain quality and productivity are common problems in wheat farming operations.

According to recent studies, insect pests significantly reduce wheat's economic value. While insect-related yield losses worldwide range from 5% to 9% annually, field insect pests in India are projected to generate an annual financial loss of USD 49.85 million in wheat. The Gujha weevil and grasshoppers were the only significant insect pests in wheat until the late 1960s. However, aphids, termites, armyworms, brown mites, pink stem borer, and grasshoppers are currently major problems for wheat. But among all insect pests Aphid one of the most damage causing pest in wheat.

Aphids (*Sitobion avenae*, *S. miscanthi*, *Rhopalosiphum padi* and *R. maidis*)

DISTRIBUTION & DEVELOPMENT

Asiatic in origin, the English grain aphid (*Sitobion miscanthi*) is common throughout China, India, the Far East, and the Pacific. Australia, New Zealand, and potentially a number of Pacific islands have been exposed to it. It is frequently referred to as the Indian grain aphid. The corn leaf aphid (*Rhopalosiphum padi*) is found all over the world in tropical, subtropical, and warmer temperate climates. All of India's wheat-growing regions, particularly the NWPZ and Peninsular India, are generally home to aphids.

Aphids come in two separate stages: sexual and asexual, winged (alates) and wingless (apterous). *S. miscanthi*'s apterous adults have a broad spindle form. The body has a bulging abdomen and is green or radish-brown to dark-brown. The alatae have similar colours, but their dorsal abdominal patterns are broader and darker. Compared to those in East Asia, they are smaller in northern India. Asexual reproduction, in which females directly produce nymphs instead of eggs, is responsible for the quick spread. Until crop maturity, infestation often happens in the second two weeks of January.

HOST RANGE

S. miscanthi feeds on a variety of Gramineae/Poaceae species. Additionally, it occasionally occurs on dicotyledons, such as *Polygonum hydropiper* in Australia. Corn (maize) is the aphid's main host. Alternative hosts include sorghums, sugarcane, tobacco, wheat, barley, green beans, millets, papaya, potatoes, rice, squash, and other Gramineae.

SYMPTOM OF DAMAGE

Punjab's wheat farming is seriously threatened by wheat aphids. The location of infestation was clearly preferred by all three species. All plant sections above ground were attacked by *R. padi*; leaves and stems were more frequently affected. *S. miscanthi* was the predominant species on ear heads, although it also infested leaves. *R.*

maidis was restricted to leaf whorls. These are louse-like, soft-bodied, green to blackish green insects that live in tiny colonies on leaves and ear heads. Aphids grow on leaves, flag leaves, leaf sheaths, and ear head spikelets. The sap from the leaves and developing grains is sucked by both nymphs and adults. They typically cover the whole surface of the stem due to their quick multiplication within a few days, which results in yellowing, curling, and subsequent drying of the leaves, which eventually reduces the quantity and size of earheads. Additionally, the aphids release honeydew, which causes black sooty mould to grow and impede the leaves' ability to photosynthesis. At the earhead stage, excessive aphid numbers might result in significant yield reductions. The damage of the aphids first starts from the periphery of the field, particularly from the side on which trees are present. If sprayed there, its further spread in the field can be checked.

MORPHOLOGY

Populations are primarily composed of females that reproduce without mating. They do not lay eggs, but instead give live young. There are four nymphal stages.

***S. miscanthi*:** The adult apterae are formed like a wide spindle. The body is reddish-brown to dark brown or green. The *siphunculi* are lustrous black or dark brown, darker than the body. The cauda is not too dark. It is six to seven times the length of the *siphunculi*, with a body length of 1.7–3.0 mm. The length of the *siphunculi* is 1.4–1.9 times that of the cauda. Segment II of the hind tarsus is 1.0–1.3 times longer than the rostrum's final segment. 4.5–6.0 times longer than the base of the final antennal segment is the processus terminalis. The alatae have larger and darker dorsal abdominal patterns, but their colours are comparable.

***Rhopalosiphum maidis*:** First instar nymphs of *S. miscanthi* are light green, with the tips of the head, antennae, and legs slightly darker than the body. The second instar nymphs appear pale green, with a darker head, abdomen, and antennae, while the legs remain paler. Their eyes are red. A distinct constriction is present on the third antennal segment, which later divides into two segments at this stage. The body remains pale green but is slightly darker on the sides, and the legs are darker than the body. The head is dark green. Adults can be winged (alate) or unwinged (apterous), elongated, and measure between 1/25 and 1/12 inch. Their colouration varies from yellow-green to dark olive green or bluish green, often with a light powdery coating. They tend to be darker in cooler weather and may be pale green in warmer weather. The head, antennae, and legs are black.



Fig. 1



Fig. 2



Fig. 3

Figures were collected from Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India

BIOLOGY

Aphids are anholocyclic across their entire geographic range. There are a few descriptions of sexual forms. Throughout its range, apterous (wingless) and alate (winged) females reproduce by parthenogenesis, giving birth to live offspring. Aphids undergo four nymphal instars, each lasting roughly two days, before maturing into adults. Development takes 7-8 days, depending on the temperature. While alatae are adapted for long-distance dispersal and are in charge of the initial colonization of pasture grasses and cereals, apterae are adapted to take advantage of the host plants on which they develop. Population breakouts can result from rapid reproduction under favourable circumstances. When the plants become nutritionally inappropriate or are overcrowded, the alates are formed. The developmental rate, number of progenies, and adult longevity are greatly influenced by temperature, host plant species and host plant age.

MANAGEMENT

Biocontrol of Wheat Aphid: Wheat aphids are attacked by a variety of predators and parasites. These include the parasitic wasps, several species of ladybeetles and green lacewings. These benefits help keep greenbug populations from increasing to damaging levels for many years.

Lady Beetles: Wheat is home to several species of lady beetles, the most prevalent of which is the seven-spotted lady beetle, *Coccinella septempunctata*. Every season, lady beetles work together to reduce aphids in little grains to some extent. However, lady beetles leave little trace of their dominance since they eat the aphids. The absence of serious aphid issues later in the year may be the only clue. Aphid populations cannot be entirely reduced by a single species of lady beetle, and studies have indicated that augmentation by the release of lady beetles is not very beneficial. Conservation is the most important thing a farmer can do to support lady beetles in controlling aphids. Conservation primarily means avoiding broad-spectrum insecticides and using the lowest rate of insecticide that achieves adequate control of the target pest. It is also helpful to apply insecticides when the lady beetle population consists of egg or pupal stages rather than young larvae.

Parasitic wasps: Tiny black wasps called *Lysiphlebus testaceipes*, *Diaeretiella rapae*, and *Aphelinus varipes* parasitise wheat aphids wherever this pest is present. Wheat growers should be able to identify the characteristic parasitised wheat aphid mummies, which stay attached to the wheat leaf, even if the adult wasps are rarely observed. The spherical, bloated greenbug mummies that are parasitised by *L. testaceipes* and *D. rapae* are either tan or beige.

Lacewings: Wheat is one of the several crops that have green lacewings. The significance of lacewings in the biological control of green bugs, however, is not well understood. All lacewings' larval stages are predators that mostly consume aphids, though they also consume insect eggs and tiny caterpillars. Certain lacewing species, like *Chrysoperla carnea*, only eat pollen or honeydew as adults. Although they are uncommon in wheat, lacewing larvae support other predators.

When aphid colonization begins, apply 40 milliliters of imidacloprid 200 SL, 20 grams of thiamethoxam 25 WG or 12 grams of clothianidin 50 WDG, 150 milliliters of dimethoate 30 EC or oxydemeton methyl 25 EC in 80–100 liters of water per acre using a backpack sprayer or 30 litres of water using a power sprayer. After fifteen days, if needed, repeat the spray. Ten randomly chosen ear heads in each of the four quarters of an acre were used to record the number of control aphids at the ear head stage at the economic threshold level of five aphids per ear head. Spray just the diseased strip to prevent the aphids from spreading farther because they first show up on the crop's edges.

CONCLUSION

In India, wheat aphids are a significant pest of wheat, particularly in the late vegetative and ear head stages under favourable circumstances. Effective management relies on integrated pest management (IPM). Regular field monitoring facilitates early detection, particularly at field edges where aphids first appear. Aphid populations can be managed, and the need for chemical treatments can be reduced, by protecting natural enemies such as lady beetles, lacewings, and parasitic wasps. Only when aphid populations surpass the economic threshold level of five aphids per ear head should chemical measures be employed; selective insecticides are preferred to safeguard beneficial organisms. Timely, need-based application of appropriate pesticides, coupled with biological and cultural techniques, can effectively manage wheat aphids while decreasing input costs and environmental concerns. Integrated techniques eventually support stable yields, improved grain quality, and sustainable wheat production.

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“Farmer Producer Organizations (FPOs): Working Together for Better Farm Incomes”



Dr. T. Sri Chandana¹, Dr. K. Raghavendra Chowdary², N. Teja Kumar³, Dr. Y. Mounika⁴, Dr. M. V. Niranjan Reddy⁵ and B. Anil Kumar⁶

¹SMS (Extension), Dept. of Agricultural Extension, Krishi Vigyan Kendra, Banavasi-518 360,

²Programme Coordinator, Dept. of Agricultural Extension, Krishi Vigyan Kendra, Banavasi-518 360, ³PA (STL), Dept. of Agriculture, Krishi Vigyan Kendra, Banavasi-518 360, ⁴SMS

(Horticulture), Dept. of Horticulture, Krishi Vigyan Kendra, Banavasi-518 360, ⁵SMS

(Veterinary), Dept. of Veterinary Science, Krishi Vigyan Kendra, Banavasi-518 360 and ⁶Young Professional-II, Special Project on Cotton, Krishi Vigyan Kendra, Banavasi-518 360

Introduction

Indian agriculture is dominated by small and marginal farmers, who constitute more than 85 per cent of the total farming community. These farmers often face multiple constraints such as fragmented landholdings, limited access to quality inputs, inadequate credit facilities, lack of timely market information, poor bargaining power, and high transaction costs. As a result, farming often becomes less remunerative and risky, affecting the socio-economic well-being of rural households.

Farmer Producer Organizations (FPOs) have emerged as one of the most promising institutional innovations to address these challenges. By collectivizing farmers into a formal organization, FPOs enable members to achieve economies of scale in production, procurement, processing, and marketing. Collective action not only reduces costs but also enhances farmers' negotiating strength in both input and output markets. FPOs also facilitate the adoption of modern technologies, improved agronomic practices, and value addition activities, thereby enhancing productivity and income.

Recognizing their importance, the Government of India has promoted FPOs through various agencies such as the Small Farmers Agribusiness Consortium (SFAC), National Bank for Agriculture and Rural Development (NABARD), National Cooperative Development Corporation (NCDC), and National Agricultural Cooperative Marketing Federation of India (NAFED). Krishi Vigyan Kendras (KVKs) play a crucial role in providing technical backstopping, capacity building, and handholding support to FPOs. Despite significant policy support, several FPOs continue to face issues related to governance, financial sustainability, professional management, and market integration, which need systematic strengthening for long-term success.

Current Status of FPOs in India

A Producer Organization is a legally recognized entity formed by primary producers such as farmers, fishermen, livestock rearers, and weavers. When the primary producers are farmers, the organization is referred to as a Farmer Producer Organization (FPO). According to NABARD (2015), FPOs are farmer-owned institutions aimed at enhancing farmers' income through collective action.

FPOs in India can be registered under different legal frameworks, including the Companies Act (as Producer Companies), Cooperative Societies Acts, Societies Registration Act, or Trust Acts. Among these, Producer Companies have gained prominence due to their hybrid structure that combines the cooperative principle of member ownership with the efficiency and professionalism of corporate management.

The concept of farmer collectivization in India is not new. Cooperative movements in dairy and sugar sectors have existed since the early twentieth century. However, many traditional cooperatives suffered from excessive government control, political interference, weak governance, and limited member participation. To overcome these limitations, the Y. K. Alagh Committee (2000) recommended the introduction of Producer Companies, leading to their inclusion in the Companies Act in 2003. The National Policy for Promotion of Farmer Producer Organizations (2013) further provided a comprehensive framework for the promotion and sustainability of FPOs.

As per recent estimates, India has over 24,000 registered Farmer Producer Companies, of which more than

23,000 are active. In addition, there are over 2.14 lakh non-credit agricultural cooperatives. Under the Central Sector Scheme for the Formation and Promotion of 10,000 FPOs, about 7,597 FPOs were registered across 34 States and Union Territories by April 2024. Major concentrations of FPOs are observed in Maharashtra, Karnataka, Madhya Pradesh, Telangana, Uttar Pradesh, and Andhra Pradesh, reflecting strong institutional support and favorable policy environments in these states.

Performance of FPOs in India

Under the Central Sector Scheme, Implementing Agencies (IAs) and Cluster Based Business Organizations (CBBOs) are responsible for mobilization, formation, and handholding of FPOs. The scheme provides financial assistance in the form of equity grants and management cost support to strengthen FPO operations during the initial years. At the national level, 7,597 FPOs have been allocated to various Implementing Agencies. Of these, 2,740 FPOs have been formally registered. A matching equity grant of ₹116.6 crore has been released, while ₹291.94 crore has been sanctioned towards FPO management costs. Additionally, ₹255.5 crore has been allocated towards CBBO management costs. These investments indicate the government's strong commitment to building robust farmer collectives. The performance of FPOs varies widely across regions and commodities. Successful FPOs have demonstrated significant improvements in input cost reduction, access to institutional credit, value addition, and market realization. However, some FPOs remain dormant or weak due to limited member participation, lack of professional leadership, and inadequate business planning. Continuous capacity building and market-oriented interventions are therefore essential.

Status and Performance of FPOs in Andhra Pradesh

In Andhra Pradesh, 461 FPOs have been allocated under the Central Sector Scheme. Out of these, 355 FPOs have been registered and are at different stages of operationalization. The state has received a matching equity grant of ₹4.39 crore, ₹7.64 crore towards FPO management costs, and ₹9.21 crore for CBBO management costs.

Many FPOs in the state have initiated business activities such as supply of quality inputs including seeds, fertilizers, and pesticides; aggregation and collective marketing of members' produce; custom hiring of farm machinery; and value addition activities like cleaning, grading, sorting, processing, and packaging. Crops such as red gram, Bengal gram, groundnut, millets, and oilseeds form the major focus of FPO operations in the state.

Major Organizations Promoting FPOs in India

Several national and state-level organizations are actively involved in the promotion of FPOs. Key institutions include the Small Farmers Agribusiness Consortium (SFAC), NABARD, National Association for Farmer Producer Organisations (NAFPO), SwitchON Foundation, and the National Cooperative Development Corporation (NCDC). These organizations provide financial support, technical guidance, policy advocacy, and capacity building to strengthen FPO ecosystems across the country.

Steps in Establishing an FPO

1. Pre-formation Stage: Mobilization and Planning

This stage involves identifying common problems faced by farmers such as low market prices, high input costs, and lack of access to technology. Awareness programs, group meetings, and exposure visits are organized to sensitize farmers about the benefits of collectivization. Generally, 300–500 farmers from a contiguous area with similar cropping patterns are mobilized. A baseline survey is conducted to understand socio-economic conditions, cropping systems, productivity levels, and income status.

2. Formation Stage: Legal Registration

During this stage, the FPO is legally registered, most commonly as a Producer Company under the Companies Act, 2013. Promoting institutions such as KVKs, NABARD, SFAC, NCDC, NGOs, or State Departments act as CBBOs. Farmers become shareholders by purchasing shares, and a Board of Directors is elected. Bylaws, governance structures, and a detailed business plan are prepared.

3. Post-formation Stage: Capacity Building and Operations

Capacity building is a critical component of FPO development. Training is imparted on governance, financial management, bookkeeping, statutory compliance, and business operations. Bank accounts are opened, and linkages are established with financial institutions. Infrastructure facilities such as storage, grading units,

processing units, and custom hiring centers are developed. FPOs undertake activities like bulk input procurement, produce aggregation, value addition, and collective marketing.

4. Sustainability Stage

For long-term sustainability, professional staff such as a Chief Executive Officer or Manager is appointed. FPOs diversify their business portfolio, build partnerships with buyers and financial institutions, adopt digital platforms, and continuously monitor performance. Profits are either distributed among members or reinvested to strengthen the organization.

Role and Impact of KVK Banavasi as CBBO

Krishi Vigyan Kendra (KVK), Banavasi, formed its first FPO in 2019 and obtained CBBO status from NCDC in 2021. As a CBBO, KVK Banavasi promoted and handheld Sevalal FPO and Sri Lakshmi Narasimha Swamy FPO in Pattikonda block of Kurnool district, Andhra Pradesh. Both FPOs were formed with 750 farmer members each and received equity grants and management cost support from NCDC.

KVK Banavasi played a pivotal role in conducting baseline surveys, organizing awareness programs, facilitating licenses, establishing market linkages, and providing continuous technical and managerial support. The FPOs diversified into value addition activities such as groundnut oil, chikki, salted peanuts, and millet-based products. Over a three-year period, the business turnover of both FPOs increased significantly, demonstrating the effectiveness of systematic handholding and business-oriented interventions.

Empowering Rural Farmers through FPOs

FPOs enhance farmers' access to quality inputs, affordable credit, and modern technologies, leading to improved productivity and reduced production costs. Collective bargaining and aggregation strengthen farmers' position in the market and ensure better price realization. Financial inclusion through institutional credit enables investment in infrastructure and sustainable practices. Skill development and capacity building improve farmers' resilience, risk management, and income stability.

Conclusion

Farmer Producer Organizations serve as powerful instruments for the economic and social empowerment of rural communities. By addressing key constraints related to markets, finance, technology, and capacity building, FPOs enable smallholder farmers to achieve sustainable livelihoods. Successful experiences from states like Andhra Pradesh and institutions like KVK Banavasi clearly demonstrate that well-supported FPOs can transform rural economies, promote inclusive growth, and build resilient agricultural systems.

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Millets to Money: Value Addition Opportunities with KVK Support



Dr. T. Sri Chandana¹, Dr. Y. Mounika², Dr. K. Raghavendra Chowdary³, N. Teja Kumar⁴ and Dr. M. V. Niranjan Reddy⁵

¹SMS (Extension), ²SMS (Horticulture), ³Programme Coordinator, ⁴PA (STL) and ⁵SMS (Veterinary) Krishi Vigyan Kendra, Banavasi-518 360

Millets in Indian Agriculture

Millets are one of the key crops in Indian agriculture. These grains have gained popularity among people in various ways as healthy food items. Finger millet (Ragi), Sorghum (Jowar), Pearl millet (Sajja), Kodo millet, Foxtail millet (Korra), and other millets are rich in nutrition, protein, fiber, vitamins, and minerals.

Challenges and Solutions

Although farmers cultivate these crops, their income remains limited due to low market value, market challenges, and a lack of processing efficiency. Keeping these challenges in mind, Krishi Vigyan Kendras (KVKs) have initiated several programs to increase the value of millets through technical assistance, training programs, and market linkage for farmers.

Role of KVKs in Andhra Pradesh

In Andhra Pradesh, Krishi Vigyan Kendras play a vital role in promoting millet-based value-added products. They provide training to farmers and rural youth on millet processing, value addition, food preparation, packaging, and marketing.

KVKs teach farmers millet processing methods and demonstrate ways to convert them into more nutritious, healthy, and high-demand products. By processing millets and increasing their value, farmers can increase their income in multiple ways.

- **Value-Added Products:** For example, by making products like millet flour, biscuits, laddus, payasam (kheer) mixes, and millet chocolates, farmers can sell their produce at higher prices in the market.

Training and Marketing

The training provided by KVK includes the manufacturing of value-added products using processing machines, packaging technology, and marketing strategies. In this way, farmers are gaining the opportunity to increase their income by bringing their products directly to the market and receiving assistance in transport and sales management.

Millet Processing Awareness

Through the program 'Millet Products after Processing – Value Added Products, trained farmers are expanding their business not just by cultivating millets, but by manufacturing various value-added products and selling them in urban markets.

Importance of Millets – Key Features

- **Eco-friendly:** Millets require less water and fewer chemicals.
- **Nutritional Value:** These grains are packed with nutrients like proteins, calcium, iron, vitamins, and fibre.
- **Production Efficiency:** They grow at a very low cost and offer opportunities for high profits.
- **Wide Market Demand:** Due to the increasing number of health-conscious people, the demand for millets has also increased.

Millet Processing Steps:

1. **First Stage:** After harvesting the grain, it must be cleaned to remove impurities. This is the first stage of processing.
2. **Second Stage:** Drying the grain thoroughly and making necessary flour or other products.
3. **Product Manufacturing:** Products made from millets are listed below:

Millet Products Table

Millet Flours	Millet Snacks	Breakfast Products	Beverages	Other Special Products
Ragi Mudda (Finger Millet Ball)	Ragi Biscuits	Ragi Java (Porridge)	Millet Pasta	(Not specified)
Jowar (Sorghum)	Millet Mixed Laddu	Korra (Foxtail Millet)	Millet Milk Powder	Ragi Noodles
Sajja (Pearl Millet)	Sajja Rotis	Korra Ponganalu	Ragi Milkshake Mix	Millet Mixed Parothas
Korra (Foxtail Millet)	Jowar Chakralu (Murukku)	Ragi Chips	Millet Coffee Mix	Ragi, Jowar Rava (Semolina)
Sama (Little Millet)	Ragi Halwa			

4. **Packaging & Marketing:** Through good packaging and branding, farmer products can attract consumers.

5. Millet Processing and Government Schemes

Central Government Schemes for Millet Processing Units

Krishi Vigyan Kendras (KVK) offer several schemes to farmers for establishing millet value-added processing units. Through these schemes, farmers can process millets, increase their value, and gain the opportunity to earn higher income.

1. PM Formalisation of Micro Food Processing Enterprises (PMFME)

- **Objective:** To increase income by processing local products like millets.
- **Key Highlights:**
 - Subsidy of 35% of the project cost (up to ₹10 Lakhs) for millet processing units.
 - Promoting the "One District - One Product" policy.
 - Training and technical guidance.
- **Benefits:** Useful for making products like Ragi Java powder, Millet Upma mix, and Millet Laddus.

2. Rashtriya Krishi Vikas Yojana (RKVY)

- **Objective:** For farmers to adopt changes in millet processing and value-added product manufacturing.
- **Key Highlights:**
 - Financial assistance for setting up processing units.
 - Support for Marketing and Branding.
 - High-value processing and low-loss management.

3. KVK Special Training Programs

- **Objective:** Teaching millet processing methods and adding value to agricultural products.
- **Key Highlights:**
 - Conducting practical training camps.
 - Awareness on the usage of processing machines.
 - Focus on product packaging and branding.
- **Benefits:** Farmers can make tasty and nutritious products with millets and sell them in the market.

4. Special Schemes for Women Farmers

- **Objective:** Encouraging women farmers to set up millet processing units.
- **Key Highlights:**
 - Small-scale machines with subsidy.
 - Marketing products through Women Farmer Groups (SHGs).
 - Training in Millet Laddu making.
- **Benefits:** Women can easily market their products and increase their income.

Conclusion

Millet processing is a significant sector bringing changes to the agricultural field. The schemes provided by KVK for setting up processing units play a key role in providing financial self-reliance to farmers. Institutions like KVK

provide technical and financial support, helping farmers add more value to their products through processing “Add value to millets, Increase farmers' income”.

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INNOVATIVE NUTRITIONAL STRATEGIES FOR REVOLUTIONIZING ANIMAL HUSBANDRY IN INDIA



Dr. Anand Kumar Pathak

Associate Professor
Division of Animal Nutrition
Faculty of Veterinary Sciences and Animal Husbandry,
Sher-e-Kashmir University of
Agricultural Sciences and Technology, R. S. Pura-181102, Jammu

Introduction

Animal husbandry occupies a central position in India's rural economy, serving as a critical source of livelihood, nutritional security and socio-economic stability for millions of households. With one of the world's largest livestock populations, India has achieved remarkable progress in milk, meat and egg production over the past few decades. However, the sector continues to face persistent challenges, including low productivity per animal, feed and fodder shortages, rising input costs, climate variability and increasing pressure on natural resources. In this context, nutrition emerges as one of the most powerful yet underutilized tools for transforming livestock productivity and sustainability. Innovative nutritional strategies have the potential to redefine animal husbandry in India by enhancing production efficiency, improving animal health, reducing environmental impacts and strengthening farmer incomes.

Nutrition forms the foundation of livestock performance. The genetic potential of animals, however superior, cannot be realized without balanced and scientifically formulated feeding practices. Traditional feeding systems in many parts of India rely heavily on crop residues, unbalanced rations and seasonal fodder availability, often leading to nutrient deficiencies that limit growth, reproduction and disease resistance. Moreover, increasing competition between humans and livestock for grains and water resources necessitates the development of alternative, efficient and sustainable feeding approaches. Innovative nutritional strategies aim to address these challenges by optimizing nutrient utilization, diversifying feed resources and integrating scientific advancements into practical farm-level applications.

One of the key aspects of nutritional innovation lies in the efficient use of locally available resources. India produces vast quantities of agricultural by-products and agro-industrial residues that remain underutilized or wasted. Scientific processing and value addition of such materials into nutritionally balanced feed can significantly reduce feeding costs while minimizing environmental waste. Technologies such as feed enrichment, densification and biological treatment improve digestibility and nutrient availability, enabling farmers to convert low-quality biomass into productive animal feed. Such approaches not only enhance animal productivity but also promote circular agricultural systems where waste from one sector becomes an input for another.

Precision nutrition represents another transformative dimension in modern animal husbandry. Advances in animal nutrition science now allow feeding strategies to be tailored according to species, breed, and physiological stage and production goals. Balanced ration formulation, mineral supplementation and strategic feeding during critical life stages such as early growth, pregnancy and lactation can dramatically improve productivity and reproductive efficiency. Precision feeding reduces nutrient losses, lowers feed wastage and enhances feed conversion efficiency, thereby contributing to both economic and environmental sustainability. In a country where feed constitutes the largest share of livestock production costs, such optimization can have far-reaching impacts on profitability and resource conservation.

The integration of biotechnology and nutritional science further expands opportunities for innovation. The use of probiotics, prebiotics, enzymes and functional feed additives is increasingly recognized for improving gut health, enhancing immunity and reducing dependence on antibiotics. These nutritional interventions support healthier animals capable of withstanding disease challenges and environmental stress. Additionally, emerging

research on nutrigenomics the interaction between nutrition and gene expression offers promising pathways for enhancing productivity while maintaining animal welfare. Although still evolving, such approaches indicate the future direction of livestock nutrition in a rapidly modernizing agricultural landscape.

Sustainability considerations are also driving the adoption of innovative feeding strategies. Livestock production is often criticized for its environmental footprint, particularly methane emissions and inefficient resource utilization. Nutritional interventions, including improved forage quality, feed additives that reduce enteric methane production and optimized protein feeding can significantly lower emissions while maintaining or even increasing productivity. By improving digestion and reducing nutrient excretion, these strategies contribute to cleaner production systems aligned with national and global sustainability goals. In the Indian context, where smallholder systems dominate, environmentally sound nutritional practices can simultaneously enhance resilience against climate variability and resource scarcity.

Equally important is the role of nutrition in ensuring animal health and welfare. Malnutrition and mineral deficiencies frequently result in reproductive disorders, metabolic diseases and weakened immunity leading to economic losses for farmers. Preventive nutrition, emphasizing balanced diets and targeted supplementation, reduces disease incidence and veterinary expenses while improving longevity and lifetime productivity of animals. Healthy animals not only produce more but also contribute to safer and higher-quality animal products for human consumption, strengthening the link between livestock nutrition and public health.

The success of innovative nutritional strategies ultimately depends on effective dissemination and adoption at the grassroots level. Strengthening extension services, promoting farmer awareness, encouraging public-private partnerships and integrating digital tools for ration formulation and advisory services are essential for bridging the gap between scientific knowledge and field application. Policy support, investment in feed research and development of region-specific feeding models can accelerate this transition toward nutrition-driven livestock development. To truly revolutionize animal husbandry in India, innovative nutritional strategies must be combined with genetic enhancement, health protection, infrastructure and capacity-building. This paper explores the latest and emerging nutritional innovations including alternative feed resources, feed technology, micronutrient supplementation, precision feeding and integrated waste-to-wealth models along with their institutional and policy foundations.

Context and policy framework

A supportive policy ecosystem is crucial for scaling nutritional innovations.

National livestock mission (NLM)

The national livestock mission promotes breed improvement, feed and fodder development and R&D, with sub-missions focused on fodder seed production, silage units, feed testing and entrepreneurial support.

Mission and genetic tools

The rashtriya gokul mission (RGM) focuses on conservation and genetic upgradation of indigenous bovine breeds. Recent innovations include genomic chips like Gau chip and Mahish chip, subsidized to enable precision breeding in cows and buffaloes.

Animal husbandry infrastructure development fund (AHIDF)

The AHIDF, with a 15,000 crore corpus supports investment in dairy processing, feed infrastructure (silage, mineral mix plants) and feed testing laboratories.

Disease control and veterinary services

Under the livestock health and disease control program (LHDCP), including national disease control programme (NADCP) and commission for agricultural costs and prices (CACP), India targets eradication of major diseases (FMD, PPR, Brucellosis), expands mobile veterinary units and ensures affordable veterinary medicines.

Integration and extension outreach

Schemes like national livestock mission's extension component and rashtriya gokul mission's fertility camps, field schools, in-vitro fertilization (IVF)/ artificial insemination (AI) with sex-sorted semen and training programmes embed nutritional strategies within wider capacity building.

Innovative feed and fodder solutions

Traditional feed enhancement

Such as fodder blocks (functional feed supplementation blocks, multi-nutrient blocks and densified functional feed blocks), silage, hay and azolla, etc. technological implementation should be undertaken. The government promotes fodder block-making units, silage-making units, chaff cutters, and Azolla cultivation units to improve fodder utilization and preserve nutrition during lean seasons. Silage units reduce wastage and ensure year-round green fodder access, while Azolla (a protein-rich fern) supports ruminants and non-ruminants (swine and poultry) health and production.

Area-specific mineral mixtures and by-pass protein units

To tackle regional mineral deficiencies, area-specific mineral mixture units are being incentivized, alongside by-pass protein production units for supporting rumen-protected protein supply.

Total mixed ration (TMR)

TMR plants, such as those being set up by Amul in Gujarat, and other private dairy organization in other parts of the country produce nutrient-balanced mixes combining forages, concentrates, protein, minerals and vitamins; these improve digestibility, reduce methane emissions and standardize feeding practices.

Alternative feed sources:

Properly processed insects and microalgae may become the emerging research highlights:

Insect-based feeds (e.g., black soldier fly larvae, crickets): highly efficient protein converters, lower greenhouse gas emissions, requiring less feed-input per unit protein compared to conventional livestock.

Microalgae-based feed (e.g. *Chlorella*, *Arthro spira*): protein content 40–60% enhances growth and product quality even when included at 4–8% of feed.

Although regulatory frameworks (Bureau of Indian Standard; BIS / food safety and standards authority of India; FSSAI) are still evolving, these alternative feeds offer sustainability and nutritional benefits.

Waste-to-wealth: Dung management, bio-fertilizer, biogas

Integrated models under Gobardhan Yojna (GY) and animal husbandry infrastructure fund (AHIDF) promote biogas plants, bio-slurry to bio-fertilizer, biogas-based energy and phosphate rich organic manure (PRoM) production and effectively converting animal waste into value while reducing methane emissions. Godhan Nyay Yojana in Chhattisgarh purchases cow dung to make vermin-compost for sale, incentivizing manure management and benefitting women self-help groups (SHGs).

Precision nutrition and monitoring

Pervasive sensing and automated monitoring

Pervasive sensing and automated monitoring involve continuous collection of animal health, behaviour and production data through sensors, wearable devices and smart farm systems. Technologies such as activity trackers, rumination sensors, temperature monitors and automated weighing systems help detect early signs of disease, stress or nutritional imbalance. Real-time data enables farmers to make timely feeding and management decisions, improving feed efficiency and animal welfare. Automated alerts reduce labour dependency and minimize production losses by allowing early intervention. These systems support precision nutrition by aligning feed delivery with individual animal needs, enhancing productivity, reducing waste and promoting sustainable livestock management through data-driven decision-making.

Recent literature surveys emphasize pervasive sensing computer vision, RF, wearable's, vibration sensors for real-time monitoring of livestock health, behaviour and feeding patterns. These enable early disease detection, optimize feeding schedules and enhance welfare compliance. Similar to automated feeding behaviour monitoring systems collect motion, sound, images and pressure data to inform nutrition delivery and efficiency.

Mobile and app-based tools

Government tools like the eGopala App assist farmers in balanced feeding recommendations, integrating breed-specific nutritional guidelines at the grassroots. Mobile and app-based tools play a significant role in precision animal nutrition by providing farmers with easy access to advisory services, feeding plans, health records and performance tracking. Smartphone applications enable real-time data entry, ration formulation, disease reporting and monitoring of milk yield or growth performance. Integration with cloud platforms allows remote expert

consultation and timely recommendations based on animal-specific data. These tools improve decision-making accuracy, enhance record keeping and support early problem detection. By simplifying complex nutritional information into practical guidance, mobile technologies empower farmers to optimize feeding strategies, improve productivity, reduce input costs and ensure better herd health management in diverse farming conditions.

Preventive mineral supplementation

Preventive mineral supplementation focuses on maintaining optimal mineral balance in animals to avoid deficiencies that affect growth, reproduction, immunity and productivity. Essential minerals such as calcium, phosphorus, zinc, copper and selenium are often deficient in natural feed resources, especially under intensive production systems. Providing balanced mineral mixtures based on regional deficiencies helps prevent metabolic disorders, poor fertility and reduced milk or meat yield. Precision nutrition approaches use soil, fodder and animal analysis to determine specific mineral needs. Regular supplementation strengthens immune response, enhances feed utilization and improves overall animal performance while reducing treatment costs associated with deficiency-related diseases. Empirical trials in Haryana using anionic mineral mixtures (AMM) around calving reduced milk fever incidence from 21% to 2%, increased milk yield by 12%, and net farmer income by 38%; demonstrating meticulously targeted mineral supplementation's economic impact.

Preventive multi-nutrient block supplementation

Preventive multi-nutrient blocks are designed to supply a balanced combination of energy, protein, minerals, vitamins and additives in a controlled intake form. These blocks support rumen function, improve digestion of low-quality roughages and help maintain consistent nutrient intake, particularly during feed scarcity or seasonal stress. Their gradual consumption prevents overfeeding and ensures sustained nutrient availability. Multi-nutrient blocks are especially beneficial for smallholder systems where ration balancing is difficult. They enhance milk production, growth rate and reproductive efficiency while reducing nutritional stress. Preventive supplementation through such blocks promotes better health, improves feed conversion efficiency and contributes to cost-effective and sustainable livestock production systems.

Genetic-nutritional synergies

Genetic–nutritional synergies refer to the interaction between an animal's genetic potential and its nutritional management to achieve optimal performance. Animals with superior genetics require precise nutrient supply to express traits such as high milk yield, rapid growth or disease resistance. Precision feeding strategies consider breed differences, production stage and metabolic requirements to match nutrition with genetic capacity. Proper alignment improves productivity, reproductive efficiency and longevity while preventing metabolic disorders caused by under- or over-feeding. Advances in genomics and data analytics enable customized feeding plans for genetically diverse herds. This integrated approach enhances efficiency, sustainability and profitability by maximizing the biological potential of livestock through balanced nutrition.

Improved genetics without matching nutrition yields suboptimal results; likewise, nutrition must complement genetic potential. AI and crossbreeding initiatives by organizations like BAIF, which combines indigenous cows with productive European breeds, rely on adequate nutrition to realize gains; BAIF provides door-step AI services, improving incomes for millions of rural farmers. Genomic tools like Gau Chip/Mahish Chip allow selection for feed efficiency and metabolic traits, requiring precise nutritional regimes to support animal genetics. The Indo-Israeli Centre of Excellence at Hisar fosters research and training blending advanced dairy technologies, feeding systems and localized husbandry practice. Thus synergistic integration ensures genetic improvements convert to production gains.

Infrastructure integration and institutional support

Modern infrastructure and extension

The AHIDF supports feed infrastructure, cold chains and processing units; National programme for dairy development builds procurement and marketing infrastructure; State initiatives (e.g., UP's cow shelters, MP's cow shelters policy, MP doubling milk via NDDDB collaboration) contribute on-ground support.

Veterinary outreach

The LHDCP's mobile veterinary units and strengthened veterinary networks ensure animal health aligns with nutrition programmes. For example, Maharashtra pushes doorstep veterinary services and nourishing cow shelters under its indigenous cow nutrition scheme; Karnataka invests in animal labs and vaccination infrastructure.

Local schemes and empowerment

Schemes such as Godhan Nyay Yojana empower small farmers and women SHGs in nutrient cycling; Gausevak training in MP builds local capacity for veterinary and nutritional outreach.

Case studies and emerging successes

Haryana – mineral supplementation study

Haryana's study on anionin mineral mixture (AMM) shows clear evidence that targeted mineral nutrition around calving prevents milk fever, raising yields and incomes substantially.

Amul TMR initiative in Gujarat

Amul's TMR plant demonstrates how cooperatives can produce standardized, balanced rations that reduce variability in feeding, enhance digestibility and reduce environmental footprint.

Gobardhan-based circular models

Biogas installations in Varanasi and Banaskantha milk unions convert dung into energy and organic fertilizer, powering dairies and benefiting farmers.

Government actions

States like Uttar Pradesh are integrating breed preservation, natural farming, cow shelters, NDDB partnership and encouraging women's involvement in dairying, showcasing multi-sectoral nutritional integration. Madhya Pradesh aims to double milk output via breed import, AI, infrastructure, NDDB collaboration and cow shelters policy.

Challenges and constraints

Regulation and standards gap: Innovative feeds like insects and microalgae lack clear standards from BIS/FSSAI in India.

Veterinary staff shortage: Persistent vacancies undermine health and nutrition cohesion (e.g., Kushalnagar taluk's shortage).

Infrastructure disparities: Rural reach of feed plants, silage units, testing labs remains uneven, especially in underdeveloped areas.

Awareness and capacity: Adoption of TMR, mineral supplementation, precision tools requires farmer training and extension support.

Cost and scale: High initial capital for sensors, bio-feed units, light-energy systems may deter smallholders without finance or subsidies.

Integration complexity: Coordinating across departments (agriculture, veterinary and small industries) and schemes can pose bureaucratic challenges.

Recommendations for scaling

1. ***Regulatory frameworks for alternative feeds:*** Fast-track guidelines on insect/microalgae feed inclusion, safety and labelling.
2. ***Subsidies and finance:*** Support smallholders to adopt silage units, feed blocks, TMR machinery through AHIDF/FPO scholarships.
3. ***Extension strengthening:*** Scale eGopala, AI outreach, nutrition workshops, linking to mobile vet units.
4. ***Data-driven precision feeding:*** Pilot sensor based monitoring in cooperative herds, generate local feeding norms, teach farmers.
5. ***Integrated waste-to-wealth models:*** Replicate Gobardhan-style biogas+bio-fertilizer systems in more union areas with cooperative investment.
6. ***Genetic-nutrition linkages:*** Design feeding protocols aligned with genetic traits (e.g. for animals selected via Gau/Mahish chip).
7. ***Capacity building:*** Train GAUSHELAs, Gausevaks, SHGs in feed technology, monitoring and micro-mineral supplementation.

8. **Public-private partnerships:** Leverage industry (e.g. Amul), BAIF, NIAB, Indo-Israeli Centre to incubate and diffuse innovations.

Conclusion

Innovative nutritional strategies represent a transformative pathway for revolutionizing animal husbandry in India. By shifting the focus from quantity-driven feeding to quality-oriented, science-based nutrition, the sector can unlock higher productivity, improved sustainability and enhanced farmer livelihoods. As India moves toward meeting the growing demand for animal-based foods while addressing environmental and economic challenges, nutrition will play a decisive role in shaping a resilient, efficient and future-ready animal husbandry system. India already has a rich policy framework the NLM, AHIDF, RGM, LHDCP and field programs like eGopala, TMR plants and waste-to-wealth models which can serve as scalable platforms. Emerging feed options (insects, microalgae) due to advance sensing systems, preventive mineral supplementation and genetic-nutrition synergy offer pathways to higher productivity, sustainability and climate resilience. The examples from Haryana, Gujarat, UP, MP and cooperative dairy unions illustrate the promise. To scale effectively, India must strengthen standards, finance and extension, link genetic tools to feeding regimes, ensure veterinary support and empower local institutions and communities. By doing so, Indian animal husbandry can not only increase yield and farmer income but also reduce environmental impact, improve animal welfare and contribute to sustainable rural prosperity.



Grain Amaranthus (*Amaranthus* spp.): An Underutilized Pseudocereal for Nutrition Security and Sustainable



A. Ajay Raja

Research scholar, Department of Vegetable Science, Horticultural College and Research Institute, TNAU, Coimbatore, Tamil Nadu, India - 641 003

Abstract

Grain amaranthus (*Amaranthus* spp.) is an ancient pseudocereal that has gained renewed attention due to its exceptional nutritional profile, climate resilience, and potential contribution to global food and nutrition security. Unlike major cereals, grain amaranth is rich in high-quality protein, essential amino acids, dietary fiber, minerals, and bioactive compounds, while being naturally gluten-free. Despite these advantages, it remains underutilized in many developing countries, including India, largely due to limited awareness, weak value chains, and insufficient research emphasis. This review provides a comprehensive overview of grain amaranthus covering its origin, taxonomy, agronomic characteristics, nutritional composition, health benefits, antinutritional factors, cultivation, processing and utilization, and future prospects. The role of grain amaranth in addressing malnutrition, climate change challenges, and sustainable agriculture is highlighted. Strengthening breeding programs, seed systems, post-harvest technologies, and market integration can unlock the full potential of grain amaranthus as a functional food crop for the future.

Keywords: Grain amaranthus; *Amaranthus* spp.; pseudocereal; nutrition security; underutilized crops; climate-resilient agriculture

Introduction

Ensuring food and nutrition security for a rapidly growing global population remains one of the major challenges of the 21st century. Dependence on a limited number of staple crops such as rice, wheat, and maize has contributed to dietary monotony and widespread micronutrient deficiencies, particularly in developing countries. In this context, underutilized and neglected crops with high nutritional value and adaptability to marginal environments have gained increasing attention.



Fig. 1. Grain amaranth – pseudocereal crop

Grain amaranthus (*Amaranthus* spp.) is one such underexploited crop with immense potential. Belonging to the family Amaranthaceae, grain amaranth has been cultivated for thousands of years by ancient civilizations such as the Aztecs and Incas. Although its importance declined after the introduction of major cereals, renewed interest has emerged due to its superior nutritional quality, tolerance to abiotic stresses, and suitability for diversified food systems.

Grain amaranth is classified as a pseudocereal because its grains are used similarly to cereals, although it is botanically unrelated to grasses. The crop exhibits remarkable adaptability to drought, heat, and poor soils, making it suitable for climate-resilient agriculture. This review synthesizes current knowledge on grain amaranthus with emphasis on its nutritional attributes, health benefits, production aspects, processing, and future prospects.

Origin, Distribution, and Taxonomy

The genus *Amaranthus* comprises more than 60 species distributed worldwide, of which a few are cultivated for grain production. The three principal grain amaranth species are *Amaranthus cruentus*, *A. hypochondriacus*, and *A. caudatus*. These species originated primarily in Central and South America, where they were domesticated as staple food crops.



Amaranthus cruentus



Amaranthus hypochondriacus



Amaranthus caudatus

Fig. 2. Different species of Grain Amaranthus

Today, grain amaranth is grown in various regions including Latin America, Africa, Asia, and parts of Europe. In India, amaranthus is more commonly cultivated as a leafy vegetable, while grain types are grown on a limited scale in hill regions and marginal lands. The crop's wide ecological adaptability makes it suitable for both tropical and subtropical environments.

Taxonomically, *Amaranthus* species exhibit considerable morphological variability, often leading to difficulties in species identification. This diversity, however, represents a valuable genetic resource for crop improvement programs aimed at enhancing yield, nutritional quality, and stress tolerance.

Agronomic Characteristics and Production Potential

Grain amaranthus is an annual herbaceous plant characterized by rapid growth, short duration, and high biomass production. The crop can mature within 90–120 days, depending on the species and growing conditions. It thrives in warm climates and can tolerate temperatures ranging from 20 to 35°C.

One of the most significant advantages of grain amaranth is its tolerance to abiotic stresses such as drought, salinity, and heat. Its deep root system and efficient water-use mechanisms allow it to perform well under rainfed and low-input conditions. Grain amaranth can grow in a wide range of soils, although well-drained loamy soils with moderate fertility are ideal for optimal yield.

Despite its adaptability, large-scale adoption of grain amaranth is constrained by limited availability of quality seed, lack of improved varieties, and inadequate agronomic packages. Strengthening seed systems and developing location-specific production technologies are essential for enhancing productivity and farmer adoption.

Nutritional Composition of Grain Amaranthus

Grain amaranthus is widely recognized for its exceptional nutritional profile, which surpasses that of many conventional cereals. The protein content of grain amaranth ranges from 13 to 18%, significantly higher than that of rice and maize. More importantly, its protein is rich in lysine, an essential amino acid that is typically deficient in cereal grains.

In addition to protein, grain amaranth contains appreciable amounts of dietary fiber, healthy lipids, and minerals such as calcium, iron, magnesium, zinc, and potassium. The lipid fraction is notable for its high proportion of unsaturated fatty acids, including linoleic and oleic acids.

Grain amaranth is also a good source of vitamins, particularly vitamin E (tocopherols), B-complex vitamins, and folates. Its carbohydrate content is primarily composed of easily digestible starch, making it suitable for infants, elderly populations, and individuals with digestive disorders.

Bioactive Compounds and Health Benefits

Beyond its basic nutritional value, grain amaranthus contains several bioactive compounds that confer health-promoting effects. These include phenolic acids, flavonoids, squalene, and phytosterols. Squalene, a triterpenoid compound found in amaranth oil, has attracted considerable interest due to its antioxidant, cholesterol-lowering, and potential anticancer properties.

Regular consumption of grain amaranth has been associated with reduced risk of cardiovascular diseases, improved lipid profiles, and better glycemic control. Its high fiber content aids in digestion and helps prevent constipation. The presence of antioxidants contributes to the prevention of oxidative stress-related disorders.

Importantly, grain amaranth is naturally gluten-free, making it a valuable food ingredient for individuals with celiac disease or gluten intolerance. Its incorporation into gluten-free food products can improve both nutritional quality and sensory attributes.

Antinutritional Factors and Their Management

Like many plant-based foods, grain amaranthus contains certain antinutritional factors such as phytates, oxalates, tannins, and saponins. These compounds can reduce the bioavailability of minerals and proteins if consumed in large amounts.

However, the levels of antinutrients in grain amaranth are generally lower than those found in many legumes and oilseeds. Moreover, traditional and modern processing methods such as soaking, germination, fermentation, roasting, and popping have been shown to significantly reduce antinutrient content while improving nutrient digestibility.

Adoption of appropriate processing techniques is therefore essential to maximize the nutritional benefits of grain amaranthus and enhance its acceptability among consumers.

Grain Amaranth Cultivation in India

Grain amaranth is cultivated in diverse agro-ecological regions of India, from hills to plains, during both kharif and rabi seasons as a sole or mixed crop. Major growing areas include Gujarat (Banaskantha, Kheda) and Uttarakhand (Chamoli, Uttarkashi), highlighting its regional importance despite limited national statistics.

For sole cropping under light-textured soils, Gujarat Amaranth-1 (GA-1) is recommended for sowing from the first to third week of November, using either broadcasting or line sowing with row spacing of 30–60 cm to obtain higher yield and profitability. Nutrient management practices suggest the application of 60 kg nitrogen and 40 kg phosphorus per hectare, with half of the nitrogen and the full phosphorus dose applied at sowing, and the remaining nitrogen top-dressed at 30 and 50 days after sowing. Under irrigated conditions, optimum productivity is achieved with six irrigations scheduled at an IW/CPE ratio of 0.6, beginning with irrigation at sowing, followed by a light irrigation after 5–6 days and subsequent irrigations at critical growth stages.

Integrated nutrient management has been found effective, particularly for GA-2. Application of 5 t FYM/ha along with the recommended fertilizer dose (60:40:0 kg N:P:K/ha) enhances soil fertility and economic returns. Further refinement through partial substitution of chemical nitrogen with organic sources, supplying 75% nitrogen through fertilizers and 25% through FYM or castor cake along with 40 kg P₂O₅/ha, has resulted in higher grain yield (about 1765 kg/ha) and superior benefit–cost ratio, demonstrating the suitability of integrated approaches for sustainable grain amaranth production in India.

Processing and Utilization

Grain amaranthus is a highly adaptable food crop with wide processing potential. Its grains can be cooked, popped, or milled into flour, which is often blended with cereal flours to enhance nutritional value. Amaranth is used in porridge, breakfast cereals, bakery products, traditional foods, weaning mixes, and popped-grain products like laddu and chikki, offering strong scope for value addition and entrepreneurship.



Fig. 3. Processed products from Grain Amaranth

Role in Food Security and Sustainable Agriculture

Grain amaranthus has immense potential to contribute to food and nutrition security, particularly in regions vulnerable to climate change and malnutrition. Its ability to grow under marginal conditions, coupled with its high nutritional density, makes it an ideal crop for smallholder farmers.

Inclusion of grain amaranthus in cropping systems can enhance agrobiodiversity, reduce dependence on major cereals, and improve resilience to climatic stresses. Promoting its cultivation and consumption can help address protein-energy malnutrition and micronutrient deficiencies among vulnerable populations.

Future Prospects and Research Needs

Despite its advantages, grain amaranthus remains underexploited due to limited research investment, weak policy support, and low consumer awareness. Future research should focus on genetic improvement for higher yield, uniform maturity, and reduced antinutrient content. Development of improved varieties through conventional breeding and modern biotechnological approaches is essential.

Strengthening post-harvest technologies, value chains, and market linkages will further enhance adoption. Policy interventions and extension efforts are needed to promote grain amaranthus as a climate-smart and nutrition-sensitive crop.

Conclusion

Grain amaranthus (*Amaranthus* spp.) is a nutritionally rich, climate-resilient, and multifunctional pseudocereal with great potential to support sustainable agriculture and nutrition security. Its superior protein quality, mineral richness, health benefits, and versatility in food processing distinguish it from conventional cereals. Addressing existing constraints through research, policy support, and value chain development can unlock the full potential of grain amaranthus. Promoting this underutilized crop can play a significant role in diversifying diets, enhancing farmer livelihoods, and building resilient food systems for the future.

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“Biofertilizers: Revitalizing Soil Fertility through Beneficial Microorganisms”



N. Senthilkumar

Department of Soil Science and Agricultural Chemistry,
Tamilnadu Agricultural University, Agricultural College and Research Institute,
Vazhavachanur-606 753, Thiruvannamalai (DT), Tamilnadu

Introduction

Soil is the living skin of the Earth a complex ecosystem that supports plant growth, stores water and nutrients, and maintains environmental balance. However, modern agriculture's heavy reliance on synthetic chemical fertilizers has degraded soil quality, reducing organic matter, harming beneficial microbes, and upsetting soil nutrient cycles. This degradation threatens long-term productive capacity of soils and challenges global food security. In response to this, **biofertilizers** have emerged as an environmentally friendly, sustainable alternative that works in harmony with natural soil processes to **improve soil fertility, enhance crop productivity, and reduce chemical inputs**. Biofertilizers contain **beneficial microorganisms** — microbes that enhance the availability and cycling of key nutrients like nitrogen, phosphorus, and potassium in the soil. Rather than merely supplying nutrients like chemical fertilizers, biofertilizers *activate soil biology*, restoring soil health and supporting resilient agricultural systems. The integration of biofertilizers into modern farming practices thus offers a promising pathway toward sustainable agriculture and long-term soil fertility enhancement.



Definition of Biofertilizers

Biofertilizers are defined as **natural products containing living microorganisms** that, when applied to seeds, plant surfaces, or soil, **colonize the rhizosphere** the root zone and increase the supply or availability of essential nutrients to plants through biological processes. These microorganisms include nitrogen-fixing bacteria, phosphate-solubilizing microbes and fungi that form symbiotic associations with plant roots. Unlike chemical fertilizers that add nutrients in a fixed form, biofertilizers enhance the soil's intrinsic biological functions, making nutrients *available at the right time and place* for plant uptake. (MDPI)

Role of Biofertilizers in Improving Soil Fertility

Biofertilizers play a multifaceted role in improving soil fertility. First, they **convert unavailable nutrients in the soil into plant-accessible forms**. For example, nitrogen-fixing bacteria capture atmospheric N_2 and convert it into ammonia, enriching nitrogen content in soil and reducing the need for synthetic nitrogen fertilizers. Phosphate-solubilizing microbes break down insoluble phosphorus compounds, increasing phosphorus availability, which is crucial for root growth and energy transfer in plants. Biofertilizers also **stimulate soil microbial diversity**, which enhances organic matter decomposition, improves soil structure and water retention, and strengthens soil nutrient cycles. Microbial activity induced by biofertilizers can help soil maintain a stable pH, promote beneficial microbial communities, and suppress plant pathogens — collectively contributing to healthier, more fertile soils. (MDPI)

Types of Biofertilizers

Biofertilizers are generally classified based on the primary nutrient process they influence:

1. Nitrogen-Fixing Biofertilizers

Nitrogen is a major plant nutrient often limiting in soils. *Rhizobium* species form symbiotic relationships with legumes where they fix atmospheric nitrogen directly into the plant. Free-living nitrogen fixers such as *Azotobacter* and associative fixers such as *Azospirillum* increase nitrogen availability in cereal and non-legume

systems as well. These biofertilizers reduce dependency on chemical nitrogen fertilizers and enrich soil nitrogen pools.

2. Phosphate-Solubilizing Biofertilizers

Phosphorus is often present in soils in insoluble forms, inaccessible to plants. Phosphate-solubilizing bacteria and fungi release organic acids and enzymes that convert bound phosphorus into plant-available orthophosphate, enhancing root development and nutrient absorption.

3. Potassium-Solubilizing Biofertilizers

Certain microbes solubilize bound potassium compounds in soil minerals, increasing potassium supply to crops. Potassium is essential for water regulation and enzyme activation in plants.

4. Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR includes bacteria such as *Pseudomonas* and *Bacillus* that improve nutrient uptake and stimulate plant growth by producing phytohormones and suppressing pathogens.

5. Mycorrhizal Fungi

Arbuscular mycorrhizal fungi (AMF) establish symbiotic associations with plant roots, extending the effective root zone and improving uptake of phosphorus, micronutrients, and water. These fungi are especially valuable in nutrient-poor soils.

Biofertilizer Application Methods and Recommendations

Biofertilizers are living microbial inoculants; therefore, **proper method of application is crucial** for their survival, establishment in soil, and effective performance. Unlike chemical fertilizers, biofertilizers must be applied carefully to ensure that beneficial microorganisms reach the root zone and remain active. The method of application depends on crop type, cropping system, and form of biofertilizer used.

1. Seed Treatment Method

Seed treatment is the **most common, economical, and effective method** of biofertilizer application, especially for field crops.

Method

- Required quantity of biofertilizer is mixed with rice gruel, jaggery solution, or starch solution to form a slurry.
- Seeds are coated uniformly with the slurry.
- Treated seeds are shade-dried for 20–30 minutes and sown immediately.

Recommended Dose

- **Rhizobium / Azotobacter / Azospirillum:**
200–250 g per 10 kg seed

Crops

- Cereals, pulses, oilseeds, millets, and cotton

Advantages

- Ensures early colonization of roots
- Reduces seedling mortality
- Enhances nitrogen fixation and early crop vigor
- Low cost and easy adoption

2. Seedling Root Dip Method

This method is mainly recommended for **transplanted crops**, particularly rice and vegetables.

Method

- Biofertilizer is mixed in water to prepare a suspension.
- Seedling roots are dipped in the suspension for 20–30 minutes before transplanting.

Recommended Dose

- **Azospirillum / Phosphobacteria:**
1–2 kg biofertilizer in 40–50 litres of water per acre

Crops

- Rice, tomato, brinjal, chilli, cabbage, onion

Advantages

- Direct contact between microbes and roots
- Improves seedling establishment
- Enhances root growth and nutrient uptake

3. Soil Application Method

Soil application is suitable for **all crops**, especially perennial crops and orchards.

Method

- Biofertilizer is mixed with FYM, compost, or vermicompost.
- The mixture is applied to soil before sowing or around the root zone.

Recommended Dose

- **2–5 kg biofertilizer per acre**
- Mixed with **50–100 kg FYM/compost**

Crops

- Field crops, horticultural crops, plantations, orchards

Advantages

- Improves soil microbial population
- Enhances nutrient cycling
- Improves soil structure and organic matter

4. Nursery Bed Application

Biofertilizers can be applied in **nursery beds** to produce healthy seedlings.

Method

- Biofertilizer is mixed with compost and applied to nursery soil.
- Can also be applied through watering.

Recommended Dose

- **1 kg biofertilizer per nursery area (100–200 m²)**

Advantages

- Produces healthy and vigorous seedlings
- Reduces transplant shock
- Improves early root development

5. Drip Irrigation / Fertigation Method

Liquid biofertilizers are increasingly used through **drip irrigation systems**.

Method

- Liquid biofertilizer is diluted and injected through drip lines.
- Applied during early growth stages.

Recommended Dose

- **500 ml – 1 litre per acre**, depending on crop and product

Advantages

- Uniform distribution
- Suitable for large areas
- Efficient root zone colonization

6. Orchard and Plantation Crop Application

For perennial crops, biofertilizers are applied in **basins or pits** around the tree.

Recommended Dose

- **25–50 g biofertilizer per tree**
- Mixed with compost and applied near feeder roots

Crops

- Coconut, banana, mango, citrus, sugarcane, tea, coffee

General Recommendations for Biofertilizer Use

- ✓ Use **fresh, quality biofertilizers** with valid expiry date
- ✓ Store in **cool, shaded conditions**
- ✓ Do not mix biofertilizers with chemical fertilizers or pesticides directly
- ✓ Avoid application during extreme heat or dry soil conditions
- ✓ Apply biofertilizers **along with organic manures** for better survival
- ✓ Irrigate immediately after soil application
- ✓ Follow **integrated nutrient management (INM)** approach

Recommended Biofertilizer Combinations

- **Cereals:** Azospirillum + Phosphobacteria
- **Pulses:** Rhizobium + PSB
- **Vegetables:** Azospirillum + PSB + PGPR
- **Orchards:** AMF + Azotobacter + PSB

Proper application methods and correct dosage play a vital role in maximizing the benefits of biofertilizers. When applied correctly, biofertilizers enhance soil fertility by improving nutrient availability, stimulating beneficial microbial activity, and sustaining long-term soil health. Adoption of appropriate biofertilizer application techniques, combined with organic manures and reduced chemical fertilizer use, is essential for sustainable and environmentally friendly agricultural production.

Review of Each Biofertilizer's Importance in Soil Fertility (with Authors & Years)

1. Multifunctional Biofertilizers for Soil Health

A 2025 review by Keerthanan P. et al. provides a comprehensive assessment of biofertilizer roles in soil health improvement, demonstrating how nitrogen-fixers, phosphate-solubilizers, potassium-mobilizers, and mycorrhizal fungi collectively enhance soil nutrient dynamics, microbial diversity, and organic matter content. The authors emphasize that biofertilizers not only improve nutrient cycling but also contribute to soil structure and carbon sequestration, making soils more resilient and productive over time. Challenges such as formulation quality and field performance variability are also discussed, with recommendations for integrating biofertilizers with precision agriculture. ([ACRI](#))

2. Enhancing Soil Fertility and Productivity

Subhendra Kumar Singh and colleagues (2025) reviewed how biofertilizers enhance soil fertility and crop productivity. They concluded that biofertilizers increase soil nutrient availability and improve crop yields through microbial processes. The authors highlighted successes in various cropping systems, noting that microbial inoculants increase soil organic matter, microbial biomass, and nutrient uptake efficiency — all critical indicators of improved soil fertility. ([Plant & Soil Science Journal](#))

3. Microbial Community Modulation and Soil Traits

A 2025 study published in *Agronomy* (via MDPI) investigated the effects of biofertilizers on soil microbial communities and fertility indicators in corn and soybean systems. The research showed that biofertilizer treatments increased soil pH, ammonium-N, and available phosphorus levels compared to chemical fertilization. Moreover, microbial community shifts towards beneficial taxa indicated improved nutrient cycling and enhanced soil health. This evidence supports the role of biofertilizers in directly modifying soil chemistry and microbiology for better fertility outcomes. ([MDPI](#))

4. Microbial Solutions to Soil Health (2023)

Pooja S. Beleri (2023) reviewed microbial solutions to soil health, emphasizing that biofertilizers including nitrogen fixers, phosphate solubilizers, and mycorrhizal fungi — enhance nutrient availability and soil structure while countering negative impacts of chemical fertilizer overuse. Beleri's work highlighted the ecological benefits of biofertilizers in maintaining long-term soil fertility and promoting sustainable agricultural ecosystems. ([microjournal.researchfloor.org](#))

5. Biofertilizers in Push–Pull Cropping Systems (2024)

Admire R. Dzvene and Cornelius Chiduza (2024) explored the role of biofertilizers within push–pull cropping systems a strategy combining biofertilizer use with pest management and diverse cropping. They reported that integrating microbial inoculants improved soil quality, nutrient dynamics, and system productivity, showcasing how biofertilizers can enhance soil fertility even in agroecological management frameworks. ([MDPI](#))

6. Practical Crop Responses to Biofertilizer Application (2025)

A recent field study by Kulbhushan W. Pawar (2025) demonstrated that combining nitrogen-fixing and phosphate-solubilizing bacteria significantly improved nodulation, growth, and yield of chickpea compared to controls. The results indicated enhanced soil nitrogen and phosphorus status, supporting the claim that well-selected biofertilizers positively influence soil fertility and crop performance in real-world conditions. ([microbiojournal.com](#))

Mechanisms of Soil Fertility Improvement

Biofertilizers improve soil fertility through several biological mechanisms:

- **Biological Nitrogen Fixation:** Microbes like *Rhizobium* capture atmospheric nitrogen and convert it into plant-available forms, enriching soil nitrogen pools and reducing synthetic nitrogen fertilizer dependency.
- **Nutrient Solubilization:** Phosphate and potassium microbes release organic acids that solubilize bound nutrients, increasing their availability to plants.
- **Microbial Community Enhancement:** Biofertilizers stimulate beneficial soil microbial populations, enhancing nutrient cycling, organic matter decomposition, and soil structure.
- **Symbiotic Associations:** Mycorrhizal fungi form networks with plant roots, increasing water and nutrient uptake beyond the root zone.
- **Stress Moderation:** Some PGPR produce phytohormones and protective compounds that improve plant resilience and indirectly improve soil nutrient retention.

These mechanisms work *synergistically* to build soil fertility rather than simply supplying nutrients transiently.

Conclusion

Biofertilizers represent a **transformative approach to sustainable soil fertility management**. Unlike chemical fertilizers that offer short-term nutrient supply, biofertilizers work by enhancing the **biological processes underlying soil nutrient cycles**, increasing availability of essential nutrients and building long-term soil health. Research shows consistent evidence that biofertilizers improve soil nutrient status, microbial diversity, and crop productivity across diverse cropping systems. By reducing dependency on synthetic inputs and promoting beneficial soil biology, biofertilizers contribute to environmental sustainability, economic viability for farmers, and greater resilience in agricultural systems. As global agricultural challenges such as soil degradation, climate change, and food security continue to intensify, biofertilizers stand out as essential tools for achieving productive and sustainable soils for future generations.

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WOMEN AS UNSUNG ARCHITECTS OF PLANT BREEDING AND CROP IMPROVEMENT



Prem Sagar S P¹, Sridhara M R², Raghavendra V C³, Yashaswini R³, B V Sinchana⁴ and Lakshmi Navya Sri N⁵

¹Assistant Professor, Department of Genetics and Plant Breeding, J.C. Diwakar Reddy Agricultural College (Affiliated to ANGRAU), Juturu Campus, Tadipatri - 515411, Andhra Pradesh, India

²Assistant Professor, Department of Agronomy, J.C. Diwakar Reddy Agricultural College (Affiliated to ANGRAU), Juturu Campus, Tadipatri - 515411, Andhra Pradesh, India

³Ph.D. Scholar, Department of Genetics and Plant Breeding, University of Agricultural Sciences, Raichur - 584104 (Karnataka), India

⁴Ph.D. Scholar, Department of Genetics and Plant Breeding, University of Agricultural Sciences, GKVK, Bengaluru - 560065 (Karnataka), India

⁵Junior Breeder, Nugenes, Hyderabad, Telangana

Women as the first plant breeders

Long before laboratories, research stations and carefully designed experiments existed, seeds were already being selected quietly, carefully and mostly by women. In early farming societies, women were often responsible for saving seeds, storing grain, cooking food and feeding families. Over seasons, they noticed which grains cooked faster, which tasted better, which stored longer and which survived drought or poor soils. Without formal training, they became the first plant selectors choosing seeds not just for yield, but for daily life.

This early, home-based selection did more than ensure food on the table. It shaped biodiversity, helping conserve a variety of plants and crops that could survive changing climates and seasons. Studies from around the world show that women's work in gardens, farms and forests has maintained both cultivated and wild plants for centuries. Their practices from careful seed saving to nurturing wild edible plants contributed to the survival of entire communities, often without recognition. Their knowledge was practical, intimate and vital.



Formal plant breeding and the loss of household perspectives

As agriculture evolved and science entered the field, plant breeding became more formal. Research institutions emerged, experiments were designed and yield became the primary measure of success. This brought remarkable progress in terms of improved varieties, food security and agricultural growth. Yet, in this transition something subtle happened: the everyday preferences shaped inside homes and kitchens slowly moved out of focus. Breeding programs focused more on numbers, uniformity and market appeal, while traits tied to cooking, processing or labour reduction were often overlooked.

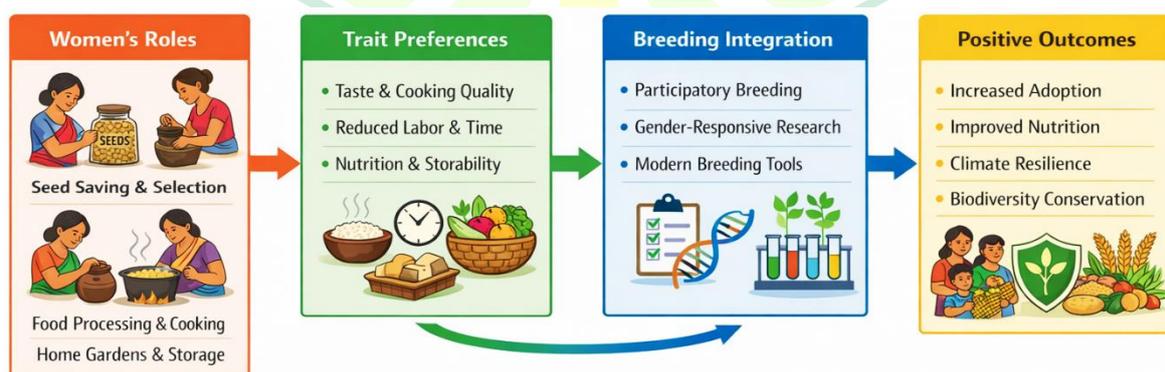
Research increasingly confirms these observations. A recent study in Uganda on cooking bananas, for example, found clear differences between men's and women's trait preferences. While men emphasized marketable and agronomic traits like drought tolerance, pest resistance and shelf life, women placed greater value on consumption traits *viz.*, taste, colour, softness, finger size and ease of peeling. When breeding programs do not consider these differences, adoption of new varieties is lower. Listening to both men and women, however, allows breeders to develop crops that succeed both in the field and in the kitchen.

Gender-based differences in crop trait preferences

Women, however continued to do much of the work on farms. They planted, weeded, harvested, processed and prepared food. They fed families, stored seeds and managed small home gardens. The varieties they used shaped their daily lives. For them, a good crop was not only high yielding but also easy to cook, nutritious, resilient and practical for household needs. A variety that looked excellent in the field might still be rejected at home if it added to daily work or did not fit cultural preferences.

This principle is true beyond bananas or Africa. Across Asia, Latin America and Europe, women's roles in selecting and using plant varieties have shaped the traits they value. Studies emphasize that women's priorities often relate to food security, household nutrition, labour reduction and sustainable use of resources, whereas men may focus on market-oriented traits focusing on getting returns. Ignoring either perspective risks developing varieties that are scientifically improved but socially impractical.

Interestingly, women have also shaped plant breeding from within science itself. Women scientists have left lasting marks on genetics and crop improvement despite historical barriers. From Nobel laureate Barbara McClintock, who discovered mobile genetic elements in maize, to Janaki Ammal, India's pioneering botanist and cytogeneticist, to Susan McCouch, who mapped the rice genome and advanced modern rice breeding, women have transformed both theory and practice. Others, like Mary-Dell Chilton, enabled the development of genetically modified crops, while contemporary scientists continue to refine participatory and gender-responsive breeding pipelines.



Conceptual framework linking women's knowledge with gender-responsive plant breeding outcomes

Modern plant breeding is increasingly aware of this. Participatory breeding approaches now bring farmers especially women into the evaluation and selection of varieties. Programs guided by the Excellence in Breeding Initiative, for instance, show that when women are included, the varieties chosen are more likely to meet household, market and ecological needs simultaneously. Varieties may not only survive in the field but also cook faster, taste better, reduce daily labour and provide fodder or fuel. These improvements reflect the realities of farm life, making adoption smoother and benefits wider.

The importance of gender-responsive breeding goes beyond adoption rates. It touches on empowerment, equity and food security. When women farmers' voices are acknowledged, they gain not only better crops but also greater agency in household and community decisions. CGIAR and other global studies highlight that integrating gender perspectives in breeding contributes to nutrition, poverty reduction, resilience and sustainable livelihoods, creating a ripple effect from seed to society.

Consider rice in India. Traditional landraces maintained by women often possess traits for early seedling vigour, drought tolerance and cooking quality. Modern breeding programs incorporating these traits guided by women's knowledge have developed varieties that are more widely adopted than high-yield lines developed without farmer input. Similar lessons emerge from sweet potato breeding, sorghum in Ethiopia and cooking bananas in Uganda: the pattern repeats globally. Women are key actors in both maintaining crop diversity and shaping the traits that breeding programs should prioritize.

Integrating women's knowledge in modern plant breeding

What lessons emerge for the future? First, breeders must listen. Not in an abstract way, but through direct engagement, participatory trials and detailed understanding of daily lives. Second, policy and science must recognize women's knowledge as complementary to formal research, not anecdotal or secondary. Third, breeding goals must integrate practical traits flavour, ease of cooking, processing efficiency and fodder provision along with yield and disease resistance.

Table 1. Gender-differentiated trait preferences in selected crops and their implications for plant breeding

Crop	Traits predominantly preferred by women	Traits predominantly preferred by men	Implications for breeding programs	Key references
Rice (<i>Oryza sativa</i>)	Cooking quality, aroma, soft texture, shorter cooking time, grain appearance suited to household consumption, ease of processing & storages	High grain yield, lodging resistance, pest and disease resistance, market price, uniform grain size	Ignoring women's preferences may lead to poor acceptance; integrating cooking & quality traits enhances adoption & nutrition security	Paris <i>et al.</i> (2011)
Cooking banana (<i>Musa spp.</i>)	Taste, pulp softness, colour after cooking, finger size suitable for cooking, ease of peeling, shorter cooking time	Marketability, bunch size, shelf life, pest and disease resistance, drought tolerance	Varieties selected jointly by men and women show higher adoption and dual suitability for markets and home consumption	Tuanama <i>et al.</i> (2007)
Sorghum (<i>Sorghum bicolor</i>)	Ease of threshing and processing, grain softness, suitability for food preparation, fodder and quality for livestock, fuel value	Grain size, overall yield, drought tolerance, market demand	Considering women's processing and fodder preferences improves food-feed systems and reduces drudgery	CGIAR (Various studies)
Sweet potato (<i>Ipomoea batatas</i>)	Flesh colour (orange for β -carotene), taste, cooking quality, nutritional value, suitability for home consumption	Root size, yield, uniformity, market acceptability	Gender-responsive breeding supports biofortification goals & improves household nutrition outcomes	CIP (International Potato Center)

This is not about rewriting history or assigning blame. It is about remembering that agriculture has always been a shared human endeavour. Seeds do not grow in fields alone; they grow in households, kitchens and communities. The varieties that thrive tomorrow will be those that blend scientific insight with the intimate, practical knowledge of women farmers.

Women farmers and varietal selection in India: Lessons from traditional landraces

Across India, women farmers have played a central role in conserving and improving crop diversity through generations of informal selection and seed management. In eastern India, particularly in Odisha and parts of West Bengal, women have traditionally maintained diverse rice landraces valued for cooking quality, aroma, drought tolerance and suitability to local agro-ecologies. These landraces, often selected and stored by women, have served as important genetic resources for modern breeding programs.

In Telangana and Andhra Pradesh, women's self-help groups (SHGs) and community seed banks have contributed to the preservation and exchange of traditional rice and millet varieties. Through collective seed selection, storage and sharing, women ensure varietal purity and adaptation while reducing dependence on external seed sources. Similar practices are observed in North-Eastern India, where women farmers actively manage upland rice, maize, pulses and tubers in shifting and terrace cultivation systems, safeguarding rich agro biodiversity.

Among tribal communities, women play a dominant role in the cultivation and selection of small millets, sorghum and pulses, where traits such as processing ease, food quality, fodder value and resilience to marginal environments are prioritized. Their experiential knowledge supports food security in rainfed and resource-poor regions. Participatory varietal selection (PVS) initiatives promoted by ICAR institutes and State Agricultural Universities (SAUs), including ANGRAU-affiliated programs, have demonstrated that varieties selected with women farmers' involvement show higher acceptance and sustained adoption. These experiences underline that India's traditional landraces and women's selection practices remain highly relevant for developing climate-resilient, nutritious and farmer-preferred varieties.

Future directions for gender-responsive plant breeding

To fully realize the benefits of integrating gender perspectives in plant breeding, future research and institutional approaches must move beyond awareness to systematic implementation:

- **Breeding pipelines should incorporate mandatory gender evaluation stages**, ensuring that women's preferences are considered from early trait prioritization to advanced variety release.
- **Sex-disaggregated data collection and trait scoring** should become standard practice in multi-location trials, enabling breeders to identify differential adoption drivers.
- **Greater representation of women farmers and women scientists** in breeding teams, evaluation committees and decision-making platforms is essential for balanced outcomes.
- **Participatory breeding approaches should be strengthened** through structured engagement with women's groups, SHGs and community seed systems.
- **Digital tools and decision-support platforms** (mobile apps, digital surveys, GIS-enabled trials) can facilitate inclusive participation, rapid feedback and wider reach, especially in remote areas.
- Policy support is required to mainstream **gender-responsive breeding indicators** within national and international agricultural research frameworks.

Embedding these directions into mainstream breeding programs will help ensure that future varieties are not only high yielding but also socially relevant, nutritionally sensitive and resilient to climatic and market uncertainties.

Conclusion

From home gardens to global laboratories, from seed-saving to genome sequencing, the story is the same: when seeds listen, everyone benefits. Food becomes more nutritious, work becomes more manageable, communities become more resilient and biodiversity is preserved. Recognizing and integrating gender perspectives in plant breeding is no longer optional; it is essential for sustainable agriculture, empowered communities and a future where the fruits of science reach all who rely on them. **“When women's knowledge shapes breeding goals, seeds become not only productive but also practical, nutritious and socially sustainable”.**

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Soil-Water Interaction and Microbial Roles in Nutrient Cycling for Aquaculture Productivity



**Padala Sai Chandu, M. Joshna, P. Anand Prasad, D. Mamatha, Salkapuram
Sandeep Kumar, Sagili Meghana, Alli Asritha**

Department of Aquaculture, Andhra Pradesh Fisheries University, College of fisheries science
Muthukur -524 344, Andhra Pradesh, India.

Abstract:

The soil–water interface serves as a critical ecological nexus in aquaculture systems, governing nutrient cycling, organic matter decomposition, and microbial transformations that directly influence productivity and sustainability. This dynamic zone integrates physical, chemical, and biological processes within sediment layers, mediating essential exchanges of nitrogen, phosphorus, and sulfur. Microbial communities—including heterotrophic, nitrifying, denitrifying, and sulfate-reducing bacteria—drive key biogeochemical reactions such as ammonification, nitrification, denitrification, and sulfate reduction, thereby regulating water quality and nutrient availability. Interactions among carbon, iron, and sulfur cycles further control phosphorus dynamics through redox-mediated transformations. Technological innovations like biofloc systems and probiotic applications enhance microbial nutrient management, improving nitrogen assimilation and reducing toxic metabolite buildup. Effective sediment management practices, including aeration, liming, and bioremediation, maintain optimal redox conditions and microbial balance. Sustainable aquaculture development depends on integrating these microbial and biogeochemical insights with circular nutrient recovery approaches such as integrated multi-trophic aquaculture, which minimize environmental impacts and support long-term ecological stability.

The Soil-Water Interface as an Ecological Nexus

The pond bottom soil forms the foundation of aquaculture ecosystems, exerting profound influence on water quality parameters including pH, alkalinity, dissolved oxygen, and nutrient availability. The interface consists of several stratified layers, with the flocculent (F) horizon and mixed sediment (S) horizon being particularly significant for nutrient exchange. These layers are characterized by high concentrations of mineral and organic solids, abundant microbial populations, and aerobic surface conditions transitioning to anaerobic zones below. The physico-chemical properties of pond soils directly influence water quality through processes such as nutrient deposition, organic matter accumulation, and redox reactions. Soil texture, organic matter content, cation exchange capacity, and pH collectively determine the rate and efficiency of nutrient cycling. Clay-loam soils with 2-4% organic matter content typically exhibit superior productivity compared to sandy soils due to enhanced nutrient retention and water-holding capacity.

Microbial Communities and Nutrient Transformations

Microorganisms play pivotal roles in aquaculture pond ecology, particularly regarding productivity, nutrient cycling, and animal nutrition. The sediment-water interface harbors diverse microbial communities that decompose organic matter, mineralize nutrients, and transform waste products into bioavailable forms. These microbial assemblages include heterotrophic bacteria, nitrifying bacteria, denitrifying bacteria, sulfate-reducing bacteria (SRB), sulfur-oxidizing bacteria (SOB), and phosphorus-solubilizing microorganisms. Heterotrophic bacteria constitute the primary decomposers in aquaculture systems, breaking down complex organic compounds from uneaten feed, fecal matter, and dead plankton. These microorganisms utilize organic carbon as both energy source and carbon substrate, simultaneously assimilating nitrogenous waste compounds. In biofloc technology systems, heterotrophic bacteria proliferate through manipulation of carbon-to-nitrogen (C:N) ratios, effectively converting toxic ammonia into microbial protein that serves as supplementary nutrition for cultured species.

Nitrogen Cycling and Microbial Processes

Nitrogen dynamics in aquaculture ponds are governed by multiple microbial processes including ammonification, nitrification, denitrification, and anaerobic ammonium oxidation (anammox). Ammonification occurs when

heterotrophic bacteria decompose organic nitrogen compounds, releasing ammonia into the water column. This process is particularly active at the soil-water interface where organic matter accumulates. Nitrification, a two-step aerobic process, involves the oxidation of ammonia to nitrite by ammonia-oxidizing bacteria (AOB) and archaea (AOA), followed by conversion of nitrite to nitrate by nitrite-oxidizing bacteria (NOB). The ammonia monooxygenase (AMO) enzyme catalyzes the initial oxidation step, which occurs primarily in the oxidized surface layer of sediments. Nitrification maintains water quality by converting toxic ammonia into less harmful nitrate. Denitrification represents a critical nitrogen removal pathway in aquaculture systems, where facultative anaerobic bacteria reduce nitrate sequentially to nitrite, nitric oxide, nitrous oxide, and finally nitrogen gas. The process is mediated by enzymes encoded by genes including *narG* (nitrate reductase), *nirK* and *nirS* (nitrite reductase), *norB* (nitric oxide reductase), and *nosZ* (nitrous oxide reductase). Denitrification occurs predominantly in anoxic zones within sediments where organic carbon availability and reducing conditions favor the process. Heterotrophic nitrification-aerobic denitrification (HNAD) represents an alternative nitrogen removal mechanism performed by versatile bacteria capable of simultaneous nitrification and denitrification under aerobic conditions. Genera such as *Bacillus*, *Halomonas*, *Cetobacterium*, *Polynucleobacter*, *Devosia*, and *Flavobacterium* have been identified as key participants in nitrogen removal in aquaculture systems. These organisms provide flexible nitrogen management options, particularly in systems with fluctuating oxygen concentrations.

Sulfur Cycling and Sediment Redox Conditions

Sulfur cycling plays crucial roles in organic matter degradation, nutrient availability, and environmental safety in aquaculture ecosystems. Microbial sulfate reduction (MSR) constitutes a major anaerobic respiration pathway in organic-rich pond sediments, where sulfate-reducing bacteria utilize sulfate as terminal electron acceptor during organic matter oxidation. Dominant SRB genera in aquaculture sediments include *Desulfobulbus* and *Desulfovibrio*, which thrive in anaerobic conditions beneath the sediment surface. The sulfide produced through MSR undergoes reoxidation by sulfur-oxidizing bacteria (SOB) such as *Dechloromonas* and *Leptothrix*, completing the sulfur cycle. This microbial sulfur cycling enhances organic matter degradation efficiency and influences sediment redox potential. However, excessive sulfate reduction under intensive culture conditions can lead to accumulation of toxic hydrogen sulfide (H_2S), which stresses cultured organisms and reduces productivity. The interaction between iron and sulfur cycles significantly impacts nutrient dynamics, particularly phosphorus availability. Under reducing conditions, hydrogen sulfide reacts with iron oxides ($FeOOH$), forming iron sulfide minerals (FeS and FeS_2) and releasing phosphate previously bound to iron. This reductive dissolution of iron oxides coupled with sulfide oxidation intensifies phosphorus desorption, increasing phosphorus availability in pore water and enhancing benthic phosphorus flux to the overlying water.

Phosphorus Cycling and Microbial Regulation

Phosphorus dynamics in aquaculture systems are tightly coupled to microbial carbon mineralization and interactions between iron and sulfur cycles. Microorganisms release phosphorus from organic matter through mineralization, making it available for phytoplankton growth. Phosphorus-mineralizing bacteria such as *Bacillus* and *Pseudomonas* species secrete phosphatase enzymes that hydrolyze organic phosphorus compounds into bioavailable inorganic phosphate. The bioavailability of phosphorus in sediments depends on its chemical speciation, which includes loosely sorbed phosphorus (Lsor-P), iron-bound phosphorus (Fe-P), biogenic apatite (Bio-P), authigenic apatite (Aut-P), detrital apatite (Detr-P), and organic phosphorus (Org-P). Iron-bound phosphorus represents a significant reactive pool that responds to redox fluctuations. Under oxic conditions, ferric iron oxides adsorb phosphate, immobilizing it within sediments. Conversely, under anoxic conditions generated by intense microbial respiration, reduction of ferric to ferrous iron releases bound phosphate into pore water. In intensive aquaculture systems with high organic loading, sulfate reduction dominates carbon mineralization, creating strongly reducing conditions that promote iron reduction and phosphorus release. The regeneration efficiency of phosphorus in such systems can reach 85%, meaning that most mineralized phosphorus is released to the water column rather than retained in sediments. This enhanced phosphorus release can contribute to eutrophication in surrounding water bodies if not properly managed. Biofloc Technology and Microbial Nutrient Management Biofloc technology (BFT) represents an innovative approach to microbial nutrient management in aquaculture systems. By manipulating C:N ratios through organic carbon supplementation, BFT stimulates

heterotrophic bacterial proliferation, which assimilates ammonia nitrogen into microbial biomass. The microbial flocs formed through this process serve dual functions: removing toxic nitrogenous compounds and providing supplementary protein-rich nutrition for cultured species. The microbial community in biofloc systems includes diverse bacterial groups, microalgae, fungi, and protozoa. Beneficial bacteria such as *Bacillus* species enhance water quality, improve feed utilization efficiency, boost immune response, and increase survival rates of cultured organisms. The biofloc microbiome also produces bioactive compounds including enzymes, vitamins, and antimicrobial substances that contribute to animal health. Optimization of C:N ratios is critical for biofloc system performance. High C:N ratios (typically 15:1 to 20:1) promote heterotrophic bacterial growth and nitrogen assimilation. Carbon sources commonly used include molasses, tapioca, wheat flour, and biodegradable polymers such as polyhydroxybutyrate (PHB). PHB not only functions as a slow-release carbon source but also serves as an effective biofilm carrier, achieving denitrification rates ranging from 168 to 980 mg L⁻¹ d⁻¹.

Sediment Management and Water Quality Maintenance

Effective management of the soil-water interface is essential for maintaining optimal pond ecology and preventing accumulation of toxic metabolites. Sediment redox potential (ORP) provides a valuable indicator of oxygen availability and microbial activity. Healthy oxidized sediments typically exhibit positive ORP values (>100 mV), favoring aerobic decomposition and efficient nutrient cycling. When ORP drops below -200 mV, severely depleted oxygen conditions promote accumulation of ammonia, hydrogen sulfide, and methane, creating stressful conditions for cultured organisms. Organic matter accumulation from uneaten feed, feces, and dead organisms increases biological oxygen demand at the sediment-water interface. Under excessive organic loading, anaerobic microbial processes dominate, producing toxic reduced compounds. Aeration strategies can maintain oxidized conditions at the sediment surface, promoting aerobic microbial activity and preventing toxic metabolite formation. Pond preparation practices including draining, drying, and tilling help oxidize accumulated organic matter, eliminate pathogens, and improve nutrient availability. Liming with calcium carbonate or other alkaline materials neutralizes soil acidity, stabilizes pH, and stimulates beneficial microbial activity. Optimal soil pH in the range of 6.5-7.5 ensures nutrient bioavailability and supports diverse microbial communities.

Probiotics and Bioremediation

Application of beneficial microorganisms (probiotics) has emerged as an effective strategy for improving water quality and suppressing pathogens in aquaculture systems. Probiotic bacteria accelerate organic matter decomposition, reduce ammonia and nitrite concentrations, and compete with pathogenic microorganisms. Common probiotic species include *Bacillus subtilis*, *Lactobacillus* species, nitrifying bacteria consortia, and photosynthetic bacteria. Potassium monopersulfate (KMPS) has been investigated as a chemical oxidant for sediment remediation in eutrophic aquaculture ponds. KMPS treatment significantly improves sediment particle size distribution, reduces organic pollutants, and enhances material cycling at the sediment-water interface. The treatment optimizes microbial community structure and ecological function, promoting sustainable aquaculture production.

Environmental Implications and Sustainable Management

The interaction between soil and water in aquaculture systems has significant environmental implications beyond the pond boundaries. Discharge of nutrient-rich effluents can cause eutrophication in receiving water bodies, potentially triggering harmful algal blooms. Benthic phosphorus flux from fish farm sediments can be extraordinarily high, potentially accounting for up to 800% of phosphorus required for primary production in surrounding waters. Sustainable intensification of aquaculture requires integrated nutrient recycling strategies. Opportunities include nutrient recovery through biofilters, bioaccumulation in integrated multi-trophic aquaculture (IMTA) systems, and utilization of aquaculture waste for agricultural fertilizer. IMTA systems that combine finfish culture with extractive species such as seaweed and bivalves can capture dissolved and particulate nutrients, reducing environmental impacts while diversifying production.

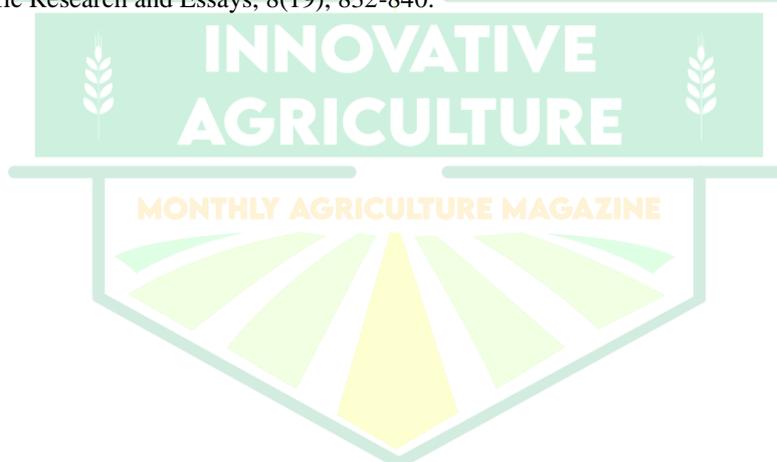
Conclusion:

The soil-water interface in aquaculture systems functions as a complex biogeochemical reactor where microbial communities orchestrate essential nutrient transformations. Understanding and managing these microbial processes—including nitrogen cycling through nitrification and denitrification, phosphorus dynamics regulated

by iron and sulfur interactions, and organic matter decomposition by diverse heterotrophic communities—is fundamental to achieving sustainable, productive aquaculture. Emerging technologies such as biofloc systems, probiotic applications, and integrated multi-trophic aquaculture offer promising approaches for optimizing microbial nutrient management while minimizing environmental impacts.

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“Biofuels: Area under maize cultivation in India increases sharply, driven by push for ethanol”



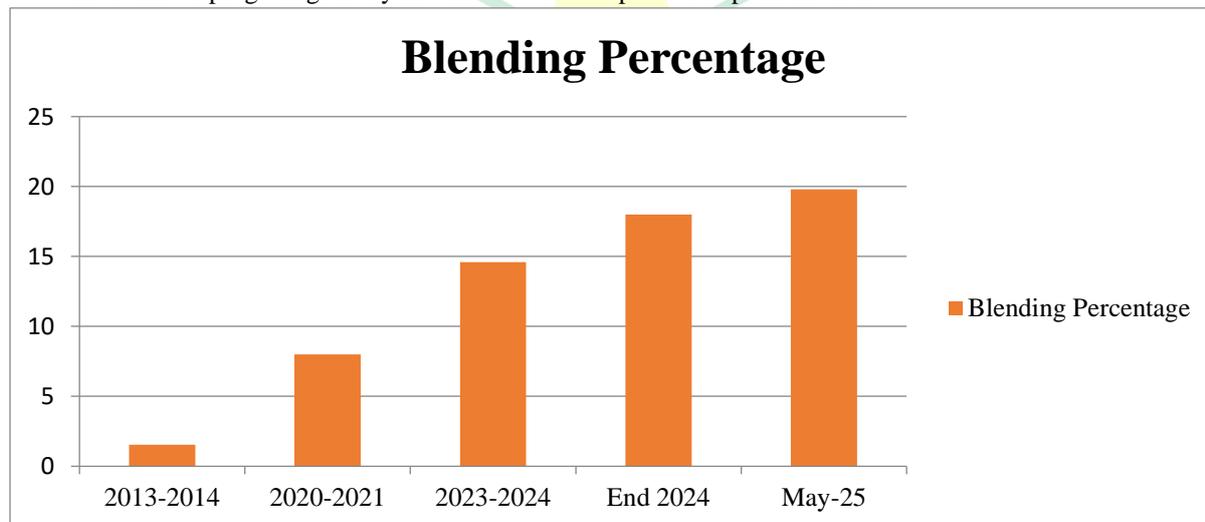
Addya Singh¹, Pooran Chand²

¹PhD Scholar, Dept. of Genetics and Plant Breeding, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh (250110), India

²Professor, Dept. of Genetics and Plant Breeding, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh (250110), India

Ethanol, a renewable biofuel primarily derived from agricultural feedstock, has emerged as a critical component of modern energy strategies worldwide. As a clean burning fuel additive, ethanol reduces greenhouse gas emission and enhances octane levels in gasoline, making it an increasingly valuable resource in the global effort to transition toward more sustainable energy sources. Among the various feedstocks used for ethanol production, maize stands as the predominant source in Particularly in United States the world’s largest producer and is increasingly a major feedstock in countries like India its dominance is not due to single factor but rather a combination of biological economic and policy driven advantage. Maize is a powerful combination of its high starch content, established and scalable agricultural system and the crucial economic of its co-products. These inherent advantages have been massively amplified by government policies and mandate designed to promote biofuel for energy security and rural economic development.

Recent growth India’s ethanol blending program has undergone a remarked Transformation over the past decades evolving for minimal blending levels to approaching the ambitious 20% target the journey begins with just 1.53% ethanol blending in petrol during the 2013 to 14. Periods with production capacity limited to merely 421 crore liters these. Characterized India’s initial steps towards biofuel integration though with limited strategic focus on policy support the transformative shift occurred following 2014 when the government initiated a concerned push towards ethanol blending as part of broader energy security and agriculture prosperity initiatives The subsequent years witnesses accelerated growth in ethanol blending deriving by policy reform economic incentives and infrastructure development by 2024 India’s ethanol blending rate had reached 18% by the end of the year a significant increase from the 12 to 30% recorded in early 2024 This progression demonstrated that effective implementation of government policies and the responsive adoption by sugar mills distilleries and oil marketing companies The most recent data indicate that India achieved 19.8% ethanol blending in May 2025 nearly reached the 20% target five year ahead of the original schedule this accelerated achievement represent one of the most successful biofuel program globally in term of scale and pace of implementation



Steps for production of ethanol through maize

Production Step	General Process Description	Application & Context in India
1. Grinding	Corn kernels are passed through a hammermill or roller mill to break them down into a fine powder.	This increases the surface area of the starch for subsequent reactions.
2. Cooking & Liquefaction	The corn flour is mixed with water to form a "mash," which is then heated. An enzyme (α -amylase) is added to break down long starch chains into shorter dextrins.	This step partially hydrolyzes the starch, lowering its viscosity.
3. Saccharification	A different enzyme (glucoamylase) is added to the cooled mash. This enzyme breaks the dextrins down into simple glucose sugar.	In some modern plants, this step is combined with fermentation (Simultaneous Saccharification and Fermentation) to save time and cost.
4. Fermentation	Yeast (<i>Saccharomyces cerevisiae</i>) is added to the sugar-rich mash. The yeast consumes the glucose and produces ethanol and carbon dioxide over 2-3 days.	This is a critical step where advanced plants may use AI to monitor and optimize conditions like temperature and pH for maximum yield.
5. Distillation	The fermented mixture, now called "beer," contains only about 12-15% ethanol. It is heated in a distillation column where ethanol, which has a lower boiling point than water, is vaporized, captured, and condensed into a concentrated liquid.	The final product is about 95% pure ethanol. The remaining water is removed in a further dehydration process to make it suitable for blending with petrol.

Benefits and challenges of ethanol production

Environmental Impact: A complex Picture

The environmental benefits of corn ethanol are a major point of contention with different studies arriving at varying conclusions.

- **Reported reduction in GHG Emission**

Multiple industry and government sources indicate that corn ethanol has a lower carbon intensity than gasoline over its life cycle. This is because the carbon dioxide released to ethanol is burned is offset by the carbon dioxide captured by the corn as it grows. Improved science and modeling have led to lower estimates of the carbon emission from land use changes associated with ethanol.

- **Scientific Criticism and other impacts**

In contrast some, independent scientific analysis conclude that the renewable Fuel Standard has increased GHG emission compared to gasoline. This is primarily due to the changes in the farming practices such as increased fertilizer uses and the conversion of natural landscapes to cropland. Beyond GHG emissions ethanol production has a significant environmental footprint contributing to water pollution from agricultural chemicals and high water usage.

Economic and agricultural considerations

The production of ethanol from Maize has significant economic ramifications both positive and negative.

- **Economic benefits**

The ethanol industry is a substantial economic driver, particularly in rural areas it supports 10,000 of jobs and contributes billion of dollars to the national GDP. For corn farmers it provides a crucial and stable market for their product.

- **Economic and agricultural cost**

This large scale demand for corn can lead to higher prices for corn itself which has ripple effect on food prices especially for products that rely on corn for animal feed. Furthermore, producing biofuels involves significant cost. One analysis found it to be billion of dollars more expensive than producing gasoline requiring government subsidies to remain competitive.

Energy and engine performance

- **Energy security and octane**

Using domestically grown corn for fuel reduces reliance on imported petroleum and increase reliance to global oil market disruption. Ethanol also has a higher octane rating than pure gasoline which can improve engine performance and efficiency.

- **Fuel economy and infrastructure**

A key drawback of ethanol is its low energy content a gallon of ethanol content about 27% less energy than a gallon of gasoline which result in lower fuel economy (fewer miles per gallon). For vehicles running on ethanol blends widespread adoption of higher level blend like E15 (15% ethanol) is also limited by a lack of infrastructure as few gas station offered them.

Future ethanol production by corn in India

The trajectory for corn based ethanol in India is one of the calculated growth the government's strategic push for energy independence and a cleaner environment will remain the primary drivers. To ensure a sustainable future the industry and policy makers will need to navigate several areas carefully,

- 1) **Managing agricultural equilibrium**

A key challenge will be finding a balance that does not overlay compromise the production of other essential crops like oil seeds, which is crucial for reducing India's massive edible oil import bill.

- 2) **Exploring feedstock avenues**

To meet booming demands India may need to diversify its feedstock resources. This could include a mix of continued domestic production increases and potential imports as seen in negotiation for US corn.

- 3) **Embarrassing technological efficiency**

Widespread adoption of AI and data analytics will be crucial for maximizing ethanol yield and minimizing energy consumption helping producers maintain profitability amid volatile cost.

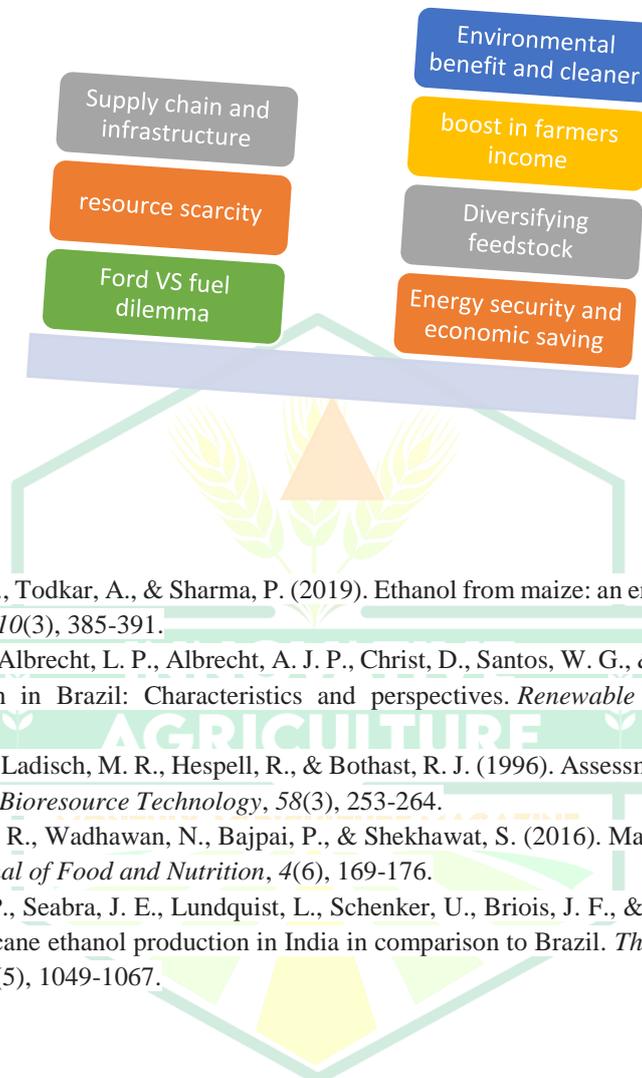
Conclusion

India's push for ethanol production from oil is a central pillar of its national energy strategy derived by several key objectives;

- **Energy security and economic savings:** A primary goal is to reduce India's heavy dependence on imported crude oil the ethanol blending program is projected to save the country \$ 6-10 billion annually once the E20 (20% blend) target is fully realized
- **Diversifying feedstock:** to meet ambitious blending targets and avoid over reliance on sugar cane the government has actively promoted alternative food stocks corn has been a major beneficiary of this shift for the first time in 2023 to 24 more than half of the India's ethanol supply came from grains primarily maize and surplus rice
- **Farmer income:** the program aims to boost rural economies by creating a stable remunerative market for agricultural produce oil marketing companies are expected to pay farmers around 40,000 crore in 2025 alone for ethanol feedstock.
- **Environmental benefits:** ethanol for cleaner Then patrol reducing ambitions of carbon monoxide and hydrocarbon ethanol from maize can reduce greenhouse gas emissions by about 50% compared to fossil fuels

Cons

Pros



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Integrated Sucking Pest Management in Bt. Cotton



N. Rajasekhar¹, M. Ravi Kishore², G. Shobhitha Rani³, Y. Sai Gopi⁴, B. Jagadeesh Naik⁵

¹Subject Matter Specialist (Plant Protection), ²Programme Coordinator, Young Professional-II³,
^{4&5}Young professional- I

Dr.K.L. Rao Krishi Vigyan Kendra, Garikapadu

Abstract

Cotton, significantly recognized as "White Gold," remains a vital commercial crop in India and specifically in the NTR district of Andhra Pradesh. While Bt hybrids provide resistance against bollworms for up to 90 days, the crop faces persistent threats from a complex of sucking pests from the seedling stage through maturity. This article details the symptoms and management of major pests including thrips, leafhoppers, whiteflies, aphids, red spider mites, and mealybugs. Successful management relies on an Integrated Pest Management (IPM) approach, including seed treatment with Imidacloprid (9 ml/kg) or Thiamethoxam (4.0 g/kg), intercropping with legumes (1:2 ratio), and the use of sticky traps. Adhering to Economic Threshold Levels (ETL) and implementing post-harvest sanitation—such as avoiding ratoon cropping and destroying crop residues—are critical for reducing cultivation costs and ensuring sustainable productivity in the region.

Keywords: Bt Cotton , Sucking Pests , Integrated Pest Management (IPM) , Economic Threshold Levels (ETL), NTR District , High-Density Planting System (HDPS)

Introduction

Cotton, often referred to as "White Gold," is a cornerstone of the Indian agricultural economy, supporting the livelihoods of millions. While Bt cotton hybrids are widely cultivated for their resistance to American bollworm, spotted bollworm, and pink bollworm for up to 90 days, the crop remains vulnerable to various sucking pests throughout its life cycle. Pests such as thrips, leafhoppers, aphids, whiteflies, red spider mites, and mealybugs can cause significant damage from the early stages to harvest. The inadvertent rise in the significance of these pests requires precise integrated management to ensure profitability. Relying on the indiscriminate use of pesticide mixtures can lead to pest resistance, environmental pollution, and increased cultivation costs. Adopting integrated management practices can effectively control these pests while reducing expenses.

Major Sucking Pests and Symptoms

1. **Thrips:** Small, slender insects that scrap the leaf surface and suck sap. Leaves curl up, showing silvery streaks on the underside, and eventually become brittle.
2. **Leafhoppers (Jassids):** Both nymphs and adults suck sap from the leaf underside. Symptoms include leaf edges turning yellow and then red, accompanied by downward curling.
3. **Whiteflies:** Nymphs suck sap and excrete a sticky substance (honeydew), leading to sooty mold growth. This reduces fiber strength and oil content in seeds.
4. **Aphids:** These insects cluster on leaves and stems to suck sap, often resulting in sooty mold development.
5. **Red Spider Mites:** Tiny red pests found on the upper leaf surface. They are more prevalent during the later stages of the crop, causing widespread damage by sucking sap from all plant parts.
6. **Mealybugs:** These pests suck sap from stems, buds, flowers, and bolls. This leads to shortened internodes, stunted growth, and premature boll opening, which significantly reduces yield and quality.

Economic Threshold Levels (ETL)

Chemical intervention should only be initiated when pest populations exceed the following levels:

- ✓ **Aphids:** 10–20% of plants infested.
- ✓ **Leafhoppers:** 2 nymphs per leaf.
- ✓ **Whiteflies:** 6 adults or 20 nymphs per leaf.
- ✓ **Thrips:** 10 adults per leaf.

- ✓ **Red Spider Mites:** 10 per square centimeter.

Integrated Pest Management (IPM) Strategies

1. Preventive Measures

- **Seed Treatment:** Treat 1 kg of seed with 9 ml of Imidacloprid or 4.0 g of Thiamethoxam using a suitable adhesive to protect the crop during its early stages.
- **Intercropping:** Grow intercrops like black gram, green gram, or soybean (1:2 ratio) to encourage natural enemies (predatory insects).
- **Border Crops:** Plant rows of sorghum or maize around the field and on bunds to act as a barrier against pest migration.

2. Monitoring and Mechanical Control

- **Sticky Traps:** Install 20 yellow and blue sticky traps per acre to monitor and trap whiteflies and thrips.
- **Sanitation:** Uproot and burn weeds like *Abutilon indicum* (Thutturabenda), *Parthenium* (Vayyari bhama), and *Trianthema* (Payalaku) which host these pests. Remove and burn plants heavily infested with mealybugs.

3. Chemical Control

If pests exceed ETL, use the following recommended sprays:

- **For Whiteflies:** Spray Profenofos (2 ml/L) or Neem oil (5 ml/L), ensuring the spray reaches the leaf underside.
- **For Aphids, Leafhoppers, and Thrips:** Spray Acephate (1.5 g/L), Imidacloprid (0.4 ml/L), Acetamiprid (0.2 g/L), Thiamethoxam (0.2 g/L), or Dicofol (2.0 ml/L).

Post-Harvest Management: Always remove and destroy crop residues (stalks) after the final picking and avoid ratoon cropping to prevent pest carryover to the next season.

Conclusion

The transition to Bt cotton has successfully managed bollworm pressure, but the emergence of sucking pests as primary yield-limiters necessitates a strategic shift in management. The demonstrations and technical guidelines provided by Dr. K.L. Rao Krishi Vigyan Kendra, Garikapadu, underscore that reliance on chemical mixtures alone is unsustainable due to rising costs and pest resistance. By adopting Closer Spacing (90 × 30 cm) combined with rigorous IPM practices—such as seed treatment, border cropping, and the timely use of recommended insecticides like Profenofos or Acephate—farmers in the NTR district can achieve significant yield increases of 30–35%. Ultimately, post-harvest discipline, specifically the destruction of crop stalks and the avoidance of ratoon crops, is essential to breaking the pest cycle and securing the long-term profitability of cotton in Andhra Pradesh.

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CONSTITUTIVE AND INDUCED PLANT DEFENCES



D. A. Akbari¹, C. U. Shinde², G. D. Bagul¹

¹Ph.D. Scholar, Department of Entomology, NMCA, NAU, Navsari (Gujarat, India)

²Associate Professor, Department of Entomology, NMCA, NAU, Navsari (Gujarat, India)

Corresponding Author: shinde.3112@nau.in

Abstract

Crop domestication and modern selective breeding have significantly enhanced yield and quality, often at the expense of resistance to insect pests. Over more than 350 million years of coexistence, plants and insects have engaged in a continuous evolutionary arms race, driving the development of complex plant defense systems that detect herbivore attack and activate immune responses. Plant defenses are broadly classified into constitutive defenses, which are continuously expressed, and induced defenses, which are activated in response to herbivory. Constitutive defenses include physical barriers such as cuticles, spines, and trichomes, along with pre formed chemical compounds that deter feeding but impose substantial metabolic costs. In contrast, induced defenses are dynamic and cost efficient, encompassing direct mechanisms such as toxins and digestive inhibitors, as well as indirect defenses mediated by herbivore induced plant volatiles (HIPVs). These volatiles influence herbivore behavior, attract predators and parasitoids, and prime neighbouring plants for enhanced resistance. The regulation of induced defenses is largely controlled by phytohormonal signalling pathways involving jasmonic acid, salicylic acid, and ethylene, which coordinate local and systemic responses. A comprehensive understanding of plant herbivore interactions and defense signalling networks is essential for developing sustainable pest management strategies and improving resistance traits in future crop breeding programs.

Keywords: Plant-insect interactions; Constitutive defense; Induced defense; Herbivore-induced plant volatiles (HIPVs); Secondary metabolites; Jasmonic acid; Integrated pest management

Introduction

Crop domestication and selective breeding have modified traits inherited from wild progenitors to develop crop plants with enhanced agronomic performance, including increased yield and improved quality. Although plant defense traits are sometimes considered when pests pose a severe threat, resistance to insect herbivores is often not a primary focus of breeding programs (Mitchell *et al.*, 2016). Plants and insects have coexisted for over 350 million years, during which co-evolution has driven both groups to develop strategies to circumvent each other's defense mechanisms. This prolonged evolutionary arms race has led to the emergence of highly sophisticated plant defense systems capable of recognizing non self-molecules or damage-associated signals and activating immune responses against herbivores, analogous to innate immunity in animals. In response to herbivore attack, plants employ two major defense strategies: constitutive defenses, which are continuously expressed, and induced defenses, which are activated only following herbivore feeding (Howe and Jander, 2008).

Herbivore attack triggers the emission of complex blends of volatile organic compounds known as Herbivore Induced Plant Volatiles (HIPVs). These compounds exert direct effects on herbivores, such as toxicity or repellence, and indirect effects by attracting predatory and parasitic arthropods that function as natural enemies. In addition, HIPVs can be perceived by neighbouring plants, enabling them to prime or adjust their defensive responses in anticipation of attack. Several studies have identified specific volatile compounds involved in defense priming or activation. In maize, for example, the green leaf volatiles (Z)-3-hexenal, (Z)-3-hexen-1-ol, and (Z)-3-hexenyl acetate have been shown to induce jasmonic acid production and stimulate sesquiterpene biosynthesis (Engelberth *et al.*, 2004). A comprehensive understanding of these complex chemical interactions between plants and herbivores is essential for optimizing resistance traits and guiding the development of improved crop varieties.

Plant defenses can be classified broadly as constitutive (permanent) or induced (temporary)

- Constitutive defenses are continuously expressed in plants and operate independently of herbivore attack. Although these defenses provide constant protection, they are not always required, resulting in significant metabolic and resource costs to the plant (Karban, 2011).
- Induced defenses, in contrast, are activated only upon herbivore infestation. According to plant defense theory, inducible resistance has evolved as a cost-saving strategy that minimizes the energetic burden associated with maintaining permanent defenses.
- While induced defenses enable plants to conserve resources in the absence of attackers, a delay in their activation can allow substantial herbivore damage to occur before effective defense responses are established. Moreover, the allocation of resources toward defense mechanisms can impose trade-offs, often leading to reduced plant growth.

1. Constitutive defense (permanent): The First Line of Protection

1.1 Structural Defenses: Plant structural traits constitute the first line of defense against herbivory and play a crucial role in Host Plant Resistance (HPR) to insect pests. This primary defense is achieved through the formation of physical barriers, including waxy cuticles (Agrawal *et al.*, 2009), as well as specialized structures such as spines, setae, and trichomes that deter insect feeding and colonization. Structural characteristics including spines and thorns (spinescence), trichomes (pubescence), hardened or toughened foliage (sclerophylly), the deposition of granular minerals within plant tissues, and divaricated branching with wiry stems and wide axillary angles play a central role in protecting plants from herbivore attack. Chamarthi *et al.* (2010) demonstrated that leaf glossiness, along with pigmentation of the plumule and leaf sheath, contributes to resistance against the shoot fly *Atherigona soccata* (Rondani) in *Sorghum bicolor* (L.) Moench. In addition, higher trichome density adversely influences insect pest oviposition, feeding behavior, and larval nutrition. Dalin and Björkman (2003) reported that feeding damage caused by adult leaf beetles (*Phratora vulgatissima* L.) on *Salix cinerea* L. resulted in increased trichome density in subsequently developing leaves. Similarly, coleopteran-induced herbivory has been shown to stimulate enhanced trichome production in *S. cinerea*. A positive relationship has been reported between trichome density and the abundance of natural enemies. In addition, trichome exudates can function as extrafloral nectar (EFN), providing a food resource for scelionid egg parasitoids of squash bugs, such as *Gryon pennsylvanicum* Ashmead (Olson and Nechols, 1995).

1.2 Pre-formed Chemical Defenses: Many plants store toxic or antinutritive compounds even before an attack occurs. Defensive (secondary) metabolites in plants may be either constitutively present in inactive, stored forms or synthesized de novo in response to insect or microbial attack. Constitutively stored compounds are referred to as phytoanticipins, whereas those produced following attack are known as phytoalexins. During herbivory, phytoanticipins are typically activated by β -glucosidases, leading to the release of biologically active aglycone metabolites with toxic or deterrent properties. A well-known example of phytoanticipins is glucosinolates, which are hydrolyzed by myrosinases endogenous β -thioglucoside glucohydrolases upon tissue damage. Phytoalexins comprise a diverse group of compounds, including isoflavonoids, terpenoids and alkaloids, which adversely affect herbivore performance and survival. Maize host plant resistance (HPR) to the corn earworm, *Helicoverpa zea* (Boddie), has been largely attributed to the presence of secondary metabolites such as the C-glycosyl flavone maysin [2"-O- α -L-rhamnosyl-6-C-(6-deoxy-xylo-hexos-4-ulosyl) luteolin] and the phenylpropanoid compound chlorogenic acid (Manachini *et al.*, 2007). Similarly, 4,4-dimethylcyclooctene has been identified as a key compound conferring resistance to the shoot fly *Atherigona soccata* in sorghum (*Sorghum bicolor*) (Chamarthi *et al.*, 2011). Flavonoid compounds, including the flavones 5-hydroxyisoderricin, 7-methoxy-8-(3-methylbutadienyl)-flavanone and 5-methoxyisoronchocarpin, isolated from *Tephrosia villosa* (L.), *T. purpurea* (L.) and *T. vogelii* Hook., respectively, have been reported to act as feeding deterrents against *Spodoptera exempta* (Walk.) and *Spodoptera littoralis* Boisd.

2. Induced Defenses: Dynamic and Adaptive Responses

Induced defense are often subdivided into direct and indirect defenses.

2.1 Direct defence: This involves the activation or synthesis of antifeedant compounds, including toxins and digestive inhibitors, which adversely affect herbivore growth and survival (Howe and Jander, 2008).

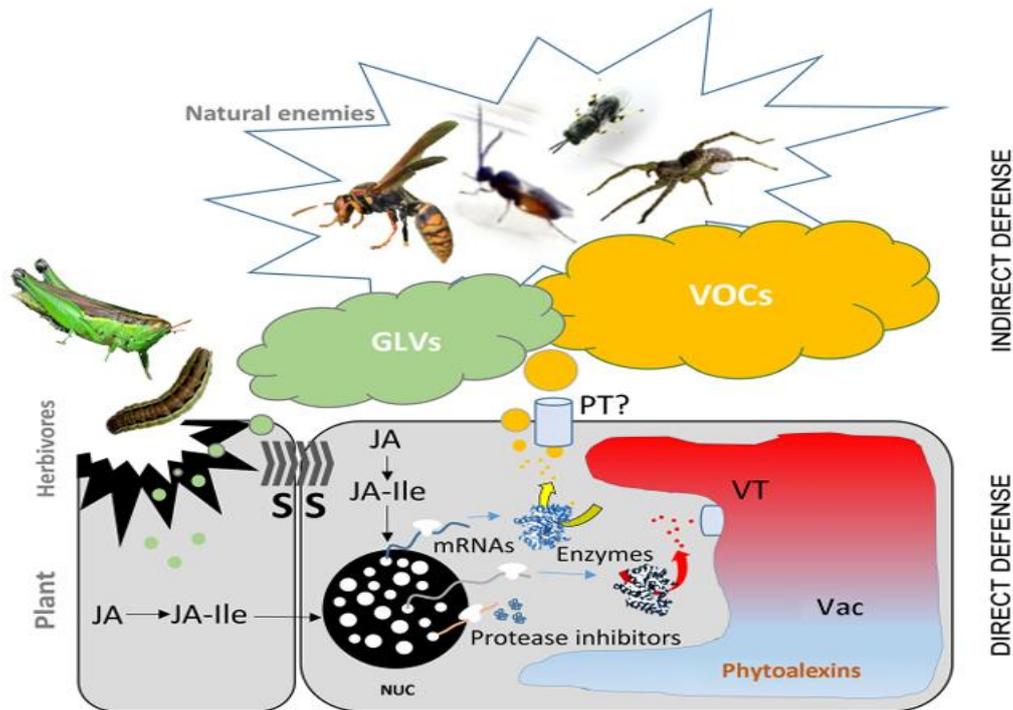


Figure 1. Schematic picture of induced plant defense

2.2 Indirect defense: Plant defensive responses that involve the attraction of natural enemies of herbivores play a critical role in protecting plants from herbivore attack. In recent years, induced indirect defenses have gained considerable attention and have been investigated extensively at genetic, biochemical, physiological, and ecological levels. Herbivore-induced plant volatiles (HIPVs) contribute significantly to plant defense by attracting natural enemies of herbivores and by directly deterring herbivore feeding and/or oviposition (Maffei *et al.*, 2010). Herbivore-induced plant volatiles (HIPVs) are lipophilic compounds with high vapor pressure that are emitted by plants from leaves, flowers, and fruits into the atmosphere, as well as from roots into the surrounding soil, in response to herbivore attack. Several plant volatiles, including methyl salicylate (MeSA) and the C₁₆ homoterpene 4,8,12-trimethyl-1,3(E),7(E),11-tridecatetraene [(E, E)-TMTT], have been shown to attract predatory mites. Infestation of rice by *Spodoptera frugiperda* induces the release of approximately 30 volatile compounds, including MeSA and methyl benzoate (MeBA), which strongly attract natural enemies of *S. frugiperda*, such as the parasitoid *Cotesia marginiventris* (Cresson) (Yuan *et al.*, 2008). A key elicitor of herbivore-induced plant volatile emission has been identified in the regurgitant of *Pieris brassicae* L. larvae, namely β-glucosidase, which triggers the release of a characteristic volatile blend from mechanically wounded cabbage leaves that attracts the parasitoid wasp *Cotesia glomerata* (L.) (Mattiacci *et al.*, 1995). The first Fatty Acid-Amino Acid conjugate (FAC) elicitor to be characterized was volicitin [N-(17-hydroxylinolenoyl)-L-glutamine], detected in the oral secretions of beet armyworm larvae, *Spodoptera exigua*. Application of volicitin to *Zea mays* L. plants induces the emission of volatile signals that attract natural enemies of the feeding larvae (Alborn *et al.*, 1997).

2.3 Role of phytohormones in induced resistance in plants:

Several plant hormones are involved in intra- and inter-plant communication following herbivore damage. Most plant defense responses against insect pests are mediated through signal transduction pathways regulated by Jasmonic Acid (JA), Salicylic Acid (SA) and ethylene. Jasmonic acid, synthesized from linolenic acid via the octadecanoid pathway, rapidly accumulates in plant tissues in response to wounding and herbivory and regulates the expression of numerous genes associated with herbivore defense. Jasmonates also induce the accumulation of key defensive compounds, such as indole glucosinolates, and have been shown to influence the transcription and activity of Calcium Dependent Protein Kinases (CDPKs) in potato plants (Ulloa *et al.*, 2002).

Herbivory by *Manduca sexta* on *Nicotiana attenuata* results in localized increases in Indole-3-Acetic Acid (IAA), followed by systemic production of JA-dependent secondary metabolites, including anthocyanins and phenolamides in the stems. This response suggests that IAA participates in plant defense signalling in coordination with JA (Yang *et al.*, 2021). In the case of *Helicoverpa armigera*, larval behavior is influenced by JA-mediated defenses, with larvae rapidly abandoning induced tissues and moving to uninduced plant parts. In contrast, *Plutella xylostella*, which exhibits resistance to certain defensive compounds in Brassicaceae, is less affected by these responses (Perkins *et al.*, 2013).

Salicylic acid, a benzoic acid derivative, is another key phytohormone involved in plant defense regulation. SA mediated signalling is particularly effective against piercing–sucking insect pests compared with chewing insects and functions in both localized defense and the induction of systemic resistance. Additionally, SA associated production of Reactive Oxygen Species (ROS) has been proposed as a mechanism contributing to insect resistance, such as in tomato plants challenged by *H. armigera* (Peng JinYing *et al.*, 2004). Ethylene, a gaseous phytohormone, also plays a role in plant development, senescence, and defense responses, particularly against necrotrophic pathogens (Chen *et al.*, 2005).

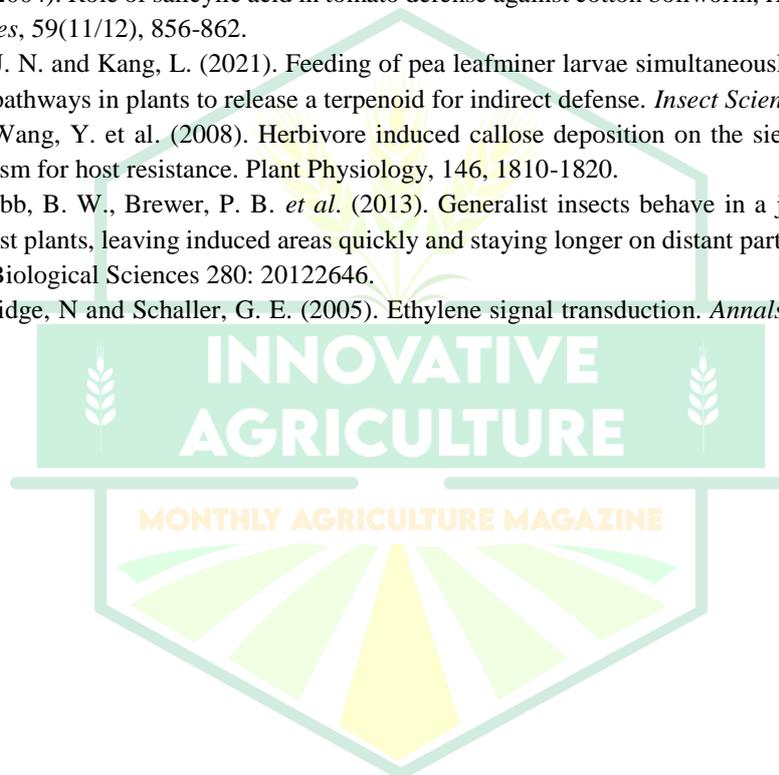
Conclusion

Plant defense against insect herbivores is the outcome of long-term co-evolution, resulting in both constitutive and inducible resistance strategies. While constitutive defenses provide immediate protection, they impose high metabolic costs on plant growth and productivity. Induced defenses offer a more efficient and adaptive response, minimizing resource expenditure while effectively countering herbivore attack. Herbivore-induced plant volatiles play a crucial role in direct deterrence, tritrophic interactions, and inter-plant communication. Phytohormone-mediated signalling networks, particularly involving jasmonic acid, salicylic acid, and ethylene, coordinate these defense responses. Integrating knowledge of plant defense mechanisms into crop breeding programs is essential for developing sustainable, insect-resistant agricultural systems.

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From Labor to Leadership: The Rise of Women Entrepreneurs in Spiti Valley



Savita Kumari¹, Meena Kumari², Sudhir Verma³, Nisha Chaudhary⁴

¹Subject Matter Specialist, ⁴Teaching Faculty, Department of Social Sciences, ²Assistant Professor, Department of Fruit Science, ³Principle Scientist, Department of Soil Science, College of Horticulture and Forestry YSPUH&F, Nauni Solan, Himachal Pradesh, India

Introduction

Lahaul and Spiti is a district defined by its dramatic contrasts, where the verdant, lush slopes of the Lahaul sub-division gradually transition into the stark, moon-like barrenness of the Spiti Valley. This region forms a critical part of the Trans-Himalaya, a high-altitude territory nestled in the rain shadow of the Great Himalayan peaks. Historically known as the "Middle Land" due to its position between India and Tibet, Spiti Valley is a high-altitude cold desert in northeastern Himachal Pradesh. It is a realm of ancient monasteries such as Ki, Tabo, and Dhankar—fluttering prayer flags, and deep-rooted Buddhist traditions that have been preserved for centuries due to the valley's geographical isolation. This unique heritage is further highlighted by the presence of some of the highest permanently inhabited villages in the world, including Kibber and Komic, where life continues to revolve around a harmonious balance of nature and spirituality. The geography and topography of Spiti are the primary architects of the resilience shown by its people. Characterized by towering mountains, deep gorges, and the winding Spiti River, the district is massive, covering 13,835 sq km, which accounts for nearly 25% of Himachal Pradesh's total land area. Despite its size, it remains the most sparsely populated region in India, with a density of only about 2 persons per sq km. The valley floor sits at a staggering average altitude of 3,800 meters (12,500 feet), while surrounding peaks frequently exceed 6,000 meters. Because it lies in a Rain Shadow Area, monsoon clouds are blocked by the mountain ranges, resulting in a climate that sees almost no rainfall but experiences extreme snowfall. Winters are particularly brutal; temperatures often plummet to -30°C, freezing the river and effectively cutting off the valley from the outside world for nearly six months each year. Even within this harsh environment, the geography supports a highly specialized and unique ecosystem. The valley serves as a prime habitat for elusive wildlife such as the Snow Leopard, the Himalayan Ibex, and the Blue Sheep. While natural vegetation is generally sparse, the region is famous for Sea Buckthorn, a hardy wild shrub that thrives along riverbeds. This plant has recently become a vital economic pillar for the community, particularly for local women's Self-Help Groups who process its nutrient-rich berries. Cultivated crops are limited to hardy varieties like peas and barley, which must be harvested during the short summer window. From its administrative headquarters in Kaza to the high-altitude connectivity provided by the Kunzum La pass, Spiti remains a testament to human and biological survival in one of the most extreme environments on Earth. Agriculture in Spiti is a race against time, dictated by a short growing season that lasts only from June to September. Because the valley is a cold desert, traditional farming is entirely dependent on Kuhls ingenious gravity-fed irrigation channels that carry glacial meltwater to the terraced fields. The primary cash crops are green peas and barley, with the Spiti pea being highly prized in mainland markets for its sweetness and late-season availability. Beyond cultivation, animal husbandry plays a crucial role in survival; yaks, cows, and *dzos* (a yak-cow crossbreed) provide milk, wool, and transportation. In recent years, the wild Sea Buckthorn has shifted from a mere thorny hedge used for fencing to a "superfood" goldmine. Local women, organized through Self-Help Groups, now harvest these berries to produce juices and oils, providing a vital source of independent income that lasts through the long, unproductive winter months.

The Socio-Economic Role and Motives of Self-Help Groups in Spiti Valley

In the high-altitude, cold desert of Spiti Valley, Self-Help Groups (SHGs) are not just financial groups; they are essential survival networks. Given the extreme geographical isolation where villages are cut off by snow for six months a year the role of SHGs is tailored to the unique Himalayan ecosystem. Self-Help Group (SHG) is a

homogenous group formed by 10-20 members of poor households having similar objectives, aims and aspirations. The group is formed under the principle of self help to promote individuals through collective actions in areas of augmenting income, gaining easier access to credit and other resources and increasing their bargaining power. The SHGs may be formed either by male members or by female members or both. This group is a voluntary association of the poor who come together to improve their socioeconomic conditions.

A Case study

According to Verma et.al 2022. A case study on impact of self-help group on women empowerment in India Self-help groups are small voluntary group of women that have a positive impact on women social, political and economic life. It is considered as one of the essential tools of rural development. Empowering women is the solution to many social and economic problems. Socio economic progress of the women is the mainstream of national Development and perhaps, therefore, been a major concern of the government. That was the reason year 2001 was declared as the “Year of women Empowerment”. Self help group is an effective strategy for the empowerment of women in all spheres. Membership helped in generating the family income, decision making, education status, risk taking ability, poverty reduction. The paper specifically focuses on the Socio-economic development of the SHG members and also tries to understand the challenges faced by them. The members of self-help group perceived to have been empowered after joining in this programme and achieved higher status by inculcating certain skills within themselves.

The study found that groups also participated in community awareness programs when needed explored that self-help groups are raising awareness among others to protect themselves from COVID pandemic. They are not only working to meet the demand for masks, sanitizers etc. but also helping people to get their pensions and access credits to their account through direct transfers. Women from self-help groups run community kitchens across the country to feed stranded workers, the poor and the vulnerable. Her resourcefulness and caring concern were widely appreciable.

Traditional foods products made by self help group

Seabukthron juice: sea buckthorn juice starts by washing your berries in cold water to get rid of any dirt or tiny thorns. Since the berries have a hard seed inside that can taste bitter if crushed, the easiest way to juice them is to put them in a blender and pulse it just a few times on a very low speed. Once the berries look mashed, pour the mixture through a fine strainer or a clean cloth into a bowl, pressing down with a spoon to squeeze out all the thick orange liquid. Because this raw juice is very sour almost like a strong lemon mix a small amount of the juice into a glass of water and add plenty of honey or sugar to make it tasty. The bottle a quick shake before you pours you a glass.

Seabukthron Jam: sea buckthorn jam, start by extracting fresh juice or pulp from the berries using a strainer or a slow juicer, ensuring you remove all the hard seeds and skins. Place the thick pulp into a heavy-bottomed pan and add an equal amount of sugar (or a 1:1 ratio), which helps balance the intense natural tartness of the fruit. Cook the mixture over medium heat, stirring constantly to dissolve the sugar and prevent it from sticking to the bottom. Since sea buckthorn is naturally high in pectin and acid, the jam will thicken on its own as it simmers its ready when it reaches a "sheet consistency" or when a small drop placed on a cold plate stays firm instead of running. Once it's thick and glossy, pour the hot jam into sterilized glass jars, leave a little space at the top, and seal them tightly.

Seabukthorn tea: Sea buckthorn tea the dried leaves or the dried berries (or a mix of both) for a caffeine-free, antioxidant-rich drink. One teaspoon of the dried material to a cup and pouring boiling water over it. Tea steep for about 5 to 7 minutes the longer it sits, the more of its signature tangy flavor and healthy oils will be released into the water. Berries, tiny orange oil droplets floating on the surface, which is a great sign as they contain the rare Omega-7.

Footwear Pula: It is traditional footwear made of sacred grass of shale-cannabis/bhang. For extra warmth or in snow walking the soul of this footwear often covered with sheep wool.

Apricot oil- Making traditional apricot oil, known as Chulli ka Tel, starts by drying apricot pits in the sun until they are easy to crack open with stones. Once the inner kernels are removed, they are crushed in a large stone bowl and ground into a smooth, thick paste. This paste is then spread onto a warm, tilted stone and kneaded firmly

by hand. The gentle heat from the stone and the pressure from the hands help break down the kernels, and by adding just a few drops of water, the golden oil begin to separate and flow. The oil trickles down the stone into a small collection groove, leaving behind a dry "oil cake" those locals often eat as a healthy snack or use as animal feed.

Sun-Dried Apricots (Pahadi Khubani): To make traditional Pahadi Khubani, start by selecting fully ripe yet firm apricots, washing them thoroughly, and patting them completely dry to prevent mold. Using your thumbs or a small knife, slit each fruit along its natural seam to remove the stone, then gently push the center of each half upward so the inner flesh faces out. Arrange these halves in a single layer, flesh-side up, on a wooden board or clean cloth, and place them in a spot with direct, intense sunlight and good air circulation. It is vital to cover the tray with a thin muslin cloth to ward off insects and, most importantly, to bring the trays indoors every night to protect them from moisture and dew. After about four to seven days of sun-curing, the apricots will turn a deep, dark brown as their natural sugars caramelize, resulting in a leathery, chewy texture that is ready for airtight storage.

Apricot squash: To make traditional Apricot Squash, begin by simmering de-stoned, ripe apricots in a small amount of water until they become soft and tender. Once cooled, blend the fruit and pass it through a fine sieve to ensure a smooth, velvety pulp free of skin or fibers. In a separate pot, dissolve sugar in water typically using a ratio of two parts sugar to one part fruit pulp and boil it to create clear syrup. Stir the apricot pulp into the hot syrup and add a splash of lemon juice or a pinch of citric acid to act as a natural preservative and balance the sweetness with a hint of tartness. Allow the golden concentrate to cool completely before pouring it into sterilized glass bottles when ready to drink, simply dilute one part of the squash with three parts of chilled water for a refreshing, mountain-inspired beverage.

Pattu Weaving: *Pattu* is a heavy, warm, and water-resistant wool fabric woven on traditional looms. It is used to make coats, gowns, and blankets. Each village often has its own specific weave pattern.

Gudma: These are heavy, soft blankets made from GI-tagged **Churu** (a cross between a yak and a cow) or sheep wool. They are usually natural white or cream with brightly colored borders.

Spiti Socks and Gloves: Famous for their vibrant, intricate geometric patterns, these are hand-knitted using local wool. The designs often represent elements of nature or Buddhist symbols.

Conclusion

Self-Help Groups (SHGs) have fundamentally transformed the women of Lahaul-Spiti, evolving them from daily laborers into confident, self-reliant entrepreneurs. This economic shift toward business ownership does more than just provide an income; it empowers the entire society by strengthening the community from its roots. Through their passion and dedication, these women are turning the "Vocal for Local" vision into a reality, proving that their products can reach far beyond the mountains. Ultimately, their journey is a testament to human resilience, showing that when one's resolve is strong, even the freezing winters and geographic challenges of the Himalayas cannot block the path to progress.

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Empowering Smallholders through Custom Hiring Centres: Driving Farm Mechanization in ATARI Zone–X



**Shaik Humera Tabbassum¹, Praneeth M², Manisha M², Harini D⁵, Vinutha D²,
Bhaskaran A³ and Shaik N Meera⁴**

¹Young Professional –II, ICAR-ATARI, Hyderabad-500059

²Senior Research Fellow, ICAR-ATARI, Hyderabad-500059

³Principal Scientist, ICAR-ATARI, Hyderabad-500059

⁴Director, ICAR-ATARI, Hyderabad-500059

⁵Data Entry Operator, ICAR-ATARI, Hyderabad-500059

Abstract:

Farm mechanization is vital for enhancing agricultural productivity and ensuring timely farm operations. However, small and marginal farmers often struggle to afford costly modern machinery. Custom Hiring Centres (CHCs) address this challenge by providing agricultural equipment on a rental basis, enabling wider access to mechanization. This article reviews the evolution, current status, and machinery profile of CHCs functioning in Krishi Vigyan Kendras (KVKs) under ATARI Zone–X. Of the 72 KVKs in the zone, only 13 have established CHCs, indicating significant scope for expansion. While CHCs reduce costs and labour shortages, improved infrastructure and wider coverage are needed to strengthen sustainable agricultural development.

Keywords: Custom Hiring Centres (CHCs); Farm Mechanization; Small and Marginal Farmers; ATARI Zone–X; Krishi Vigyan Kendra's (KVKs); Sustainable Agriculture

Introduction:

Indian agriculture is gradually moving from dependence on human labour and draft animal power to the use of modern machinery. Today, farm mechanization has become essential to increase productivity and ensure timely agricultural operations. However, many small and marginal farmers face difficulties in adopting machinery due to high cost of equipment. In addition, lack of knowledge about operating and maintaining machines, as well as limited storage space, further restricts their use. To overcome these challenges, Custom Hiring Centres (CHCs) have been established. CHCs provide farm machinery and equipment on a rental basis, allowing farmers to use modern technology without purchasing it. This helps farmers reduce cultivation costs, complete operations on time, and improve crop yield and Productivity. Thus, CHCs play an important role in promoting farm mechanization, especially among small and marginal farmers.

Evolution of Custom Hiring Centres (CHCs):

The concept of Custom Hiring Centres (CHCs) in India began as early as 1912, when a steam The concept of Custom Hiring Centres (CHCs) in India dates back to 1912, when a steam thresher was introduced for custom hiring in Punjab. The idea gained momentum in the 1960s with the establishment of Agro-Industries Corporations promoting cooperative mechanization. In 1971, agro-service centres were set up in Punjab, Haryana, and Rajasthan to provide machinery hiring services along with repair and input facilities. Government support expanded after the 1990s and was institutionalized under the Sub-Mission on Agricultural Mechanization (SMAM) during the Twelfth Five-Year Plan (2012–2017), with special focus on small and marginal farmers. Between 2014–15 and March 2022, ₹5,490.82 crores were allocated for agricultural mechanization. In 2022, the number of CHCs increased from 16,007 to 18,824, while Hi-Tech Hubs expanded from 378 to 403 and Farm Machinery Banks from 16,309 to 16,791. Additionally, a 2019 credit-linked subsidy scheme supported the establishment of machinery banks and Hi-Tech Hubs, leading to the creation of 1,000 additional CHCs by 2022. Over time, CHCs and Hi-Tech Hubs have emerged as key mechanisms for promoting inclusive mechanization in India (Dilip *et. al*, 2025) A Chronology of significant turning points in the development of CHCs in Indian Agriculture is presented in Fig.1.

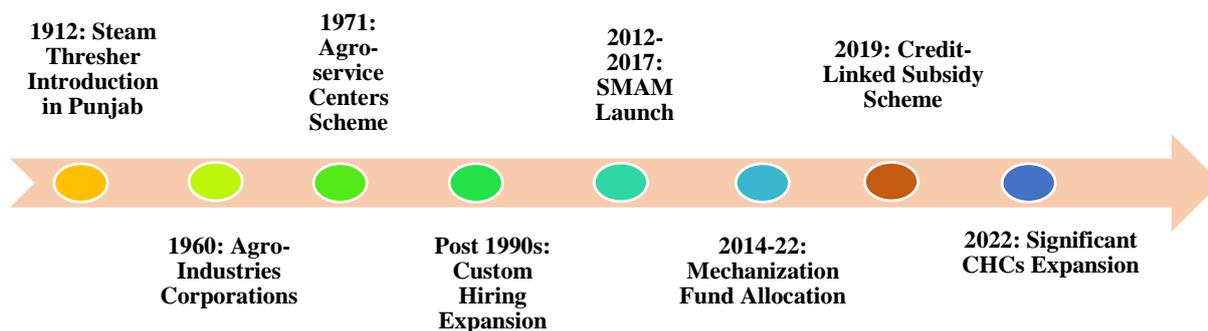


Fig.1. A Chronology of significant turning points in the development of CHCs in Indian Agriculture

Current Status of Establishment of Custom Hiring Centres (CHCs) in KVKs of Zone-X

In ATARI Zone-X, a total of 72 Krishi Vigyan Kendra's (KVKs) are functioning across four states and Union Territory. Among them, 16 KVKs are located in Telangana, 31 in Tamil Nadu, 23 in Andhra Pradesh, and 2 in Puducherry. Out of these 72 KVKs, only 13 KVKs have established Custom Hiring Centres (CHCs). This indicates that mechanization support has been initiated in the zone, there remains considerable scope to expand CHC services to more districts. The data presented in table 1

Table:1 State-wise Distribution of KVKs and Custom Hiring Centres in ATARI Zone-X

S.No.	State/UT	Total KVKs	Number of CHCs available
1	Andhra Pradesh	23	08
2	Telangana	16	03
3	Tamil Nadu	31	02
4	Puducherry	2	00
	Total	72	13

Profile of Custom Hiring Centres (CHCs) Machinery in KVKs under ATARI, Zone-X

The Custom Hiring Centres in ATARI Zone-X are equipped with a wide range of agricultural machinery covering various stages of crop production. The available equipment can be broadly categorized as follows: The data is presented in table 2

Table-2: Category-wise Profile of Custom Hiring Centres (CHCs) in Machinery under ATARI Zone-X

Category	Machinery/equipment Available	Uses
Land Preparation Equipment	MB Plough (2, 3 & Reversible), Disc Plough, Hydraulic Disc Plough, Chisel Plough, Sub-Soiler (Single & 3 Tyne), Cultivators (5, 7, 9 Tyne; Spring Type; Tractor Drawn), Rotavator, Laser Guided Land Leveller, Bed Maker, Bund Former / Maize Bund Former	These machines support primary and secondary tillage operations and help in proper soil preparation
Sowing and Planting Machinery	Seed Drills (8 Row, Zero Seed Drill), Seed Cum Fertilizer Drill, Manual Seed Drill, Manual Push Seeder, Manual Planter, Pair Row Planter, BBF Planter, Paddy Transplanter (4 Row), Drum Seeder	These implements ensure uniform seed placement, proper spacing, and efficient fertilizer application
Intercultural & Weed Management Equipment	Power Weeder, Cono Weeder, Hand Rotary Weeder, Brush Cutter, Push Hoe, Rotary Slasher, Tractor Operated Slasher	These tools help in effective weed control and crop maintenance.
Plant Protection Equipment	Taiwan Sprayer, Portable Sprayer, Battery Sprayer, Power Sprayer, Tractor Operated Sprayer, Orchard Sprayer, Mist Blower, Agricultural Drone	These machines facilitate efficient spraying of pesticides, herbicides, and micronutrients.
Post-Harvest & Processing Equipment	Multi Crop Thresher, Groundnut Pod Stripper, Maize Dehusker, Tamarind Dehuller & Deseeder, Sugarcane Bud Chipper, Cotton Shredder, Chipper Shredder, Shredder Cum Pulveriser	These machines support post-harvest handling and value addition
Utility & Support Equipment	Post Hole Digger (Manual & Hand Operated), Auger, Chain Saw, Tarpaulins, Kuoto Mini Tractor (24 HP) with Rotavator, Tractor	Utility and support equipment assist in plantation, fencing, pruning, drying, transportation, and in providing power for various farm operations.

The role and importance of CHCS in promoting farm mechanizations:

- 1. Expanding access to modern technology:** Custom Hiring Centres (CHCs) make modern agricultural machinery accessible to small and marginal farmers who cannot afford expensive equipment. By providing machinery on a rental basis, they remove financial barriers and promote wider adoption of improved technologies.
- 2. Promoting sustainable agriculture:** Access to mechanized tools ensures precision in field operations, better water management, and reduced soil degradation. Mechanization also minimizes manual drudgery, contributing to environmentally sustainable farming.
- 3. Reducing the impact of labour shortages:** During peak seasons such as sowing and harvesting, labour scarcity can delay farm operations. CHCs provide timely access to planters, reapers, and harvesters, ensuring smooth and timely completion of activities.
- 4. Providing economic relief to farmers:** Farmers avoid heavy capital investment and recurring maintenance costs by hiring machinery as needed. This reduces operational expenses and improves farm profitability.
- 5. Promoting adoption of innovative practices:** CHCs act as platforms for introducing advanced and improved farm equipment, allowing farmers to test technologies before making investment decisions.
- 6. Addressing the Challenges of Small Land Holdings** in regions with fragmented farms, shared use of machinery through CHCs makes mechanization economically viable.
- 7. Role of Government in Strengthening CHCs:** subsidies, cooperative models, and awareness programs strengthen CHCs and enhance their outreach and effectiveness.

Advantages of CHCs:

- Promotion of Cost-effective farming practices
- Increased productivity and overall farm efficiency
- Timely execution of farm operations
- Minimize the dependence on human labour
- Improved quality and precision of farm work
- Enhanced economic opportunities for farmers
- Transfer of technical knowledge
- Institutional support through government schemes and subsidies
- Scope of multiple opportunities and diversified livelihoods

Disadvantages of CHCs:

- Limited accessibility in remote and unreserved areas
- Increased Competition among operators
- Technological gaps in available of advanced and updated machinery
- High transportation costs for shifting equipment
- Inadequate utilization available machinery
- High operational and maintenance costs

Scope for Strengthening CHCs in ATARI Zone–X:

Although Custom Hiring Centres are functioning in selected KVKs of ATARI Zone–X, their overall coverage remains limited when compared to the total number of KVKs in the zone. There is significant potential to expand CHCs to more districts to ensure wider access to farm mechanization services. Strengthening infrastructure, increasing awareness among farmers, ensuring timely maintenance of machinery, and promoting efficient management practices can enhance the effectiveness of CHCs. Greater institutional support and strategic expansion can further improve mechanization outreach, particularly for small and marginal farmers.

Conclusion:

Custom Hiring Centres have emerged as an important mechanism for promoting inclusive farm mechanization in India. In ATARI Zone–X, CHCs are playing a valuable role in providing access to modern agricultural machinery, improving productivity, and reducing the financial burden on small farmers. However, the limited number of operational centres indicates the need for expansion and strengthening of services. With continued government

support, effective management, and wider coverage, CHCs can significantly contribute to sustainable agricultural growth and improved livelihoods in the region.

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Microplastic Pollution in Global Aquatic Ecosystems: Distribution, Analytical Methodologies and Ecological Implications



Komal Prasad Sahu¹, Bhoopendra^{2*}, Khilesh Kumar², Nitesh Kumar Chandravanshi²,

¹M.F.Sc. Department of Aquatic Environment and Health Management

²M.F.Sc. Department of Fish Harvest and Post Harvest Technology

LSPN College of Fisheries, Kawardha, DSVCKV, Durg, Chhattisgarh

*Corresponding author: bhupendrachandravanshi6688@gmail.com

1. Introduction

The worldwide distribution of plastic waste has recently become one of the most relevant environmental problems during the Anthropocene, with microplastics (MPs) among the most dangerous categories of pollutants. Broadly classified as small plastic particles less than 5 mm in size, microplastics are ubiquitous across the world's aquatic ecosystems, ranging from surface waters of the open ocean, deepest marine trenches and most secluded freshwater lakes (Vivekanand et al., 2021). The widespread presence of these particles is a direct result of booming worldwide plastic production since the middle of the 20th century, with poor waste treatment infrastructure and natural non-degradability (as it has been named as from synthetic polymers) for who abstains. Upon their introduction in the water environment, these materials experience complex physical and chemical processes leading to heterogenous size, shape and chemical composition that complicates both monitoring and mitigation (Ivleva et al., 2017). The presence of approximately 5.25 trillion plastic particles floating in global oceans underscores the magnitude of this crisis, with these materials releasing significant amounts of dissolved organic carbon that can disrupt fundamental microbial dynamics and carbon cycling.

Microplastic pollution has far-reaching ecological consequences, affecting everything from the molecular level to entire ecosystem services. It is known that aquatic creatures of all trophic levels, such as fish, molluscs, crabs, and microalgae, consume or attach to these particles, resulting in internal damage, physical obstructions, and physiological stress. In addition to causing physical harm, microplastics act as carriers of a variety of dangerous compounds, including as heavy metals, per- and polyfluoroalkyl substances (PFAS), and persistent organic pollutants (POPs), which adsorb onto plastic surfaces and then bioaccumulate in the food chain (Pal et al., 2025). This autovector and effectuate presents serious questions about human health and food safety because infected seafood may eventually allow microplastics and the toxins they contain to reach human consumers. Even with the increasing amount of research, there are still a lot of unanswered questions about the long-term ecological effects and the standardized techniques needed to precisely measure these dangers. In order to give a thorough picture of the status of the science in 2024, this study attempts to compile the most recent information on the distribution, analytical difficulties, and biological effects of microplastics.

The urgency of addressing microplastic pollution is further highlighted by the realization that these particles are not static entities but dynamic components of the aquatic environment (Ma et al., 2020). It is challenging to forecast the particles' environmental fate because of these interactions, which affect their buoyancy, movement, and bioavailability. Moreover, even if primary plastic imports were to be stopped right away, the breakdown of bigger plastic products into secondary microplastics guarantees a steady and growing supply of these pollutants. Therefore, it is essential to comprehend the developments and difficulties associated with microplastic contamination in order to create technological solutions and effective regulatory frameworks. This article aims to emphasize the urgent need for international collaboration and standardized protocols to protect the health of aquatic ecosystems around the world and the human populations who depend on them by looking at the nexus of analytical chemistry, environmental science, and toxicology.

2. Analytical Methodologies for Microplastic Detection and Characterization

2.1. Sampling Strategies and Pre-treatment Protocols in Diverse Aquatic Matrices

The first step in accurately assessing microplastic contamination is to use sampling techniques that are reliable and can take into consideration the high temporal and geographical variability of these particles in aquatic settings. Whether the matrix under study is surface water, the water column, benthic sediments, or biological tissues, sampling methods differ greatly (Pal et al., 2025). With mesh widths usually between 300 and 333 micrometres, manta trawls and neuston nets are frequently used for surface waters; nevertheless, these techniques frequently fall short of capturing tiny microplastics, resulting in an overestimate of the overall particle count (Xu et al., 2020). On the other hand, although the amount of water that can be treated is restricted, bulk water sampling and filtration enable the capture of smaller fragments. The difficulty in sediment sampling is separating the low-density plastic particles from the much denser mineral matrix, which calls for core or grab samplers. Because variables like wind speed, current patterns, and proximity to urban runoff can significantly affect the observed concentrations of microplastics, the sample location and timing selection are also crucial [4].

Strict pre-treatment procedures are necessary to separate microplastics from both organic and inorganic interference when samples are gathered. Usually, this procedure consists of multiple steps, such as drying, sifting, and chemical digestion to remove organic debris (Ivleva et al., 2017). Hydrogen peroxide (H₂O₂), potassium hydroxide (KOH), and different enzymatic treatments are common digestive agents; each has a different level of effectiveness and the ability to harm the plastic polymers themselves [6]. After digestion, concentrated salt solutions like sodium chloride (NaCl), zinc chloride (ZnCl₂), or sodium iodide (NaI) are used to perform density separation, which floats the lighter plastic particles away from the heavier silt grains [2], [3]. Because leftover organic residue might skew later spectroscopic analysis and result in false positives or incorrect polymer identification, the effectiveness of these procedures is crucial. One of the biggest obstacles to comparing data from various research and geographical areas is the absence of a generally recognized standard for these pre-treatment procedures.

2.2. Advanced Spectroscopic and Imaging Techniques for Polymer Identification

It is necessary to go beyond ocular assessment, which has a high error rate and is especially problematic for particles smaller than 1 millimetre, in order to definitively identify microplastics. The gold standard for determining the polymer composition of suspected microplastics is advanced spectroscopic methods, particularly Fourier-Transform Infrared (FTIR) spectroscopy and Raman spectroscopy. Infrared light absorption is measured by FTIR spectroscopy, which offers a special chemical interaction that enables researchers to distinguish between typical polymers like polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Vivekanand et al., 2021). Larger particles are usually analysed using Attenuated Total Reflection (ATR)-FTIR, although particles as small as 10–20 micrometres can be analysed using micro-FTIR (μ -FTIR). Although Raman spectroscopy can detect particles as small as 1 micrometre and provides even greater spatial resolution, it is more vulnerable to interference from fluorescence brought on by organic residues or pigment (Xu et al., 2020).

To give a more thorough evaluation of microplastic samples, imaging and thermoanalytical techniques are being used more and more in addition to spectroscopy. Energy Dispersive X-ray Spectroscopy (EDS) in conjunction with Scanning Electron Microscopy (SEM) produces high-resolution pictures of particle shape and elemental composition, which is especially helpful for finding adsorbed heavy metals or inorganic additions. By examining their thermal degradation products, Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) and Thermal Extraction Desorption-Gas Chromatography-Mass Spectrometry (TED-GC-MS) are effective methods for mass-based quantification that can simultaneously identify and quantify several polymer types. These techniques supplement the particle counts discovered by spectroscopic imaging by providing information on the overall mass of particular polymers in a sample. Understanding the origin and source of microplastics requires the integration of these cutting-edge approaches since the kind of polymer and surface properties frequently indicate specific industrial or domestic precursors (Yu et al., 2018).

2.3. Challenges in Standardization and Quantification of Microplastic Abundance

Research on microplastics is now hindered by a lack of standardized procedures for reporting and quantification, despite major technical developments. The inconsistent lower size limit of detection across studies is one of the

main problems; some researchers report particles as small as 300 micrometres, while others employ advanced equipment to detect particles in the sub-micrometre range. Establishing trustworthy baseline levels for various aquatic habitats or comparing microplastic quantities internationally is practically difficult due to this disparity. Furthermore, the units used to report abundance vary widely ranging from particles per cubic meter of water to particles per kilogram of sediment or per individual organism further complicating the synthesis of data for large-scale environmental assessments (Pal et al., 2025). Additionally, the lack of approved reference materials for microplastics makes it more difficult for labs to verify their analytical techniques and guarantee the accuracy of their findings (Vivekanand et al., 2021).

The considerable likelihood of sample contamination during collecting and laboratory processing is another major obstacle to microplastics quantification. Strict "clean room" procedures and the use of procedural blanks are necessary to guarantee that the particles discovered are genuinely environmental in origin because plastic is present in all aspects of contemporary laboratory settings, including clothing, equipment, and even the air. Furthermore, the manual nature of many identification stages limits the throughput of samples by introducing human bias and being incredibly time-consuming. Although machine learning techniques and automated imaging are being developed to expedite the identification process, these tools are not yet standardized or publicly accessible. Resolving these issues is essential to the establishment of evidence-based policies and successful monitoring programs. Without established procedures, the ambiguity around the precise amounts of microplastic contamination will keep making it difficult for us to determine the full scope of the threats to the environment and public health (Ma et al., 2020)

3. Environmental Distribution, Transport and Transformation Processes

3.1. Sources and Pathways of Primary and Secondary Microplastics in Water Bodies

There are several ways that microplastics might enter aquatic environments, however they are mostly classified as main and secondary sources. Primary microplastics are ones that are purposefully made to be small, like the microbeads found in toothpastes and exfoliants and the industrial "nurdles" or plastic pellets used as raw materials to make plastic. Due to their small size, these particles frequently avoid wastewater treatment plants (WWTPs) or are accidentally released during transportation. The bulk of plastic waste in the environment is made up of secondary microplastics, which are produced when bigger plastic objects like packaging, fishing gear, and synthetic textiles break apart and weather. For instance, the washing of synthetic clothing is a major source of microfibers, which are transported via sewage systems into rivers and oceans. Similarly, one important but sometimes disregarded source of secondary microplastics in urban aquatic ecosystems is tire wear particles from road runoff.

Complex hydrological and atmospheric factors control the movement of these particles from land sources to the open ocean. Rivers serve as important transportation routes, transporting microplastics from industrial and urban areas inland to coastal areas. The physical characteristics of microplastics, such as their size, shape, and density, as well as environmental elements like wind, waves, and currents, affect their dispersal once they are in the aquatic environment. Low-density plastics, such as polyethylene and polypropylene, have a tendency to float on the surface and are carried by surface currents over great distances, frequently building up in oceanic gyres. On the other hand, plastics with a higher density, such as polyvinyl chloride (PVC), or those that have been weighed down by biofouling the buildup of living things on the surface end up sinking and accumulating in benthic sediments [2], [5]. Because of this vertical transport mechanism, microplastics are dispersed throughout the water column and accessible to a variety of creatures with varying feeding preference.

3.2. Physicochemical Degradation and the Role of Environmental Factors in Fragmentation

Following its discharge into the environment, plastic waste undergoes a variety of biotic and abiotic degrading processes that cause it to break apart into ever-tinier fragments. The primary cause of the initial breakdown of plastics floating on the water's surface is photodegradation, which is fuelled by ultraviolet (UV) radiation from sunlight. The polymer chains undergo photo-oxidation when exposed to UV light, which results in the production of free radicals and the subsequent breaking of chemical bonds. Because of this process, the plastic becomes brittle and more vulnerable to physical abrasion against rocks or sand and mechanical fragmentation by wave action. Another factor is thermal degradation, especially in tropical areas where high temperatures can hasten the

oxidation process. The kind of polymer greatly influences the pace of deterioration; for instance, certain plastics are designed with UV stabilizers to greatly slow down their breakdown, while others are more naturally susceptible to environmental stressors (Pal et al., 2025).

Microplastics in aquatic systems are transformed by biological processes in addition to physical and chemical influences. can result in biodegradation, in which enzymes secreted by specific bacteria and fungi break down polymer chains. However, compared to the rate of physical fragmentation, the rate of real biodegradation is incredibly slow under most environmental conditions. More significantly, the presence of a biofilm modifies the microplastic particle's surface chemistry and density, changing its physicochemical characteristics. The particles' ability to absorb chemical contaminants from the surrounding water is improved by this "aging" process, which frequently increases the particles' surface area and porosity. Because increasingly smaller particles may be able to pass through biological membranes and induce systemic toxicity in aquatic creatures, the ongoing fragmentation of plastics into the nanoscale range (Nano plastics) is a growing issue.

3.3. Interaction with Co-pollutants and the Vector Effect for Persistent Organic Pollutants

The fact that microplastics can serve as carriers of other dangerous substances is among the most alarming features of microplastic pollution. Microplastics easily absorb persistent organic pollutants (POPs) from the surrounding water, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and organochlorine insecticides, because of their hydrophobic nature and high surface-area-to-volume ratio. These contaminants can be several orders of magnitude more concentrated on the surface of a microplastic particle than in the surrounding water, thereby transforming the plastic into a concentrated. A number of environmental conditions, such as pH, salinity, the presence of natural organic matter, and the age of the plastic itself, influence the adsorption process. Older, weathered microplastics often exhibit a higher affinity for contaminants due to increased surface roughness and the presence of oxygen-containing functional groups created during degradation (Xu et al., 2020).

Microplastics are known to interact with developing contaminants such as per- and polyfluoroalkyl substances (PFAS) and heavy metals like lead, cadmium, and mercury in addition to organic pollutants. These substances could have been added to the plastic during manufacturing as plasticizers, flame retardants, or stabilizers, or they could be found in the water column. When a microplastic particle is consumed by an organism, the altered chemical environment, such as the reduced pH in the digestive tract, may cause the adsorbed and added chemicals to desorb and be released into the tissues of the organism (Ma et al., 2020). As the pollutants are transferred from prey to predator, this promotes the bioaccumulation and possible biomagnification of toxins within the food chain (Pal et al., 2025). Although there is still much disagreement among scientists regarding the relative significance of microplastics as a vector in comparison to other routes (like direct absorption from food or water), their contribution to the overall chemical load on aquatic life is becoming more widely acknowledged as a serious ecological hazard.

4. Biological Accumulation and Multi-level Ecological Consequences

4.1. Mechanisms of Ingestion, Bioaccumulation and Trophic Transfer in Food Webs

A diverse range of animals, including zooplankton, bivalves, crustaceans, fish, and marine mammals, have been shown to consume microplastics. There are several ways that ingestion happens: deposit feeders eat microplastics that have accumulated in the sediment, whereas filter feeders, like as mussels and oysters, indiscriminately absorb particles from the water column. Trophic transmission is the process by which many predators indirectly consume microplastics by eating prey that has previously contaminated itself. Because some creatures may confuse microplastics for natural prey items like fish eggs or plankton, the physical properties of the particles such as their size, form (fibres, pieces, beads), and colour often affect the chance of ingestion. When microplastics are consumed, their fate is determined by their size; smaller pieces may become stuck in the digestive tract or even go to other tissues and organs, whereas bigger particles may be swallowed.

When the pace of microplastic ingestion surpasses the rate of removal, bioaccumulation takes place, causing a gradual accumulation of particles within the organism. In species with longer lifespans and higher trophic levels, this process is especially worrisome. According to studies, microplastics can pass from primary producers to top predators at different levels of the food chain, increasing the likelihood of biomagnification, in which the

concentration of microplastics or the toxins they are linked to rises with each level. Microplastics, for instance, can be passed from small crustaceans to fish that consume them and then to larger predatory fish or birds. Both the physical and chemical pollutants they carry are dispersed by this trophic transfer, which may have systemic ecological effects. The possibility that these contaminants could make their way into the human food chain and directly endanger public health is further highlighted by the discovery of microplastics in economically significant seafood species.

4.2. Toxicological Impacts on Cellular Function and Organismal Health

Microplastics have complicated toxicological effects on aquatic species that can show up at several levels of biological organization, ranging from cellular and molecular alterations to effects on growth, reproduction, and survival. Microplastics can cause oxidative stress at the cellular level, which is typified by an excess of reactive oxygen species (ROS) that harm proteins, lipids, and DNA. This oxidative stress can cause cellular necrosis or apoptosis and frequently sets off inflammatory reactions. Additionally, it has been demonstrated that microplastics disrupt the action of vital enzymes, including acetylcholinesterase, which is necessary for neurological function in a variety of aquatic species. Particles can occasionally physically harm cells or tissues, interfering with regular physiological functions and rerouting energy from development and reproduction to repair and detoxification.

Consuming microplastics can have a variety of detrimental effects on health at the organism level. A false sense of satiation brought on by physical obstructions in the digestive tract can result in decreased food intake, malnutrition, and ultimately starvation (Xu et al., 2020). Additionally, internal abrasions and sores from ingested particles can serve as pathways for germs to enter the body. Another significant worry is reproductive toxicity, as research has shown that species exposed to microplastics have changed sex ratios, decreased fecundity, and poor larval development (Pal et al., 2025). The chemical additives and adsorbed pollutants that leak from the plastic frequently make these effects worse since they can interfere with hormonal signaling and function as endocrine disruptors. The long-term, chronic effects on wild populations particularly when coupled with other stressors like climate change and habitat loss remain a crucial field of research, even though certain creatures seem to be quite resistant to microplastic exposure in short-term laboratory studies.

4.3. Implications for Microbial Dynamics and Ecosystem Services

Microplastics have the ability to alter basic microbial dynamics and the ecological services they offer, in addition to their effects on individual organisms. Significant amounts of dissolved organic carbon (DOC) are released by microplastics in the ocean, as was previously reported, and this can change the makeup and activity of microbial communities. The carbon, nitrogen, and phosphorus cycles which sustain the entire aquatic food web are among the nutrient cycles in which these bacteria are essential. The development of a distinct microbial population that lives on plastic waste can also help harmful bacteria and genes that cause antibiotic resistance spread over long distances. Microplastics operate as a stable substrate for the production of biofilms, which enables some microbial species to flourish in otherwise uninhabited habitats. This could lead to the outcompeting of native microbial populations and a change in the ecological balance.

The cumulative impact of these chemical and biological disturbances may have profound effects on ecosystem services as fisheries productivity, carbon sequestration, and water purification. For example, the effects of microplastics on the ocean's main producers, microalgae, can lower photosynthetic efficiency and oxygen production, which impacts the marine ecosystem as a whole. In a similar vein, species that are crucial for nutrient recycling and sediment aeration may have their functions disrupted by contamination of benthic environments. Microplastics have the potential to cause significant ecological changes as they continue to build up in the ecosystem. These effects have significant financial repercussions, including losses to the fishing and tourism sectors as well as the costs of environmental cleanup. For the sustainable management of aquatic resources worldwide, it is therefore both scientifically and socioeconomically necessary to comprehend the multi-level ecological effects of microplastic contamination.

5. Conclusion and Future Work

The widespread presence of microplastic contamination in aquatic environments around the world is a complicated and multidimensional environmental emergency that requires immediate attention from the public,

politicians, and scientific community. According to this assessment, microplastics are dynamic pollutants that interact with the environment's physical, chemical, and biological elements in ways that we are only now starting to fully understand. They are not just inert waste. Microplastics pose a serious threat to the integrity of aquatic food webs and the vital ecosystem services they provide due to their varied sources and pathways, their function as carriers of dangerous chemicals, and their profound effects on organismal health and microbial dynamics. The extent to which these pollutants can disrupt global biogeochemical cycles is demonstrated by the annual release of up to 23,600 metric tons of dissolved organic carbon from floating plastics alone (Pal et al., 2025).

One of the most critical findings of this review is the persistent challenge posed by the lack of standardized analytical methodologies. It is challenging to reconcile data from various research and create a coherent global knowledge of microplastic dispersion due to the variation in sample methods, pre-treatment procedures, and quantification units. The development of standardized, high-throughput, and cost-effective monitoring protocols is urgently needed, even though sophisticated spectroscopic and imaging techniques like μ -FTIR, Raman spectroscopy, and SEM-EDS have greatly improved our ability to identify and characterize these particles. To guarantee data quality and comparability, future research must give top priority to the development of verified reference materials and the verification of automated identification techniques. Additionally, nano plastics, which may present even higher toxicological hazards because of their capacity to pass through biological membranes, should be included in the scope of monitoring.

Although the consumption and bioaccumulation of microplastics are widely known, there are still a lot of unanswered questions regarding the long-term, chronic repercussions on communities and populations. The complex mixture of worn, irregularly shaped particles found in the environment is not fully reflected by the majority of toxicological studies to date, which have been carried out in laboratory settings utilizing high concentrations of pristine spherical beads. Future research should concentrate on exposure scenarios that are pertinent to the environment, taking into account the combined impacts of microplastics and the chemicals POPs, heavy metals, and PFAS that are linked with them. Further research is also necessary to understand the impact of disease transmission and antibiotic resistance, as these issues may have serious consequences for human and wildlife health.

In the end, combating the microplastic threat will necessitate an all-encompassing strategy that incorporates technical innovation, strong policy initiatives, and scientific study. Reducing plastic usage, enhancing waste management infrastructure, and creating more sustainable materials that are actually biodegradable in natural settings must be the main goals of mitigation initiatives. Since microplastic contamination is a transboundary problem that no one country can resolve on its own, international cooperation is crucial to establishing worldwide standards for plastic production and disposal. We can provide the evidence-based basis required to create efficient management strategies and protect the health of our planet's aquatic ecosystems for future generations by expanding our knowledge of the distribution, transformation, and ecological effects of microplastics.

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Pesticide Residues in Aquatic Environments: Sources, Fate, Bioaccumulation and Ecological Impacts



Komal Prasad Sahu¹, Khilesh Kumar^{2*}, Khuleshwar³, Laxmikant⁴

¹M.F.Sc. Department of Aquatic Environment and Health Management

^{2,4}M.F.Sc. Department of Fish Harvest and Post Harvest Technology

³M.F.Sc. Department of Fish Resource Management

LSPN College of Fisheries, Kawardha, DSVCKV, Durg, Chhattisgarh

*Corresponding author - khileshdhruw6@gmail.com

Abstract

Pesticide residues are widely detected in freshwater, estuarine and marine environments due to agricultural runoff, wastewater discharges, industrial effluents, direct application and remobilization of legacy contaminants. Once introduced, these chemicals undergo complex fate processes and accumulate in aquatic organisms through direct uptake and dietary exposure, leading to bioaccumulation and biomagnification along food webs. Scientific evidence shows that even low, chronic pesticide concentrations can cause neurotoxicity, endocrine disruption, reproductive impairment and biodiversity loss in aquatic ecosystems. This review summarizes the major sources, environmental fate and ecological impacts of pesticide residues in aquatic systems and emphasizes the need for improved monitoring and sustainable pesticide management to safeguard aquatic biodiversity and ecosystem health.

Key words: Pesticide residues, Aquatic ecosystems, Water pollution, Environmental contamination, Agrochemical.

1. Introduction

A chemically varied class of chemicals known as pesticides is used to manage organisms deemed detrimental to stored goods, public health, or agricultural output. Insecticides, herbicides, fungicides, defoliants, desiccants and plant growth regulators are all considered pesticides by the Food and Agriculture Organisation (FAO), even though they don't directly manage pests. From a functional standpoint, pesticides are used to safeguard crops against insects, fungi, weeds, nematodes, rodents and microbiological diseases during the production, storage, transportation and processing of agricultural products. The Green Revolution in the 1950s, especially in the United States, marked the beginning of the widespread use of pesticides, which eventually spread around the world as part of intensive farming methods meant to boost food production (Farah et al., 2025). Only a small percentage of pesticides are able to reach their intended species, though. Pesticide residues result from the remainder entering nearby environmental compartments. Unmetabolized parent molecules, transformation products and metabolites that endure in soil, water, sediments and living things are examples of these residues. Because of their toxicity, chemical stability, resistance to degradation and capacity to bioaccumulate and bio magnify across food webs, many pesticide residues pose environmental challenges.

1.2 Importance of Aquatic Ecosystems and Their Vulnerability

Earth's life-support systems depend on aquatic ecosystems, which include freshwater systems (lakes, rivers, wetlands), estuaries and marine habitats. These ecosystems provide drinking water, support fisheries and aquaculture, maintain biodiversity, control hydrological and biogeochemical cycles and support the livelihoods of millions of people worldwide. Over 70% of the Earth's surface is made up of marine ecosystems alone, which are essential for controlling the climate because they absorb excess heat and carbon dioxide from the atmosphere. Mangroves, seagrass meadows and coral reefs are examples of coastal ecosystems that offer long-term carbon storage, fish nursery environments and shoreline protection (Halpern et al., 2008). Aquatic habitats are extremely susceptible to chemical pollution despite their significance. Rivers, lakes and seas serve as terminal sinks for pollutants produced on land because they collect runoff from large catchment regions. By impacting delicate

creatures like plankton, benthic invertebrates, fish larvae and amphibians, even trace-level pesticide residues can upset aquatic habitats and have a domino effect on higher trophic levels.

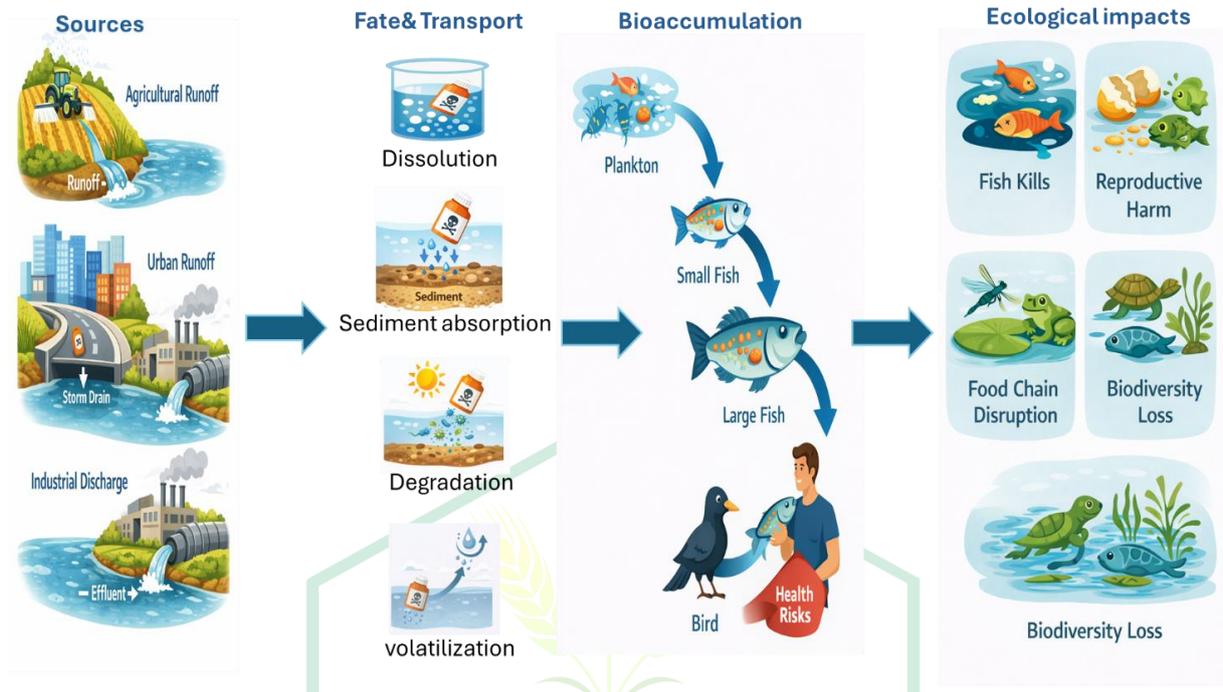


Fig. 1. Pesticide Residues in Aquatic Environments

1.3 Rising Global Concern over Pesticide Contamination of Water Bodies

Pesticide pollution of water bodies has become a significant worldwide environmental concern in recent decades. Pesticide residues are often found in surface waters, groundwater, sediments and aquatic creatures at amounts ranging from nanogrammes to microgrammes per litre, according to developments in analytical techniques. Agricultural runoff, leaching through soils, spray drift, industrial effluents, municipal wastewater discharges and inappropriate pesticide container disposal are some of the main sources of pollution. Particularly in areas where intensive agriculture predominates, many monitoring studies have shown pesticide concentrations beyond regulatory thresholds. It has been demonstrated that long-term exposure to low levels of pesticide residues, which are frequently regarded as "safe" for the environment, can change physiological processes, hinder growth and reproduction, interfere with the immune and endocrine systems and decrease species diversity. These sub-lethal consequences emphasise the shortcomings of risk assessments based only on acute toxicity, endangering food safety, fisheries productivity and ecosystem stability (Stehle & Schulz, 2015).

2. Sources of Pesticide Residues in Aquatic Environments

Numerous interrelated mechanisms allow pesticide residues to infiltrate aquatic habitats. These include pesticides used now, legacy pollutants and their breakdown products, which vary significantly in terms of toxicity, mobility and persistence. In surface waters, sediments and aquatic biota, monitoring studies often find complex combinations of herbicides, insecticides, fungicides and metabolites (Farah et al., 2025).

2.1 Agricultural Runoff and Subsurface Drainage

It is commonly known that the main cause of pesticide pollution in freshwater habitats is agricultural runoff. Pesticides used on crops are carried into nearby ditches, streams and rivers by surface runoff and subsurface tile drainage systems after rainfall or irrigation. Soil texture, organic matter content, slope, crop type, timing of pesticide application in relation to rainfall and physicochemical characteristics like water solubility and soil adsorption coefficients (K_{oc}) all interact to determine the extent of pesticide transport. Compounds that are very soluble and poorly sorbed are especially vulnerable to leaching and runoff losses. Acute toxicity to aquatic creatures can result from episodic pulses of pesticide pollution that coincide with storm events in areas with large tile drainage networks and intense row cropping.

2.2 Industrial and Agrochemical Processing Effluents

If wastewater treatment is insufficient, industrial point sources such as pesticide manufacturing plants, formulation facilities and agrochemical processing units may release concentrated pesticide residues. Localised pollution hotspots are also caused by spills, leaks and inappropriate waste management. The significance of regulatory enforcement and technological advancements in industrial effluent management has been highlighted by recent studies that show advanced and hybrid wastewater treatment technologies, including physicochemical and biological approaches, can significantly reduce pesticide loads (Akinapally et al., 2021).

2.3 Wastewater Treatment Plants and Urban Inputs

It is becoming more widely acknowledged that municipal wastewater treatment plants (WWTPs) are ongoing sources of pesticide residues. Domestic use, veterinary medications, lawn and garden items and agricultural runoff that enters combined sewer systems are all ways that pesticides get into sewer systems. Many contemporary pesticides and their metabolites, especially polar and water-soluble substances like neonicotinoids, cannot be eliminated by conventional wastewater treatment methods. As a result, receiving waterways get low but persistent pesticide concentrations from WWTP effluents, which have been shown to have an influence on invertebrate communities downstream (Muenze et al., 2017).

2.4 Direct Application to Aquatic Systems

To manage aquatic weeds, control mosquitoes and prevent disease in aquaculture, several pesticides are purposefully sprayed directly into aquatic environments. Fish, amphibians and benthic invertebrates are among the non-target animals that may be exposed because of repeated treatments or incorrect dose, even though these applications are regulated (Farah et al., 2025).

2.5 Legacy Sources: Sediments and Groundwater

Long after their usage has been outlawed, persistent pesticides especially organochlorines like DDT remain retained in sediments and groundwater. Through desorption, sediment disturbance, flooding and bioturbation, these legacy toxins function as secondary sources, gradually releasing pesticides back into the water column. The lengthy environmental lives of prohibited pesticides are highlighted by recent research that continues to show measurable quantities in fish and sediments.

3. Types of Pesticides Commonly Detected in Aquatic Systems

Herbicides, fungicides and insecticides are the predominant pesticide classes in aquatic habitats, according to monitoring studies. Acute toxicity and long-term sub-lethal effects are often linked to insecticides, especially organophosphates, organochlorines, pyrethroids and neonicotinoids. Owing to their widespread usage and mobility, herbicides like glyphosate and atrazine are frequently discovered, but fungicides, particularly those based on copper and carbamates, provide hazards owing to sediment buildup and prolonged exposure.

4. Distribution and Fate of Pesticide Residues in Aquatic Environments

Once introduced into aquatic systems, pesticide residues undergo complex physical, chemical and biological processes that govern their persistence and ecological impact.

4.1 Persistence, Degradation and Transformation

Pesticides are broken down by photolysis, microbial biodegradation and hydrolysis. Even for substances with comparatively short half-lives, ongoing inputs may cause pseudo-persistence and long-term exposure. Transformation products dominate groundwater contamination and are frequently more mobile and permanent than parent substances, making regulatory monitoring more difficult (Kolpin et al., 2020; Klöckner et al., 2019).

4.2 Sediment Adsorption and Remobilization

Sediments serve as long-term sinks and delayed secondary sources for hydrophobic insecticides. Sediment-bound pesticides can be remobilised by environmental disturbances like flooding, dredging and changes in redox conditions. This might result in episodic contamination events with serious ecological repercussions (Commelin et al., 2022).

5. Bioaccumulation and Biomagnification

5.1 Uptake Pathways in Aquatic Organisms

Pesticides are directly absorbed by aquatic species through food and water. While hydrophobic substances mostly build up through food consumption, water-soluble pesticides easily permeate through gills, skin and cell

membranes. Pesticide characteristics and organism characteristics including fat content, feeding habits and trophic position affect uptake rates.

Table 1. Pathways and Consequences of Pesticide Fate in Aquatic Environments

Process	Description	Key Factors Influencing Fate	Environmental Implications	References
Persistence and degradation in water	Persistence describes the residence time of pesticides in aquatic systems before breakdown. Degradation occurs through hydrolysis, microbial biodegradation and abiotic reactions. Some modern pesticides show pseudo-persistence due to continuous inputs.	Chemical structure, temperature, pH, microbial community, sunlight exposure	Long-term exposure of aquatic organisms; chronic toxicity and ecosystem-level effects	Mitra <i>et al.</i> , 2024
Adsorption to sediments	Hydrophobic and moderately polar pesticides bind to suspended solids and sediments, which function as sinks and delayed secondary sources of contamination. Fine particles carry higher pesticide loads.	Sediment organic carbon, clay content, pesticide K _{oc} , particle size	Toxicity to benthic fauna; long-term persistence and remobilization during disturbance	AbuQamar <i>et al.</i> , 2024
Volatilization	Volatilization involves transfer of pesticides from water surfaces to the atmosphere, contributing to long-range transport and redeposition in distant aquatic ecosystems.	Vapor pressure, temperature, wind speed, water turbulence	Redistribution of pesticides to remote freshwater and marine systems	Leal <i>et al.</i> , 2025
Photodegradation	Solar radiation (UV-visible) degrades pesticides via direct and indirect photolysis, especially in surface waters. Natural organic matter can enhance or inhibit photolysis.	Light intensity, turbidity, dissolved organic matter, water depth	Reduction of parent compound but formation of potentially toxic photoproducts	Guo <i>et al.</i> , 2023
Transformation into metabolites	Pesticides undergo biotic and abiotic transformation into metabolites that are often more mobile and persistent than parent compounds (e.g., AMPA from glyphosate, atrazine metabolites).	Microbial activity, redox potential, molecular stability	Metabolites dominate groundwater contamination and complicate regulatory monitoring	Pasquini <i>et al.</i> , 2025
Re-release and remobilization	Previously sorbed pesticides can be released from sediments due to flooding, resuspension, redox changes or bioturbation, leading to episodic contamination.	Hydrological extremes, sediment disturbance, pH and redox shifts	Sudden exposure events affecting aquatic organisms and food webs	Maqsood <i>et al.</i> , 2025

5.2 Bioaccumulation across Taxa

Pesticides enter aquatic food webs mostly through plankton, which quickly concentrates pollutants even at low ambient concentrations. Pesticides build up in metabolically active tissues of fish, molluscs and crustaceans, greater concentrations are frequently seen in predatory species.

5.3 Biomagnification along Food Chains

Top predators, such as birds, animals and people that eat contaminated fish and shellfish, have substantial exposure risks due to biomagnification, which raises pesticide concentrations at successive trophic levels.

6. Effects of Pesticide Residues on Aquatic Organisms

6.1 Acute Toxicity

Fish and invertebrate mass death can result from acute pesticide exposure, which is frequently linked to runoff events or unintentional spills. Organophosphates, carbamates and pyrethroids are examples of neurotoxic pesticides that interfere with nerve transmission, causing paralysis, respiratory failure and even death (Stehle & Schulz, 2018).

6.2 Chronic and Sub-lethal Effects

Growth inhibition, reproductive impairment, endocrine disruption, immunosuppression and oxidative stress are all consequences of long-term exposure to low pesticide concentrations. Over time, these minor effects compound to decrease ecosystem stability and population resilience.

7. Impacts on Aquatic Biodiversity and Ecosystem Health

Pesticide residues disrupt trophic relationships, change the composition of communities and decrease species diversity. Reduced ecosystem services including fisheries productivity and water quality regulation result from the reduction of sensitive taxa, the dominance of pollution-tolerant species and the simplification of food webs (Yamamuro et al., 2019).

8. Monitoring and Detection of Pesticide Residues

Integrated sampling of water, sediments and biota is necessary for effective monitoring, along with sophisticated analytical methods like GC-MS and LC-MS/MS. Bioindicator organisms and passive sampling tools offer time-integrated evaluations that are crucial for assessing ecological risk and adhering to regulations (Katagi et al., 2016).

7. Conclusion

Pesticide residues pose a continuing threat to aquatic ecosystems due to their widespread entry into water bodies and their ability to persist, accumulate and move through food webs. Even at low concentrations, long-term exposure can impair aquatic organisms, reduce biodiversity and disrupt ecosystem functioning. Addressing this issue requires improved monitoring, responsible pesticide use and sustainable management strategies to protect aquatic life, ecosystem services and human health.

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From Biology to Field Success: The Role of Male Sterility in Hybrid Vegetables



S. Hima Bindu¹ and B. Girivarsha²

Research Scholars, ^{*1}SKLTGHU, ²Dr. YSRHU

Abstract

Vegetable cultivation has shifted from traditional varieties to high-yielding hybrids to meet the growing demand for productivity, quality, and market uniformity. One of the key biological tools enabling large-scale hybrid seed production in vegetable crops is male sterility. Male sterility refers to the inability of plants to produce viable pollen while retaining functional female reproductive organs, making them ideal female parents in hybridization programmes. This natural mechanism eliminates the need for manual emasculation, reduces labour costs, and ensures higher genetic purity of hybrid seeds. Different forms of male sterility, including genetic, cytoplasmic, and environment-sensitive systems, are used in vegetable breeding, with cytoplasmic male sterility being the most widely adopted for commercial hybrid seed production. The technology has been successfully utilized in important vegetable crops such as onion, carrot, cabbage, chilli, tomato, and brinjal. By facilitating efficient hybrid development, male sterility contributes to higher yields, uniform produce, improved stress tolerance, and better shelf life, ultimately benefiting farmers, consumers, and the seed industry. With the integration of modern molecular tools, male sterility is expected to play an even greater role in future vegetable improvement programmes aimed at ensuring sustainable production and food security.

Key words: Vegetables, Male sterility, Hybrids, Yield and Uniformity

Introduction

Vegetable cultivation has undergone a major transformation in recent decades. Farmers are no longer satisfied with traditional varieties that give low yields and uneven produce. Instead, they prefer hybrid vegetables that provide higher productivity, better quality, uniform size, and improved resistance to pests and diseases. The large-scale success of hybrid vegetables is made possible by several scientific tools, and one of the most important among them is **male sterility**. Though it is a biological phenomenon, male sterility has become a practical and powerful tool that supports profitable vegetable farming and efficient seed production systems (Acquaah, 2012; Singh, 2015).

What is Male Sterility?

Male sterility refers to the inability of a plant to produce viable pollen grains. Since pollen is essential for fertilization, a male-sterile plant cannot pollinate itself. However, its female reproductive organs remain functional, so it can receive pollen from another plant and produce seeds normally. Because of this unique feature, male-sterile plants are extremely useful in hybrid seed production, where one parent must act only as a female. Under normal conditions, breeders must remove the anthers of flowers manually to prevent self-pollination. This process, known as emasculation, requires skilled labour, precision, and a large amount of time. Male sterility eliminates this step completely and simplifies hybridization procedures (Kaul, 1988).

Male sterility can arise in different ways:

- **Genetic male sterility (GMS)** – controlled by nuclear genes
- **Cytoplasmic male sterility (CMS)** – governed by cytoplasmic factors and maternally inherited
- **Environment-sensitive male sterility** – influenced by temperature or photoperiod

Among these, CMS systems are the most widely used in vegetable crops because they provide stable and reliable sterility suitable for commercial hybrid seed production (Allard, 1999).

Role of Male Sterility in Hybrid Seed Production

Hybrid seeds are produced by crossing two genetically distinct parents so that the offspring show hybrid vigour or heterosis. For this to happen, the female parent must not self-fertilize. Male sterility ensures this naturally.

When male-sterile plants are grown alongside fertile pollen parents, cross-pollination takes place through natural agents such as insects or wind, producing true hybrid seeds (Acquaah, 2012).

This biological mechanism allows breeders to produce hybrids efficiently without complicated manual operations. As a result, male sterility has become a cornerstone of modern vegetable breeding programmes and commercial seed production (Singh, 2015).

Major Advantages of Male Sterility

1. Simplifies Hybridization: In many vegetable crops, flowers are small, delicate, or produced in large numbers, making manual emasculation extremely difficult. For example, in chilli, onion, or cabbage, removing anthers manually can damage flowers and reduce seed set. Male sterility solves this problem by naturally preventing pollen formation, allowing breeders to focus on selecting good parents rather than managing tedious crossing work (Kaul, 1988).

2. Reduces Labour Requirement and Production Cost: Hybrid seed production traditionally involves a large workforce for emasculation and controlled pollination. This raises production costs and limits the scale of hybrid seed availability. Male sterility reduces labour needs drastically and makes hybrid seed production economically viable even on large farms. This has played a key role in expanding the hybrid vegetable seed industry worldwide (Allard, 1999).

3. Ensures High Genetic Purity of Hybrid Seeds: One of the biggest challenges in hybrid seed production is maintaining genetic purity. If even a small proportion of flowers self-pollinate, the resulting seeds will not be true hybrids. Male sterility prevents self-pollination entirely, ensuring that almost all seeds produced are genuine hybrids. This leads to uniform crop performance, consistent fruit quality, and predictable yield in farmers' fields (Singh, 2015).

4. Enables Large-Scale Commercial Seed Production: Male sterility allows hybrid seeds to be produced on a large scale under open field conditions. Seed companies can plant male-sterile lines with pollen parents in specific ratios and rely on natural pollination systems such as bees. This makes hybrid seed production faster, cheaper, and more efficient, helping meet the rising demand for hybrid vegetable seeds in many countries (Dhaliwal *et al.*, 2020).

5. Promotes Development of Superior Hybrids

Hybrid vegetables often show heterosis, which results in several desirable traits:

- ✓ Higher yield potential
- ✓ Early maturity
- ✓ Better tolerance to biotic and abiotic stresses
- ✓ Uniform fruit size, colour, and shape
- ✓ Improved shelf life and transportability

Male sterility makes the production of such hybrids feasible on a commercial scale and supports the development of improved vegetable varieties suited for modern markets (Acquaah, 2012).

Vegetable Crops Where Male Sterility is Used

Male sterility has been successfully utilized in several important vegetable crops:

- **Onion** – one of the earliest and most successful CMS-based hybrid systems (Havey, 2000)
- **Carrot** – widely used to obtain uniform root shape and size
- **Cabbage and cauliflower** – helps to produce compact and uniform heads
- **Chilli and sweet pepper** – reduces cost of hybrid seed production
- **Tomato and brinjal** – increasingly using male-sterile lines in breeding programmes

These examples show how male sterility has moved beyond research into large-scale practical application.

Benefits to Farmers

For farmers, male sterility may not be visible directly in the field, but its impact is significant because it enables hybrid technology. Hybrids produced using male sterility often provide:

- ✓ Higher yield per unit area
- ✓ Better resistance to pests and diseases
- ✓ Uniform fruits fetching premium prices

- ✓ Greater adaptability to different climates
- ✓ Improved storage and transport quality

These advantages increase profitability and reduce production risk, making hybrid vegetables an essential component of modern horticulture (Dhaliwal *et al.*, 2020).

Benefits to Consumers and Markets

Consumers also benefit from male-sterility-based hybrid vegetables because they receive:

- ✓ Attractive, uniform produce
- ✓ Better taste and cooking quality
- ✓ Consistent market supply
- ✓ Improved nutritional value in some hybrids

Thus, male sterility contributes not only to production efficiency but also to food quality, nutrition, and market stability.

Future Scope of Male Sterility

With increasing population pressure, climate variability, and shrinking agricultural land, vegetable production must become more efficient and resilient. Scientists are now integrating male sterility systems with molecular breeding, marker-assisted selection, and biotechnology tools to develop next-generation hybrids that combine high yield, stress tolerance, and nutritional quality (Acquaah, 2012).

In the coming decades, male sterility will continue to play a central role in sustaining vegetable productivity and ensuring food security.

Conclusion

Male sterility is a natural biological mechanism that has transformed hybrid seed production in vegetable crops. By eliminating the need for manual emasculation, reducing labour costs, ensuring genetic purity, and enabling large-scale hybrid development, it has become one of the most valuable tools in modern vegetable breeding. As the demand for high-yielding, quality vegetables continue to rise, male sterility will remain a key technology supporting profitable farming and sustainable vegetable production.

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Reimagining Agriculture 2026: From Autonomous Fields to Self-Fertilizing Crops



Harsh Pharande, Shreya Patil, Prerana Shere

School of Food Technology, MIT Art, Design and Technology University, Pune- 412201

1. Smart Farming and the Rise of Autonomous Agribusiness

The advent of cutting-edge technology like automation, robots, and artificial intelligence is drastically altering agriculture. Global farmers have been dealing with issues such as a lack of workers, growing input costs, and the need to increase food production in a sustainable manner in recent years. Autonomous technology such as robotic weed eaters, harvesting robots, agricultural drones, and self-driving tractors are therefore becoming more and more significant. In addition to increasing productivity, these instruments open up new doors for entrepreneurs hoping to launch agribusinesses in 2026. The demand for increased productivity and sustainability is predicted to propel the global agricultural robots and drones market, which was valued at over USD 7.43 billion in 2025 and is projected to reach over USD 24 billion by 2034, according to latest industry data. This demonstrates that agricultural automation is no longer merely an experimental practice but is becoming embedded within modern farming.

One of the most significant developments in precision agriculture is the adoption of autonomous tractors. These tractors carry out activities like plowing, sowing, and spraying with little assistance from humans thanks to GPS navigation, sensors, cameras, and artificial intelligence.

The increased productivity of autonomous tractors is one of their main benefits. Automation allows equipment to operate consistently for extended periods of time. In addition, studies indicate that autonomous solutions can save labor costs by up to over 70% in some processes. This is particularly significant in regions where there is a labor shortage.

A small workforce may oversee several machines, increasing productivity and lowering long-term operating expenses.

The quick rise in the use of semi-autonomous and guided tractors is another significant development. By 2026, sales of tractors with autosteer or guiding systems are expected to surpass 660,000 units yearly, demonstrating the rapid adoption of this technology.

This implies that fewer employees are needed to oversee greater land expanses for someone launching an agribusiness. A small workforce could manage several machines, increasing productivity and minimizing long-term operating expenses.

Drones for agriculture are quickly becoming as one of the most popular instruments in contemporary farming. According to reports, drones make up between 35 and 40 percent of the agricultural robotics market and are frequently employed for mapping, spraying, and crop monitoring. Drones offer a number of quantifiable advantages. According to a Karnataka study, drone spraying can save up to 90% of the water used for pesticide spraying while increasing crop yields by roughly 5% to 10% for some crops, like ragi and tur dal. As stated in The Times of India

Furthermore, drones are significantly faster than manual spraying techniques, covering many acres each hour.

Drones can be utilized by agribusiness businesses as a service model in addition to on owned farms. On a per-acre basis, entrepreneurs can provide farmers services like insect identification, fertilizer spraying, and crop monitoring. This creates additional cash streams and lessens the need for significant land investments.

Robotic Weeders and Sustainable Farming

One of the most time-consuming and chemically dependent agricultural operations is weed control. To address this issue, robotic weed eaters are being created using artificial intelligence and machine vision.

Herbicide consumption may be decreased by 35% on average and up to 65% in instances without compromising the effectiveness of weed management, according to field tests of robotic spot-spraying systems.

Robots that remove weeds using lasers and artificial intelligence are also being developed; these robots have a detection accuracy of over 85% and can target weeds with great precision.

Reduced chemical costs, better soil health, and the opportunity to promote product as ecologically sustainable—a quality that customers are becoming more and more interested in—are all benefits for agribusinesses.

Robotic Harvesting and Labor Savings

It takes a lot of manual labor to harvest fruits and vegetables, and for some crops, labor costs might reach 25% annually due to duties like trimming and harvesting.

To overcome this difficulty, robotic harvesting devices are being created. These devices recognize ripe fruits and carefully choose them using cameras, sensors, and artificial intelligence.

This technology can assist new agribusiness endeavors maintain regular harvesting schedules and lessen their reliance on seasonal labor, which enhances supply chain dependability and lowers post-harvest losses.

Market Expansion and Commercial Prospects

The field of agricultural robots is growing quickly. Precision farming and sustainability efforts are likely to propel the worldwide agricultural robotics industry, which was estimated to be worth USD 5.66 billion in 2024, to rise dramatically during the next ten years.

The importance of automated field activities is demonstrated by the fact that autonomous tractors alone accounted for more than 37% of the agricultural robotics and mechatronics market share in 2025.

This expansion suggests promising prospects for new businesses and entrepreneurs in sectors like:

Services for drone-based monitoring and spraying Accurate nutrient management and irrigation

Contract farming with automated equipment Agriculture in controlled environments and smart greenhouses

A platform for agricultural management and data analytics

How These Technologies Help Start an Agribusiness in 2026

Compared with traditional farming, starting an agribusiness is made easier by modern technologies. Among the main benefits are:

1. Decreased labor requirements: Automation lessens the need for manual labor.
2. Higher productivity - the ability of machines to operate for extended periods of time without sacrificing quality.
3. Better use of resources - Pesticides, fertilizers, and water are used effectively.
4. Sustainability benefits: Less environmental effect and less chemical use.
5. New business models: In addition to producing crops, entrepreneurs can offer technology-based services.

Agriculture is becoming a more data-driven, sustainable, and efficient sector thanks to autonomous tractors, drones, robotic weed eaters, and harvesting robots. The market for agricultural robots is expanding quickly, and quantifiable gains in output and resource efficiency demonstrate that these technologies are evolving from optional novelties to indispensable instruments.

In 2026, traditional agricultural practices are no longer the only way to launch an agribusiness. Entrepreneurs may save expenses, increase yields, and establish new service-based agriculture enterprises by implementing autonomous technology. Smart and automated farming is anticipated to be crucial to maintaining global food security and sustainable agricultural growth as technology develops.

2. Sustainable Nitrogen Management through Biological Fixation Technologies

Nitrogen (N) is a vital element for plant growth and crop productivity. However, the heavy reliance on synthetic nitrogen fertilizers has created significant environmental and economic challenges for global agriculture. Nitrogen is the most limiting nutrient in agricultural ecosystems. Nitrogen is approximately 80% of the atmosphere in the form of N₂ gas, but plants cannot absorb this gaseous form directly. The conventional approach of supplementing nitrogen through synthetic fertilizers has been shown to result in substantial economic costs, including elevated production expenses, inefficiencies in nutrient uptake, and significant environmental impacts, such as greenhouse gas emissions, water pollution, and soil degradation. In response to these challenges, biological nitrogen fixation (BNF)—a natural process that converts atmospheric nitrogen into plant-accessible ammonia through microbial

activity—has emerged as a promising sustainable alternative that can substantially reduce dependence on chemical nitrogen inputs while enhancing soil health and environmental sustainability.

Microbial Nitrogen Fixation: Mechanisms and Microbial Agents

Some special types of bacteria called diazotrophs are responsible for this process. They have a biochemical called nitrogenase, which works with oxygen to change nitrogen from the air into ammonia. This ammonia is then available for plants to use. These nitrogen-fixing microorganisms are very important for sustainable agriculture because they use a natural process that has kept land ecosystems alive for thousands of years. It is interesting that more than 60% of the nitrogen in the Earth's atmosphere comes from this process, which is important for the whole planet. Nitrogen-fixing microorganisms are divided into three main groups. The first group are symbiotic rhizobia bacteria. These form nodular associations with legume crops. The second group are free-living diazotrophs. These include species such as *Azotobacter* and *Azospirillum*. They colonize the rhizosphere. The third group are cyanobacteria. These can both fix nitrogen and synthesize various beneficial metabolites. These microorganisms can promote plant growth in a number of ways, including fixing nitrogen, breaking down phosphate, producing plant hormones, creating substances that make iron available, and producing compounds that stop the growth of harmful organisms.

Microbial Inoculants and Biofertiliser Technologies

The commercialisation of microbial nitrogen-fixing products is an important step in turning laboratory discoveries into useful agricultural applications. A big step forward in this area was finding, making and selling the first product made from microbes that helps plants make their own nitrogen in fields with fertiliser (*Zea mays*). This breakthrough involved using synthetic biology tools to engineer a wild nitrogen-fixing microbe called *Klebsiella variicola* 137-1036, which was isolated from agricultural soils. The modified strain was able to grow in corn roots, and it could fix nitrogen much better than the original strain – 122 times better, in fact! This is important because it means the technology works well even in places where synthetic nitrogen fertiliser is used. Experiments were carried out across the U.S. Corn Belt over several years and on different sites. These experiments showed that fields treated with this product had higher yields (0.35 ± 0.092 t/ha or 5.2 ± 1.4 bushels/acre more than the control) and less variation in how much was produced in each field. This variation was 25% less in 2018 and 8% less in 2019 in fields that received this product compared to fields that received synthetic nitrogen fertilisers only.

Researchers have continued to build on this work, creating new gene-edited strains that are even better at fixing nitrogen in soil. These new strains can also remove more ammonium in conditions where there is a lot of nitrogen. These specially designed diazotrophs are the most advanced in biotechnology for nitrogen fixation. They combine the study of microbes with the study of genes to overcome the historical limitation that nitrogen fixation is typically stopped by the presence of reactive nitrogen in the root zone. Field tests using these new microbial technologies have shown that labeled nitrogen moves from the root zone to plant chlorophyll.

Genetic Engineering and Metabolic Reprogramming Approaches

As well as creating engineered microbial inoculants, another good idea is to change the genes of cereal plants so that they can make more nitrogen-fixing bacteria by changing how their roots work. A big step forward showed that changing the genes of a kind of wheat called hexaploid wheat to increase the amount of a special chemical called apigenin in the root liquids could help soil bacteria that help with nitrogen grow more biofilms and fix more nitrogen in the soil. In this study, plants that contain a substance called apigenin released this into the soil. This led to the growth of bacteria on the roots and the formation of a slimy layer around them. The biofilms' low oxygen permeability protected the bacterial nitrogenase from oxygen inhibition and stimulated nitrogen fixation activity. In experiments where they limited the amount of nitrogen, the wheat lines with high levels of apigenin had more nitrogen, performed better in photosynthesis and produced higher yields of grain compared to the normal controls. This shows that it might be possible to change how cereals grow to make them able to fix nitrogen with the help of microbes in the soil. Similar methods have worked well in rice, where using CRISPR-based gene editing to target the breakdown of apigenin led to plants with higher levels of apigenin and increased apigenin secretion from the roots. This increased the amount of grain produced under conditions where there was limited nitrogen, while also changing the structure of the root microbiome to encourage the growth of diazotrophic bacteria.

Nitrogen Fixation in Legume-Based Systems

While the use of microbes to fertilize cereal crops is an exciting new area of research, legume crops have long been known for their ability to help with sustainable agriculture. This is because they can work with rhizobial bacteria to fix nitrogen, which is important for plant growth. Legumes, including peanuts, chickpeas, soybeans, and common beans, work together with special bacteria called rhizobia. These bacteria help the plants use nitrogen from the air, which is available to the plants. Legume crops are able to make their own nitrogen, which is different from cereal crops that need outside nitrogen fertilizer. This process is more complicated than other traits in crops because it involves the genes of both the host plant and the bacteria that help it. Research has shown that we can improve nodulation and nitrogen fixation by combining different types of bacteria, such as *Rhizobium* species and plant growth-promoting rhizobacteria (PGPR), like *Azospirillum*, *Pseudomonas*, and *Bacillus* strains. These co-inoculation approaches have a combined effect that improves root development, increases nodulation efficiency, enhances nitrogen uptake, and boosts yields under different agro-climatic conditions

Keeping the environment and economy healthy

It is important for the economy and the environment to have technologies that fix nitrogen. At the moment, most farm produce relies on synthetic nitrogen fertilisers, but about half of the reactive nitrogen in these fertilisers ends up in the environment. This causes water pollution, ozone depletion, the formation of atmospheric particulates and global greenhouse gas emissions. Using too much fertiliser on farms has caused big problems with the nitrogen cycle. This is shown by more and more nitrates being found in soils and waters, and more nitrogen oxides in the air. A new way of measuring this is to look at how much fertiliser is needed, and to compare this to the total amount of inputs. This can be used to see how well achievements are going and how much effort is being put in to make farming more independent. Furthermore, the large-scale use of agrochemicals and changes to the climate have had a big effect on the environment and crop failures worldwide. This has created problems for the environment and the economy. This has made people interested again in using natural communities of microbes that live in the soil to reduce the need for expensive and harmful chemicals.

3. Problems and Future Potential

Nitrogen fixation technologies show a lot of promise, but there are several problems that make it hard for them to be used and work well. These challenges include things like how well the inoculant works, how stable it is, how it's delivered, how it performs in the field, how farmers accept it, how long it lasts, and rules that aren't clear enough. Things like the pH of the soil, how much nutrients are there, the temperature, how much competition there is between microbes, and how the host genotype interacts with them can all make it so that microbial inoculants aren't as consistent or effective. Soil differences and microbial competition make it hard to apply lab results to the field. Research is still needed to standardize biofertilizer formulations, optimize strain-host plant compatibility, and develop microbial consortia tailored to local conditions.

Future research should focus on several key areas, including designing microbes that can perform better when they are under stress, assessing the ecological risks of microbial invasions to prevent unwanted ones, and combining agronomy and microbiology to improve the connection between soil health and agricultural development. Additionally, it will be essential to study how plants and microbes interact at the molecular level, develop strategies to match genotypes with strains, and validate the performance in different environments over time. It is essential to start managing nitrogen using data from different sources, including microbes, synthetic biology, and digital innovation. This will help agricultural systems deal with climate change.

4. Conclusion

Nitrogen fixation technologies are a big step towards sustainable farming. This includes growing and using nitrogen-fixing microorganisms found in nature, as well as changing crops and microbes so they can fix more nitrogen. These methods mean that they do not need as much synthetic nitrogen fertiliser, which reduces costs, reduces greenhouse gas emissions, prevents groundwater pollution and helps the environment. By including ways of getting rid of excess nitrogen into various types of farming, improving soil microbes and what they do, and continuing to advance technology in improving strains of plants and changing their genes, we can make sure that everyone on the planet has enough food in future and look after the planet.

Kachari (*Cucumis callosus*): The Desert's Hidden Superfood



Rohit Kumar, Dr. Shweta* and Shivani

Department of Horticulture, School of Agriculture, Lovely Professional University, Phagwara,
Punjab. 144411, India

Corresponding author email: shwetaguleria228@gmail.com

Abstract

Kachari (*Cucumis callosus*) is an underexploited desert fruit as well as vegetable that naturally grows in the arid and semi-arid regions of India, particularly in Rajasthan, Gujarat and Haryana. It is a hardy crop which thrives with minimal care and often grows along field boundaries, wastelands and water channels. Despite its resilience and long history of traditional use, it remains underutilized. The plant produces small, striped fruits that are consumed fresh, dried, or powdered and plays a significant role in supporting rural livelihoods in harsh environments. Nutritionally, Kachari is rich in moisture, dietary fiber, proteins, essential amino acids, vitamins such as Vitamin C & B3 and several beneficial phytochemicals. These bioactive compounds contribute to its antioxidant, anti-inflammatory, antidiabetic, antihyperlipidemic, and anticancer properties. Traditionally, it is used in curries, pickles and regional dishes like panchkutta, while its dried powder is valued for digestive health and even used as a natural meat tenderizer due to its proteolytic enzymes. Considering its adaptability, nutritional richness and therapeutic potential, it can be considered as an important vegetable for crop diversification, improved nutrition and enhanced livelihood opportunities in arid regions, warranting greater research attention and large-scale promotion.

Keywords: Wild melon, Drought tolerance, Arid fruit, Functional food, Nutritional properties

Introduction:

Cucumis callosus (Kachri) is an underexploited fruit of the Cucurbitaceae family, distributed majorly in the arid regions of India in the states of Rajasthan, Gujarat and Haryana. It is known by various names like kachria, kaachr, mat-kaachr, kaachra, sainda, goradi and kothimbda in different parts of the country. It is called as mango melon, higher cucumber in English whereas chitrphala, mrigakshi, chitra in Sanskrit (Samadia et al., 2024). The fruit is traditionally used by the native people on a small scale by home-level processing. In India, Kachari is grown by the side of water channels in the field, waste land, on the sides of the roads and railway tracks. The indigenous vegetable, kachri (*Cucumis callosus*) help in sustaining livelihood in the adverse environmental conditions, wherein vegetable crop diversification is not very feasible.

Kachri needs hot and dry climate along with long growing season, preferably with warm days for growing as a rainy as well as summer season crop. The dry climate and high atmospheric temperature are beneficial for dehydration of Kachari fruits, favouring maturation and quality of fruits. (Jatav et al., 2016). Kachari is a drought and heat tolerant cucurbitaceous vegetable which naturally grows in abundance in wild form or acts as a weed during kharif season in mixed cropping system. The immature fruits have bitter pulp but are edible at maturity and can be harvested from October to November.



Figure 1. An overview of Kachri plant and its fruit

Botanical Description:

Kachri is a perennial herb characterized by deeply lobed sub-orbicular leaves with 5-7 lobes. The roots are tuberous, stem type is slender and very less branched and drooping. The petiole is slender, shape of leaf lamina is sub-orbicular and leaves are having hirsute type of pubescence. The male flowers are borne singly. The petal colour is light greenish yellow. The pedicel of female flower is looped and 'U' shaped. The fruit shape of Kachri varies from round to obovoid with 6-10 longitudinally variegated green strips and small edible seeds. The fruit is 3-5cm long and has smooth textured surface with pointed, tasteless and nearly flat yellowish coloured seeds (Deepika et al., 2023).

The ovary pubescence is tomentose (the surface is densely covered with a compact layer of fine, soft, down-like hairs). The seed size is medium and bulged, while the seed funicle is sharp, stiff, or abrupt point (mucronate) (John et al., 2013). It is a cross-pollinated crop with high heterozygosity due to its compatibility with other species.

Nutritional importance:

C. callosus has various health promoting therapeutic properties because of the presence of all essential nutrients and amino acids like leucine, lysine, histidine, valine, isoleucine, phenylalanine and threonine. It has (0.48%) crude fats, (2.15-3.66%) proteins, (4.12%) dietary fibre and high moisture content (88.9-89%) (Dahot et al., 1999). It contains a good amount of carbohydrates, minerals, Vit-C and Vit-B3 which supports metabolism and nervous system. Besides this, various secondary metabolites like alkaloids, tannins, flavonoids and phenols are also present which exhibits anti-inflammatory, anti-adipogenic, anti-cancerous and antioxidant properties.

Uses and Benefits of Kachri:

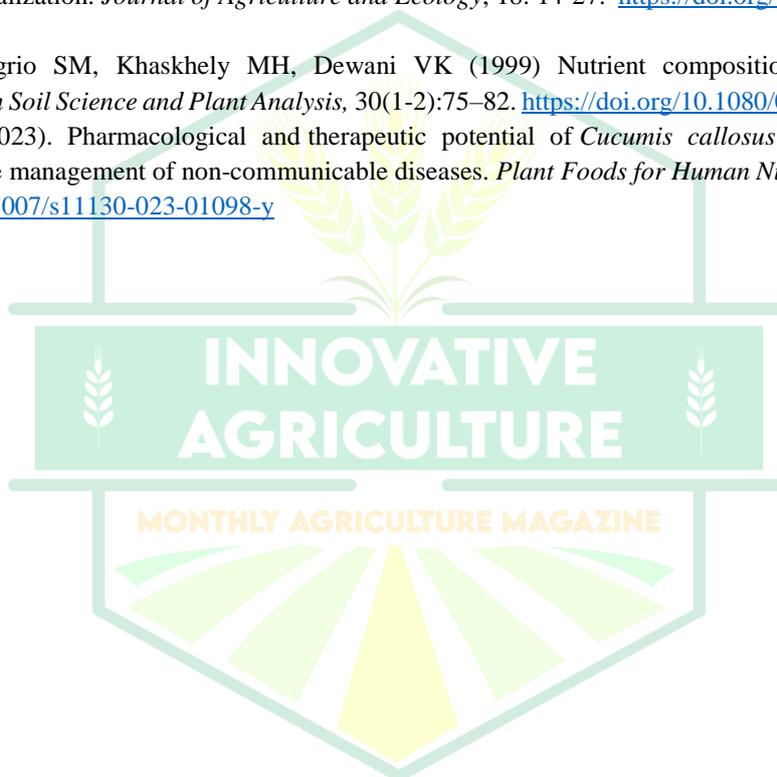
- It is rich in Vitamin C and can be utilized in different culinary purposes, such as curries, pickles and salads, etc.
- Moreover, the traditional systems have utilized Kachri on account of its medicinal uses, treating conditions including stomach pain, nausea and constipation. The dehydrated form of Kachri has been recognized for its properties of suppressing cough and acting as a diuretic (Nandhini and Sumathi, 2023).
- Seeds act as a coolant in treating bilious disorders and vertigo.
- It is used for making 'Panchkutta' which is a traditional dish in north-western desert regions like Rajasthan.
- Mature fruits are dried and stored in powdered form for off-season and impart sweet-sour taste so combined with other condiments and spices for making curry powders.
- Kachri powder used for making 'Kach-churan', which is effective for treating nausea, vomiting and stomach related disorders.
- Kachri is rich in essential nutrients and has antioxidant, antidiabetic, anti-inflammatory, anti-hyperlipidemic and anti-cancerous properties.
- It is also used as a meat tenderizer because of protease enzymes present in it.
- A triterpenoid, cucurbitacin B, is present in fruit pericarp, which has antiproliferative activities against cancer.
- Glycosyringic acid present in seed extract is beneficial in industries for bioremediation, laccase activation and photocatalytic ozonation as well as protective against neurological and cardiovascular disorders (Deepika et al., 2023).

Conclusion and Future Prospects:

With further research being carried out, Kachri may prove to be a vital part of health and nutrition practices, especially in areas where it is widely grown. It provides crop improvement opportunities to the breeders as it has high variability in fruit shape (globose, oblong, oval, round, ovate, spindle, long), fruit size, hairiness, surface thickness and number of seeds per fruit. The fruits are produced annually and can be easily stored in dried or powder form, which fulfils year-round availability. Additionally, all parts of fruit like seeds, roots, leaves, peel and whole fruit are edible with numerous health promoting medicinal benefits. By intensifying its large-scale cultivation, farmers can supply it as a raw material in the pharmaceutical and cosmetic industries, along with making it available as a vegetable in the market and fetch good price.

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AN OVERVIEW OF PLANTS, COMPOUNDS, AND ANTICOCCIDIAL HERBAL REMEDIES FOR COCCIDIOSIS MANAGEMENT IN POULTRY



Dr. Susmita Thullimalli

Associate Professor, Poultry Science, NTR College of
Veterinary Science, Sri Venkateswara Veterinary University

ABSTRACT:

Coccidiosis has a serious negative effect on poultry farming and causes large financial losses. As protozoan parasites, *Eimeria* species are known to infect hens and cause disease and death. In addition to anticoccidial medications and vaccinations, natural products are beginning to be acknowledged as an additional and alternative approach to controlling avian coccidiosis. The main focus is on the mechanisms by which the anticoccidial plants and substances function, such as disrupting the life cycle of *Eimeria*, regulating human immunity to *Eimeria*, regulating the growth of gut bacteria, and/or a combination of these mechanisms. Biological actions, mechanisms, and prophylactic/therapeutic potential of the compounds and extracts of plant origin in coccidiosis are summarized and discussed.

1. INTRODUCTION:

Each year, over 50 billion chickens are raised for meat, providing more than one-third of the protein food supply for humans. However, poultry production is challenged by significant diseases, notably avian coccidiosis and avian influenza. Avian coccidiosis is caused by gut parasites belonging to the genus *Eimeria*, which are classified under the subclass Coccidia. Nine *Eimeria* species have been identified in chickens: *E. acervulina*, *E. brunetti*, *E. maxima*, *E. necatrix*, *E. praecox*, *E. mitis*, *E. tenella*, *E. mivati*, and *E. hagani*. These parasites infect the mucosal epithelium of various gastrointestinal tract sections and replicate through the oral route. The infection causes significant gut damage in poultry, leading to inflammation, hemorrhage, and diarrhea, which impacts morbidity and mortality rates.

The poultry operations suffer significant financial losses as a result of avian coccidiosis because of stunted growth, the need to replace more chicks, and the expense of medical care. Anticoccidial chemicals are the main and most economical way to control the disease in chicken production. Other management options include vaccinations, natural products, and anticoccidial chemicals. The poultry industry is looking for alternative control measures as a result of issues like resistance to drugs and customer expectations for meat free of residues. To prevent coccidiosis, vaccination regimens using wild-type or attenuated strains of *Eimeria* species have been established. To increase cross-species protection and these vaccines' overall effectiveness, however, more work has to be done.

Natural products are emerging as potential solutions for coccidiosis, with four plant-derived anticoccidial feed additives for animals. Notable components include *Quercus infectoria*, *Rhus chinensis*, and *Terminalia chebula*. Research into these plants may lead to new synthetic anticoccidial chemicals, as seen with halofuginone, a synthetic derivative of febrifugine from the plant *Dichroa febrifuga*.

Despite the benefits of natural products, challenges such as ensuring anticoccidial efficacy, identifying active compounds, understanding mechanisms of action, ensuring safety, and confirming cost-effectiveness need to be addressed for their effective use against coccidiosis.

1.1. Life Cycle of *Eimeria* Species: The life cycle of *Eimeria* species involves three main developmental stages: sporogony, schizogony/merogony, and gametogony. Initially, oocysts are excreted in poultry feces and undergo sporulation in environments with high humidity at temperatures between 25–30°C. When ingested by birds, these sporulating oocysts use physical and chemical processes in the digestive tract to develop into infectious sporozoites within sporocysts. The sporozoites invade epithelial cells in the gut, forming trophozoites and later schizonts during the schizogony/merogony phase. Merozoites released from schizonts can penetrate the epithelium and continue the merogony stage 2 to 3 times, enhancing the quantity of merozoites through asexual

reproduction. Alternatively, merozoites can enter the sexual reproduction stage by developing into male microgametes and female macrogametes within host cells. Following fertilization, zygotes develop into oocysts and are excreted in poultry stool. *Eimeria* species may complete their life cycles in 4–7 days, with both asexual and sexual reproduction stages targeted by anticoccidial compounds.

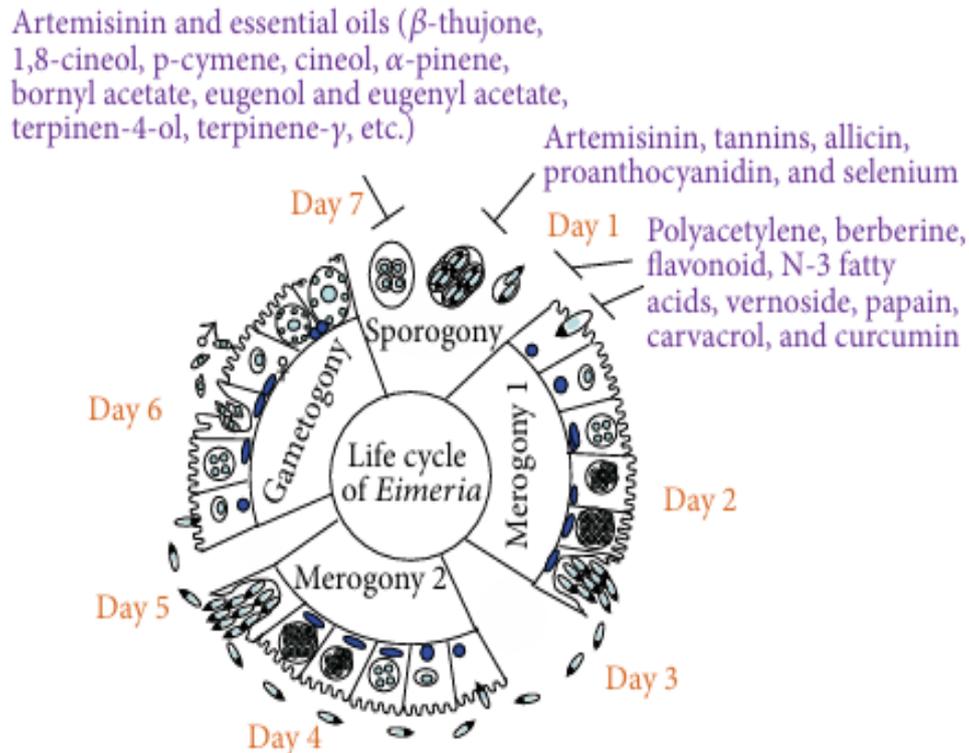


FIGURE 1: Plant compounds target different stages of the life cycle of *Eimeria* species. *Eimeria* species take 4–7 days to complete their life cycles. They have 3 different developmental stages in poultry: sporogony, merogony, and gametogony. This scheme is modified from the previous publication [40]. Different phytochemicals inhibit the growth of *Eimeria* species at sporogony and merogony stages.

Prophylaxis and Therapy for Avian Coccidiosis:- Coccidiosis is a considerable difficulty in intensive chicken husbandry. Medicinal plants and phyto compounds are gaining appeal among environmentally concerned customers as alternatives to anticoccidial drugs and vaccinations, and they are in line with the European Union's chemical-free treatment regulations. These plants generate a diverse range of phytochemicals, including phenolics and terpenoids, which have distinct bioactivities. According to reports, medicinal plants have the potential to successfully treat many disease pathways.

2. Plants and Compounds for Avian Coccidiosis:-

Over 300,000 species of flowering plants exist globally, but fewer than 1% have been studied for their potential against protozoan diseases. This section outlines 68 plants and phytochemicals examined for their effectiveness against *Eimeria* species. Notably, Table 1 highlights anticoccidial plants, detailing the need to clarify their active compounds and mechanisms of action.

Table 1:

Plant / Source	Active Compound(s)	Mechanism of Action
Artemisia annua	Artemisinin	Disrupts parasite sporulation via oxidative stress
Garlic (<i>Allium sativum</i>)	Allicin	Inhibits sporulation of <i>Eimeria tenella</i>
Green tea (<i>Camellia sinensis</i>)	Polyphenols, Selenium	Blocks sporulation enzymes, antioxidant effects
Papaya (<i>Carica papaya</i>)	Papain (proteolytic enzyme)	Proteolytic destruction of parasite structures
Oregano, Thyme, Clove oils	Essential oils (carvacrol, thymol, eugenol)	Kill oocysts and sporozoites, disrupt membranes
Turmeric (<i>Curcuma longa</i>)	Curcumin	Multi-target: anti-inflammatory, immune modulation, parasite inhibition
<i>Bidens pilosa</i>	Polyacetylenes	Multi-mechanistic: parasite inhibition + immune support
Grape seed	Proanthocyanidins	Reduce oxidative stress, protect gut lining
Aloe vera	Acemannan	Enhances host immunity, modulates gut microbiota
Wheat bran	Arabinoxylans	Prebiotic effect, boosts immune response

Details about active phytochemicals present in the other anticoccidial plants and their mechanisms are summarized below:

1. **Artemisinin (from *Artemisia annua*)** Generates oxidative stress, blocking oocyst wall formation and sporulation. Effective against *E. tenella*, *E. acervulina*, *E. maxima*.
2. **Condensed Tannins (from pine bark, *Pinus radiata*)** Penetrate oocyst walls, disrupt sporulation enzymes, cause abnormal sporocysts. Active against *E. tenella*, *E. maxima*, *E. acervulina*.
3. **Allicin (from garlic, *Allium sativum*)** Inhibits sporulation and sporozoite development. Effective against *E. tenella*.
4. **Polyacetylenes (from *Bidens pilosa*)** Inhibit sporozoites and modulate immunity. Active against *E. tenella*.
5. **Berberine (from *Berberis lyceum*)** Induces oxidative stress, killing sporozoites. Effective against *E. tenella*.
6. **N-3 Fatty Acids, Flavonoids, Vernoside (from flaxseed, *Ageratum conyzoides*, *Vernonia amygdalina*)** Trigger oxidative stress, reducing parasite survival. Active against *E. tenella*.
7. **Papain (from papaya, *Carica papaya*)** Proteolytic digestion of sporozoites in the gut. Effective against *E. tenella*.
8. **Saponins (from guar bean, *Cyamopsis tetragonoloba*)** Bind parasite cell membranes, causing lysis of oocysts. Effective against *E. tenella*.
9. **Essential Oils (oregano, thyme, clove, rosemary, tea tree, citrus, etc.)** Destroy oocysts and sporozoites, prevent development. Broad activity across *Eimeria* species.
10. **Curcumin (from turmeric, *Curcuma longa*)** Destroys sporozoites, modulates immunity. Effective against *E. tenella*, *E. maxima*.
11. **Maslinic Acid (from olive tree, *Olea europaea*)** Reported anticoccidial activity, mechanism unclear. Active against *E. tenella*.
12. **Proanthocyanidins (from grape seed)** Antioxidant action, reduce gut damage and mortality. Effective against *E. tenella*.
13. **Selenium (in green tea, *Camellia sinensis*)** Inhibits sporulation enzymes. Active against *E. tenella*, *E. acervulina*, *E. maxima*.
14. **Febriofugine (from *Dichroa febrifuga*)** Inhibits parasite multiplication. Basis for synthetic drug halofuginone. Effective against *E. tenella*.

Phytochemicals from diverse plants directly interfere with *Eimeria* development. Their mechanisms include: **Oxidative stress induction** (artemisinin, berberine, fatty acids, flavonoids). **Direct parasite destruction** (papain, saponins, essential oils). **Immune modulation** (polyacetylenes, curcumin). **Enzyme inhibition** (selenium, tannins). Together, these compounds represent promising natural alternatives to synthetic anticoccidials.

2.1. Phytochemicals Enhancing Host Immunity: Key Compounds & Their Effects

1. **Arabinoxylans (from wheat bran)** Act as prebiotics, stimulating beneficial gut microbes. Enhance immune response, reduce lesion scores in infected birds.
2. **Acemannan (from Aloe vera)** Polysaccharide that boosts macrophage activity and cytokine production. Strengthens host defenses against *Eimeria*.
3. **Phenolic compounds (from plum extract)** Antioxidant and immunomodulatory effects. Reduce oxidative stress and improve gut health.
4. **Mannan-oligosaccharides (MOS, from yeast cell walls)** Bind pathogens, preventing colonization. Stimulate immune system and improve intestinal integrity.
5. **β -glucans (from yeast, oats, barley)** Activate macrophages and natural killer cells. Enhance resistance to coccidial infection.
6. **Inulin (from chicory root)** Prebiotic effect, promoting beneficial gut microbiota. Improves immune response and reduces parasite load.

Plant-derived polysaccharides and phenolics don't directly kill *Eimeria* but instead strengthen the bird's immune system and gut health. Prebiotics (arabinoxylans, inulin, MOS) → improve microbiota balance and immunity. Immuno modulators (acemannan, β -glucans, phenolics) → boost host defense mechanisms. Together, these compounds complement direct anticoccidial agents, offering a dual strategy: parasite suppression + host resilience.

2.2. Plants and Compounds That Possess Prebiotic Properties:-

Poultry health depends on gut bacteria, which aid in pathogen suppression, immune system maintenance, gut development, and nutrient digestion. Poultry development and health depend on the balance of good and bad bacteria. Although their precise modes of action are yet unknown, research points to probiotics in particular, *Lactobacillus*, *Enterococcus*, and *Bifidobacterium* as having the ability to reduce coccidiosis and improve chicken development. Competitive exclusion, immunological modulation, gut integrity promotion, and improved digestive efficiency are some of the suggested causes. Inulin, AOS, FOS, MOS, XOS, IMOS, SOS, and pyrodextrins all of which are derived from different plants are examples of prebiotics, which are non-digestible feed elements that increase probiotic activity. Poultry diets also frequently contain prebiotics.

They stimulate beneficial intestinal flora, bolster immune defense, and can indirectly reduce pathogen load and mortality, with some evidence suggesting they can inhibit coccidiosis similarly to probiotics. This emerging focus on prebiotic dietary supplementation represents a novel approach in controlling coccidiosis in poultry.

Phytochemicals Regulating Gut Microbiota; Key Compounds & Their Effects- Mannan-oligosaccharides (**MOS, from yeast cell walls**) Bind pathogens, preventing colonization. Promote beneficial gut bacteria and improve intestinal integrity. Fructo-oligosaccharides (**FOS, from chicory root, Jerusalem artichoke**) Prebiotic effect, stimulating growth of *Lactobacillus* and *Bifidobacterium*. Enhance gut health and reduce parasite load. Inulin (**from chicory root, Cichorium intybus**) Fermented by gut microbes into short-chain fatty acids (SCFAs). Improves gut barrier function and immune response. Arabinoxylans (**from wheat bran**) Act as dietary fiber and prebiotics. Support beneficial microbiota and reduce lesion scores. β -glucans (**from yeast, oats, barley**) Stimulate gut-associated immune cells. Improve resilience against coccidial infection.

Together, they help maintain gut health, reduce parasite impact, and complement direct anticoccidial agents and immune boosters.

2.3. Plants and Compounds with Multiple Mechanisms to Inhibit Coccidiosis:

2.4.1. Curcumin and Curcuma longa: Turmeric (*C. longa*) has demonstrated medicinal properties, notably its anticoccidial effects documented in various studies. Curcumin, an active compound in turmeric, effectively destroys sporozoites of *E. tenella* and enhances resistance to coccidiosis in broilers, leading to improved body weight gains and reduced gut damage. Additionally, curcumin boosts host immunity against *Eimeria* species, thereby mitigating gut lesions and oocyst shedding.

2.4.2. Polyacetylenes and Bidens pilosa: Yang et al. demonstrated that *B. pilosa* shows anticoccidial activity in *E. tenella*-infected chickens, indicated by survival rates, fecal oocyst counts, gut pathology, body weight, and bloody stool. The active compounds responsible for this effect remain unidentified, but *B. pilosa* is rich in

phytochemicals, including 70 aliphatics, 60 flavonoids, and various other compounds. Notably, one polyacetylene and one flavonoid have been suggested as active against the Plasmodium protozoan parasite. The identity of active compounds in *B. pilosa* needs further investigation, as their role in affecting the Eimeria life cycle is not fully understood. Unlike traditional anticoccidial drugs, *B. pilosa* exhibits little to no drug resistance in Eimeria, likely due to its compounds targeting various resistance pathways. Plant-based remedies, including *B. pilosa*, can be utilized alone or alongside other anticoccidial agents, as demonstrated by the use of Echinacea to enhance immunization efficacy in chickens with anticoccidial vaccines.

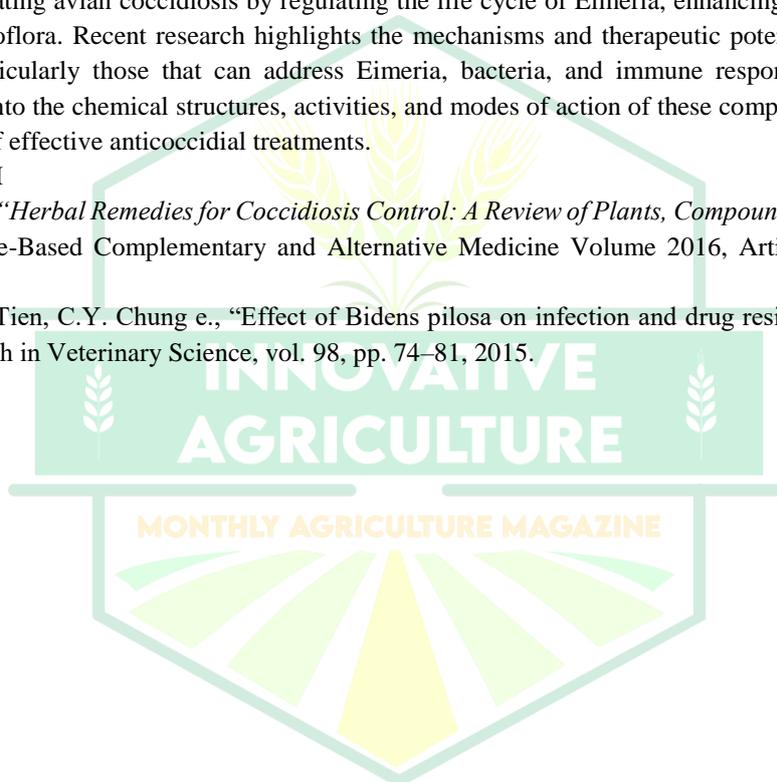
3. Conclusions and Perspectives

Coccidiosis is a significant infectious disease in poultry caused by Eimeria species, which are enteric protozoan parasites that lead to gut damage and various clinical symptoms, including sick appearance, bloody stools, hemorrhages, and lesions. The disease's clinical outcomes can be influenced by factors such as pathogen load, host genetics, and environmental conditions. Current prevention and treatment methods include anticoccidial drugs, vaccines, and natural remedies. This summary focuses plants and compounds that show efficacy in preventing and treating avian coccidiosis by regulating the life cycle of Eimeria, enhancing host immunity, and affecting gut microflora. Recent research highlights the mechanisms and therapeutic potentials of these plant-based agents, particularly those that can address Eimeria, bacteria, and immune responses simultaneously. Detailed insights into the chemical structures, activities, and modes of action of these compounds are critical for the development of effective anticoccidial treatments.

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Carbon Farming: A Win-Win for Farmers and the Planet



Ankita Kumari¹ and Sunil Kumar^{2*} and Amrendra Kumar²

¹B.Sc. (Hons) Agriculture Scholar, Tirhut College of Agriculture (TCA), Dholi

²Department of Agronomy, TCA, Dholi

Dr Rajendra Prasad Central Agricultural University, Pusa, Bihar

*E-mail: sunil.kumar@rpcau.ac.in

Abstract:

This article provides a comprehensive analysis of how carbon farming decreases atmospheric CO₂ concentrations by increasing carbon stocks in soil. Carbon farming reduces global warming and improves agricultural sustainability through various techniques, including carbon sequestration, agroforestry, intercropping, cover crops, reduced fertilizer application, livestock management, reduced tillage, using organic mulch, working with biochar, etc. Carbon farming is a farm-based solution to climate change that provides revenue to farmers for shifting to soil carbon sequestration farming techniques. It is a process that involves monitoring, reporting, and verification to generate carbon credits and sold to organizations looking to offset their greenhouse gas emissions. By storing carbon in soil, farmers can earn additional income by carbon trading, reduce production costs, and build sustainable farming system, thus making carbon farming as a promising revenue stream for farmers. The article discusses the carbon farming initiatives and emission reduction projects and schemes, challenges such as farmer awareness, market instability etc. and future directions to enhance carbon farming in India.

Introduction:

Carbon Farming refers to sustainable agricultural practices that aims to increase the storage of carbon in biomass/ trees and soil while reducing greenhouse gas emissions. Carbon farming aims at maximizing carbon sequestration through:

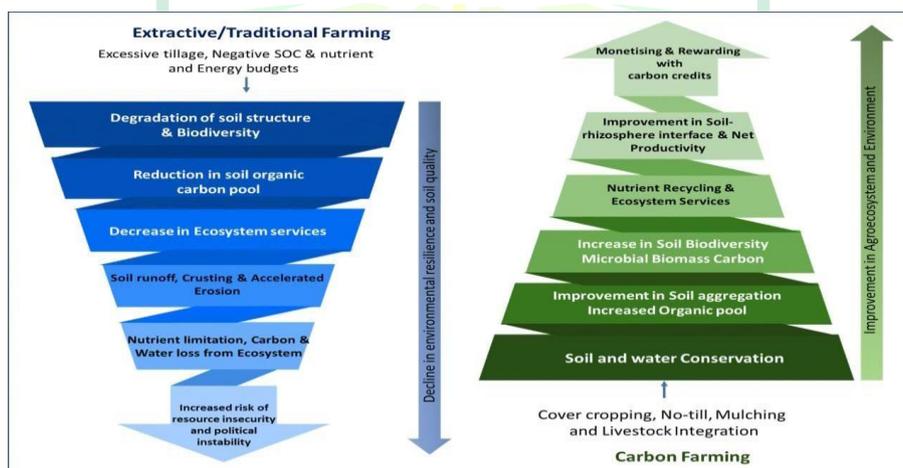
- Geological sequestration i.e. storing anthropogenic CO₂ deep underground in geological formations to prevent it from entering the atmosphere,
- Oceanic sequestration i.e. storing carbon in the oceans either through biological pump that involves marine organisms, phytoplankton absorb CO₂ during photosynthesis and after their death, they sink taking carbon to deeper ocean layers or through physical pump that involves CO₂ dissolved in cold deeper ocean water and is transported by ocean currents.
- Terrestrial sequestration i.e. storing carbon in forests, soils, and vegetation. It mainly occurs through photosynthesis, whereby plants absorb CO₂ and convert it into organic carbon compounds.

Carbon farming is also known as “Regenerative Agriculture” because it restores soil health and fertility by increasing soil organic matter, reverses environment degradation, mitigates climate change and enhances ecosystem services. Carbon farming provides economic incentives to farmers through carbon trading. Carbon can be traded in the form of credits (1 carbon credit = 1 Metric ton of CO₂ equivalents). The act of buying and selling of carbon credits is called carbon trading or Cap and Trade system (CAT).

Techniques for Carbon Farming:

- **Agroforestry:** The integration of trees with agriculture is called Agroforestry. It contributes climate change mitigation through carbon sequestration and is an important component of carbon farming. Agroforestry sequesters carbon by storing carbon in above ground (trees, shrubs, and crops) and below ground biomass (roots and soil organic matter). Trees within agroforestry systems uptake atmospheric CO₂ during photosynthesis and store it in their leaves, branches, and trunks. Tree leaves, twigs and organic residues fall to the ground and enrich the soil organic content. As they break down over time, they release carbon into the ground, which goes towards long-term carbon storage. Agroforestry also provides an additional source of income to farmers.

- **Cover Crops:** Cover crops play a vital role in carbon farming by acting as a link between atmospheric CO₂ and long-term soil carbon storage. When these crops are grown between main crop cycles, they capture CO₂ through photosynthesis and store it in their roots, stems, and leaves. When incorporated into soil, organic matter increases and fertility is enhanced. Deep-rooted species are particularly effective as they deposit carbon deeper into the soil making it less prone to decomposition. Moreover, cover crops protect existing soil carbon by forming a protective layer that protects the soil from erosion.
- **Zero-Tillage:** Frequent and heavy tilling increases the rate of CO₂ release from the soil and breaks up soil structure which reduces the productivity of the soil. Zero tillage eliminates ploughing operations, reducing CO₂ emissions from machinery. Moreover, soil aggregates remain stable and trap organic carbon within, physically protecting it from microbial attack.
- **Biochar application:** Biochar is produced through pyrolysis. During this process, a large portion of the carbon in the biomass is converted into stable aromatic carbon rings. Unlike the crop residues or manure that decompose quickly and release CO₂, biochar is highly resistant to microbial breakdown. It can remain in soil for hundreds and thousands of years, effectively locking carbon in soil.
- **Terra-Preta:** Terra Preta (meaning “black earth” in Portuguese) is an ancient biochar-based soil management technique. It is made by adding charcoal (biochar), food waste, manure, bones and organic residues into nutrient-poor tropical soil. The charcoal (biochar) in Terra Preta is highly stable and locks carbon in soil for centuries.
- **Rotational grazing:** It involves periodically relocating livestock to new pastures, this practice prevents overgrazing and allows previously grazed land to rejuvenate and grow deeper root systems. These roots deposit soil organic matter which increases soil organic carbon over time. This practice prevents soil erosion, increases water retention and overall ecosystem resilience, making it a key strategy in regenerative agriculture.
- **Reduced fertilizer application:** Chemical fertilizers reduce the capacity of soil to sequester carbon and significantly cuts greenhouse gas emissions which are released during the manufacturing of fertilizers. Organic manures and cover crops are used for nutrient management in place of these fertilizers which reduces the cost of cultivation and makes farming sustainable and profitable.
- **Integrating Silvi-pastoral systems:** Integrating trees with livestock increases carbon stocks both above and below ground. It provides shade and fodder for animals besides maintaining soil health and climate resilience.



Significance of Carbon Farming:

- **Climate Change Mitigation:** Carbon farming is one of the powerful weapons to fight climate change by reducing Greenhouse gas emission by sequestering atmospheric CO₂ in soil and biomass turning agriculture farms from emitters to sink of carbon. Key practices such as agroforestry, conservation tillage, biochar application and improved crop and livestock management help in achieving this.

- **Soil Health Enhancement:** Carbon Farming boosts soil health by increasing soil organic matter and water retention capacity of soil. In addition to this it also reduces soil erosion resulting in amplified crop yields and agricultural productivity.
- **Biodiversity Enrichment:** Carbon farming enhances biodiversity by safeguarding beneficial microbes in soil, attracting beneficial insects and pollinators that enhances crop health and reduces dependency on pesticides.
- **Economic opportunities:** Carbon farming practices offers significant economic opportunities by allowing farmers to earn income from carbon credits and reduces input costs (fertilizers, diesel). The emerging carbon economy creates jobs in data tracking, verification, and project development. India's carbon stock has reached 30.43 billion tons of CO₂ equivalent, indicating that the country has already achieved 2.29 billion tons of additional carbon sequestration compared to the 2005 baseline, approaching its target of N 2.5 to 3 billion tons by 2030.



Policies and Institutional support:

- **National action plan on climate change:** NAPCC was released by the Prime Minister on June 30, 2008 focusses on national strategy to enable country to adapt to climate change and enhance ecological sustainability through sustainable development. There are 8 national missions under NAPCC which encompasses The National Mission for a Green India and National Mission on Sustainable Agriculture and Carbon farming directly supports these missions under NAPCC by promoting carbon sequestration, climate-smart agriculture and sustainable land management.
- **National Mission on Sustainable Agriculture:** The National Mission on Sustainable Agriculture (2014-15) is a key component of the National Action Plan on Climate Change (NAPCC) which considers the sustainable use of land and resources under agriculture. It promotes subsidies and financial help to encourage the adoption of climate-resilient technologies, efficient use of water resources, conservational tillage techniques, all of which contribute towards carbon farming.
- **Soil Health Card Scheme:** This scheme launched by the GOI on 19 Feb, 2015, guides farmers on soil improvement by providing them with a printed report on their soil's nutrient status (12 parameters like NPK, micronutrients, pH etc.) improving soil fertility and productivity which enhances soil's capacity for carbon sequestration, a core aspect of carbon farming.
- **National Agroforestry policy and sub-mission on agroforestry (SMAF):** India was the first country in the world to adopt agroforestry policy on 2014. Its main agenda is to integrate trees with crops and livestock which increases productivity, income, and environmental resilience. SMAF was launched in 2016 onwards

under National Mission for Sustainable Agriculture (NMSA). Its main objective is to promote farmers to adopt agroforestry by providing financial assistance for nursery, sapling distribution, and plantation.

- **Carbon Credit Trading Scheme:** The Carbon Credit Trading Scheme, 2023 introduced under the Energy Conservation (Amendment) Act, 2022, replaces the Perform, Achieve, and Trade (PAT) scheme to establish the Indian Carbon Market (ICM), aligning with India's climate commitments under the Paris Agreement. The CCTS is a market-based mechanism to decarbonize the Indian economy by pricing greenhouse and facilitates carbon trading. It issues Carbon Credit Certificates (CCC) each representing 1 ton CO₂ equivalent reduction.



Challenges in the adoption of Carbon farming:

Despite its potential for climate change mitigation and sustainable agriculture, the adoption of carbon farming is hindered by multiple challenges. One of the major barriers is economic uncertainty associated with carbon farming practices. Farmers face high initial costs for adopting practices such as cover cropping, agroforestry, etc., while financial returns from carbon credits are delayed and uncertain. Lack of knowledge, training and awareness about the mechanism and benefits of carbon farming further limits its adoption. A 2022 survey by the National Bank for Agriculture and Rural Development (NABARD) revealed that most of Indian farmers were unaware of carbon farming opportunities.

Additionally, limited technical expertise on measurement, reporting and verification (MRV) of soil carbon is a significant challenge. It is very difficult to accurately measure soil carbon changes over time. High cost of monitoring and verification particularly for small landholders limits this practice.

Limited access to carbon markets, especially in developing countries and insufficient digital and institutional infrastructure for participation in carbon trading poses threat in the extension of carbon farming techniques.

Future Directions to Enhance Carbon Farming:

- **Scalable MRV System:** Applying knowledge of artificial intelligence (AI), machine learning (ML), satellite imagery, and remote sensing to develop cost-effective, transparent, and credible MRV system which is essential for wider adoption across various farm sizes.
- **Policy support and incentives:** Establishing farmer-friendly policies like simplified certification processes, subsidies for initial investments and assured minimum carbon credits prices to mitigate market fluctuation. Integration of carbon farming into national climate action plans and agricultural policies.
- **Precision Agriculture:** Use of IoT devices and drones for hyper-customized advisories for irrigation, nutrient management, and yield optimization. This helps farmers adapt to new practices and minimizes the overall environmental footprint of farming operations.
- **Capacity building & farmer awareness:** Encouraging training programs, demonstrations and extension services for farmers helps in wider adaptability of carbon farming practices. Carbon farming concepts are to be integrated in agricultural education and curricula.

- **Research & Innovation:** Enhancing research practices to develop low-cost, high impact carbon farming practices. Development of improved crop varieties with deeper root systems and higher biomass can increase carbon inputs in soil.

Conclusion:

Carbon Farming provides a crucial way to achieve the goal of climate change mitigation through on-site carbon sequestration and reduction of greenhouse gas emission. It also considers its role in sustainable agriculture development, food security, and supply of multiple ecosystem services. Additionally, the potential for monetization through carbon credits provides economic incentives for farmers, especially for rural communities, making carbon farming both environmentally and economically viable. Techniques like agroforestry, cover cropping, management of livestock, crop residues and biochar application enhances soil organic carbon, improves soil structure and biodiversity. Therefore, promoting carbon farming through supportive policies, awareness programs and scientific innovation is essential for achieving the global target of sustainable development.

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Regenerative Agronomic Practices for Long term Soil Carbon Sequestration



Nikita Kumari Meel

Department of Agronomy, College of Agriculture, Jodhpur, Agriculture University, Jodhpur (Rajasthan) – 342304

Introduction

Climate change mitigation has become a global priority due to rising atmospheric carbon dioxide (CO_2) concentrations driven by fossil fuel combustion, land use change and unsustainable agricultural practices. Agriculture contributes nearly 25–30% of global greenhouse gas (GHG) emissions; however, it also offers significant potential to act as a carbon sink through soil carbon sequestration. Soil organic carbon (SOC) plays a central role in improving soil health, crop productivity and environmental sustainability. Carbon sequestration refers to the process of capturing atmospheric CO_2 and storing it in stable carbon pools such as soil and vegetation. Among terrestrial ecosystems, agricultural soils represent one of the largest and most manageable carbon reservoirs. Soil carbon exists in two primary forms: soil organic carbon (SOC), derived from plant and animal residues and soil inorganic carbon (SIC), mainly in carbonate forms in arid and semi-arid regions.

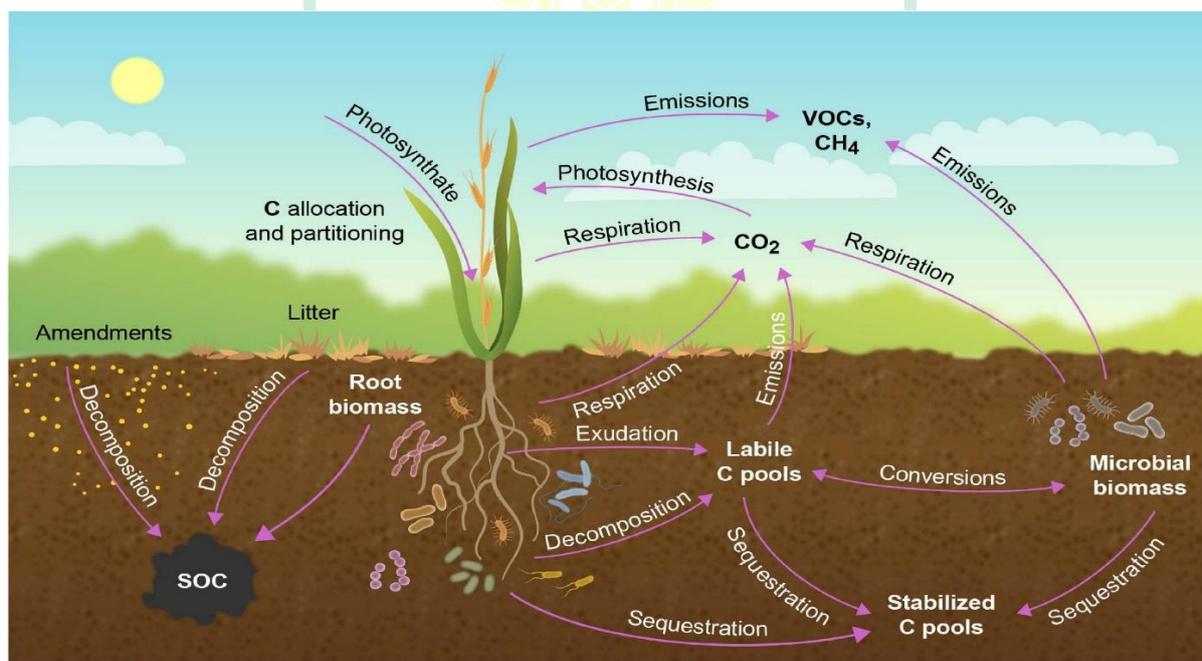


Figure 1: Process of carbon sequestration in soil (Source: www.frontiersin.org).

Major Agronomic Practices Enhancing Carbon Sequestration

1. Conservation Tillage and No-Till Systems

Conservation tillage involves maintaining at least 30% crop residue on the soil surface, whereas no-till eliminates mechanical soil disturbance. These systems reduce soil aeration and organic matter oxidation, thereby slowing carbon loss. Residue retention enhances aggregate formation, which physically protects SOC from microbial decomposition.

2. Crop Rotation and Cover Cropping

Diversified cropping systems enhance carbon inputs by increasing root biomass and residue return. Continuous monocropping often depletes SOC, whereas crop rotations involving legumes and cover crops enhance carbon stabilization. Cover crops contribute additional biomass during fallow periods and reduce erosion losses.

Inclusion of legumes such as chickpea, lentil, and sesbania improves nitrogen availability, promoting greater plant growth and higher carbon inputs.

3. Integrated Nutrient Management (INM)

Integrated Nutrient Management combines inorganic fertilizers with organic amendments such as farmyard manure (FYM), compost, crop residues and green manure. Balanced nutrient supply enhances biomass production and increases carbon return to soil.

4. Mulching and Residue Management

Mulching protects soil from erosion, moderates temperature fluctuations and enhances moisture retention. Organic mulches such as straw, crop residues and leaves decompose gradually, contributing to soil organic matter formation.

5. Green Manuring

Green manure crops, particularly leguminous species like Sesbania, add substantial biomass to the soil and improve labile carbon fractions. Green manuring is beneficial in enhancing nutrient cycling and soil aggregation which contributing to carbon sequestration.

6. Agroforestry and Afforestation

Agroforestry integrates trees with crops and livestock systems, increasing both aboveground and belowground carbon storage. Trees provide continuous biomass inputs through litter fall and extensive root systems, contributing to deeper carbon sequestration.

7. Rotational Grazing and Pasture Management

Improved grazing management enhances root growth and soil structure. Practices such as rotational grazing and controlled stocking densities prevent overgrazing and promote biomass accumulation. Application of compost in grasslands has been shown to significantly enhance soil carbon stocks. Conversion of degraded croplands to managed grasslands can lead to substantial carbon gains over time.

Conclusion

The balance between carbon inputs (crop residues, root biomass, organic amendments) and outputs (decomposition, erosion, oxidation) determines soil carbon stocks. Intensive tillage, monocropping and residue removal accelerate SOC loss, while conservation-oriented agronomic practices promote carbon stabilization. Given that agriculture occupies nearly one-third of the Earth's land area, improving soil carbon through agronomic interventions offers a practical and scalable climate solution. Agronomic practices play a crucial role in enhancing soil carbon sequestration and mitigating climate change. Adoption of these practices can substantially contribute to climate resilience, soil restoration and food security.

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Geographical Information Systems (GIS)



Shivani Pathak¹ and Tasaduq H. Shah²

¹Ph.D. Department of Fisheries Resource Management, SKUAST-K, 190001.

²Professor and Head, Department of Fisheries Resource Management, SKUAST-K, 190001

ABSTRACT

Geographical Information Systems (GIS) have emerged as a critical tool in global marine fisheries by enabling the integration, visualization and analysis of spatially referenced data. Historically, early applications focused on mapping fishing grounds, coastal habitats, and basic resource distribution. With technological advances through the 1990s and 2000s, GIS evolved to support complex spatial analyses such as fish stock assessment, vessel monitoring, habitat modelling, and marine protected area (MPA) planning. In the present era, GIS acts as a central platform linking remote sensing, GPS, sonar, ecological models, and socio-economic datasets, thereby enhancing fisheries management, biodiversity conservation, and climate-resilience planning. Looking ahead, future GIS applications in marine fisheries will increasingly rely on artificial intelligence, cloud-based geospatial data infrastructures, real-time analytics, and participatory mapping to support sustainable and ecosystem-based management. As global fisheries face pressures from overexploitation, habitat degradation, and climate change, GIS will continue to play a transformative role in improving decision-making, promoting responsible fisheries, and enabling data-driven governance.

Keywords: GIS, past, present, future applications, decision making

1. Introduction

Geospatial technologies are systems that acquire and handle location-specific data about Earth surface. Remote sensing, the Global positioning system (GPS), and Geographic information systems (GIS) are important geospatial technologies (Goodchild, 2007). Remote sensing and the GPS are methods for collecting information about Earth's surface; GIS is a mapping tool for organizing and analyzing information. Geographical Information Systems (GIS) have become an essential analytical framework in marine fisheries, enabling the integration of spatial data on resources, habitats, environmental variables and human activities. GIS allows data to be captured, stored, analysed and displayed in a spatially explicit manner, supporting evidence-based decision-making in fisheries management and marine spatial planning (Longley *et al.*, 2015; FAO, 2009). Over the past four decades, GIS has evolved from simple mapping tools into dynamic platforms that integrate satellite remote sensing, vessel tracking systems and ecological models. A Geographical information system (GIS) may be defined as a collection of computer hardware, software, data and personnel designed to collect, store, update, manipulate, analyze and display geographically referenced information. (Chang, 2016).



Literal Definition:-

- **Geographic** relates to the surface of the earth.
- **Information** is a knowledge derived from study, experience, or instruction.
- **System** is a group of interacting, interrelated, or interdependent elements forming a complex whole.

2. Past: Early Development and Applications of GIS in Marine Fisheries

Historically, the fishing community (e.g., fishermen, resource managers) has used geographical information systems (GIS) technologies has been made by either the fishing industry, fishery resource managers, or by the general oceanographic community. This latter omission is unfortunate because GIS has the potential to overcome two long-standing problems associated with satellite-directed fisheries: 1) the absence of information due to clouds; and 2) the general lack of support for nonpelagic fisheries. Finally, an attempt is made to provide some possible directions this new technology may take during the 1990s. These shortcomings of traditional satellite support strategies for marine fisheries are just now being recognized by the American, Canadian, Russian, Japanese, Taiwanese, Korean, and European fishing industries, but as yet relatively little has been done to improve the situation.

The world's first true operational GIS was developed in 1960 in Ottawa, Ontario, Canada, by the Federal Department of Forestry and Rural Development. Designed by Dr. Roger Tomlinson, the system—known as the Canada Geographic Information System (CGIS)—was created to store, analyze, and manage spatial data for the Canada Land Inventory (Tomlinson, 1967; Foresman, 1998). The first known use of the term "geographic information system" was by Roger Tomlinson in the year 1968 in his paper "**A Geographic Information System for Regional Planning**". Roger Tomlinson is also acknowledged as the "Father of GIS".

The use of GIS in marine fisheries began in the 1980s when computerised cartography and early spatial databases were first applied to fisheries research and coastal planning (Nath, 2000). Early applications primarily focused on mapping fishing grounds, charting species distribution and identifying key coastal habitats such as coral reefs, seagrass beds and mangroves (de Graaf, 2003). FAO and regional fishery bodies played a major role during this period by developing guidelines, capacity-building programmes and demonstration projects to introduce GIS technology in developing countries (de Graaf, 2003). These early systems provided foundational spatial layers—bathymetry, coastline maps and catch/effort plots—used for visualising fishing patterns and supporting policy decisions. As with most technological advances, GIS arose out of a necessity to tackle a novel problem.

Key early uses included:

- Habitat mapping and coastal resource inventories
- Visualisation of catch and effort distribution
- Planning of fishing zones and coastal aquaculture sites
- Identification of fish nursery and spawning areas (Nath, 2000)

These early applications helped managers conceptualise spatial patterns in fisheries that were traditionally assessed through non-spatial data.

3. Present: Current Uses of GIS in Marine Fisheries

In the present era, GIS has become highly integrated, data-rich and analytical, driven by advances in remote sensing, high-performance computing and global vessel tracking systems. Concurrently, with the technological revolution in the field of genetics, geography experienced its own revolution through the implementation of digital mapping and analyses. In particular, geographic information systems (GIS) have facilitated powerful analyses in many different disciplines through their ability to: (1) integrate large data bases with the geo-referenced locations from which the data were collected; and (2) rigorously and efficiently quantify spatial patterns. These two important properties that a GIS provides have been assimilated successfully by civic planners, geologists, wildlife biologists, conservationists and to an increasing extent ecologist. One of the remaining disciplines that will largely benefit from this powerful technology is evolutionary biology. Here, I briefly review the historical link between geography and evolutionary biology, provide a recent history of quantitative GIS analyses of spatial data used in hybrid zone, phylogeographic and speciation research and highlight potential ways in which GIS can be further integrated into these fields.

At present, use of such a system should increase the catch per unit effort (CPUE) for the fisherman and significantly enhance the ability of stock assessment managers to provide for the continued fecundity of the fishing resource. Finally, the report also attempts to summarize accurately the possible directions such efforts might take in the 1990s. Space precludes an exhaustive treatment of all such activity. Therefore, only representative results from some geographically widely distributed fisheries are discussed. GIS technology can have a profound impact on an activity, such as the management of an operational fishery, which historically is information-poor and labour-intensive. Thus, it is important that a GIS needs assessment be performed prior to the design, development, and use of a RS/GIS system.

4. Applications of Geographical information System (GIS):

4.1 Habitat and Essential Fish Habitat Mapping

Modern habitat mapping combines satellite imagery, multibeam sonar and ecological surveys to produce detailed maps of benthic habitats, including coral reefs, seagrass meadows and soft-sediment communities (FAO, 2009). These maps inform the designation of Essential Fish Habitat (EFH) and support ecosystem-based fisheries management.

4.2 Marine Spatial Planning (MSP) and Zoning

GIS facilitates MSP by integrating fisheries data with other marine uses such as shipping, protected areas and offshore energy. Managers use GIS overlays to identify conflicts, optimise zoning and design marine protected areas (Morzaria-Luna *et al.*, 2020).

4.3 VMS/AIS-Based Fishing Effort Mapping

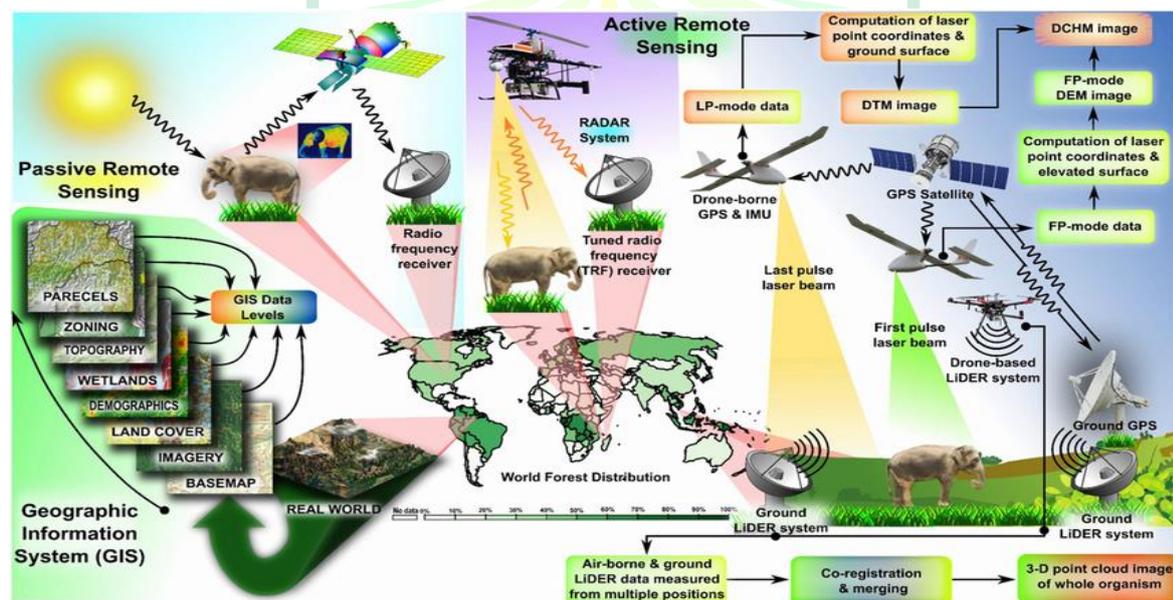
Real-time vessel tracking systems (VMS and AIS) provide high-resolution information on vessel movements. Combining this with catch databases allows managers to map fishing effort, identify hotspots of overfishing and monitor compliance (NOAA, 2022).

4.4 Species Distribution Modelling (SDM)

GIS integrates environmental layers (SST, chlorophyll, salinity, depth) with species occurrence data to generate predictive habitat models. These SDMs help managers anticipate shifts in fish distributions driven by climate change (NOAA, 2022).

4.5 Decision-Support Systems

Cloud-based GIS platforms now support real-time decision-making through interactive dashboards, automated alerts and predictive analytics for fisheries management (Longley *et al.*, 2015).



Source: Rout *et al.*, 2022

5. Future: Emerging Trends and Innovations in Fisheries GIS

5.1 Real-Time and Dynamic Fisheries Management

Integration of real-time AIS/VMS, electronic logbooks and remote sensing data will enable dynamic management measures such as real-time closures and adaptive fishing zones (NOAA, 2022).

5.2 Artificial Intelligence (AI) and Machine Learning

AI and machine learning will increasingly automate habitat classification, identify illegal fishing patterns and improve predictive models of fish distribution (Morzaria-Luna *et al.*, 2020).

5.3 Autonomous Platforms and High-Resolution Mapping

Autonomous underwater vehicles (AUVs), drones and gliders will dramatically improve the spatial resolution of seabed and habitat maps, feeding richer datasets into GIS (FAO, 2009).

5.4 Digital Twins and Scenario Modelling

Digital twins of marine ecosystems—virtual spatial models updated continuously with real-time data—will allow managers to simulate fishing impacts, climate change scenarios and policy outcomes.

5.5 Participatory and Open Data GIS

Future GIS platforms will include stakeholder-driven mapping, citizen science and open-access spatial databases to improve transparency, compliance and community engagement (Longley *et al.*, 2015).

5. Limitations and Challenges

Despite advancements, GIS in fisheries faces challenges such as data gaps, inconsistent taxonomic resolution, limited seabed mapping in many regions and scale mismatches between ecological processes and management boundaries (FAO, 2009). Technical capacity and data-sharing policies also constrain adoption, particularly in developing regions.

6. Conclusion

GIS has transformed marine fisheries from traditional, descriptive mapping to advanced, data-driven spatial decision systems. From its early use in basic habitat mapping to present-day applications in predictive modelling and real-time monitoring, GIS now underpins core fisheries management tools. Future developments—AI, digital twins and autonomous sensing—will continue to strengthen GIS as a pillar of sustainable and ecosystem-based fisheries management. There is a need, shared by all segments of the operational fisheries oceanography community, to develop and invest in the transfer of remote-sensing and geographic information system technologies to operational commercial fishing fleets and to stock assessment personnel charged with managing fisheries resources. Strategies should be developed to make this technology portable. Once implemented, such portable strategies would increase the catch-per-unit effort of the world's commercial fishing fleets as well as make the goal of near-real time management of a fishery more feasible. The combination of remote sensing capabilities with a geographical information system and its associated data bases (e.g., hydrographic, bathymetric) can help eliminate the historical deficiencies in satellite support of operational fisheries (e.g., no support for mid- and deep-water species; absence of information if clouds are present).

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Fig-Fig Wasp Mutualism: A Specialized Plant-Insect Interaction



V. M. Khimani¹, Nisarg Panchal¹ and C. U. Shinde^{2*}

¹Ph.D. Scholar, Department of Entomology, NMCA, NAU, Navsari (Gujarat) – 396 450

²Associate Professor, Department of Entomology, NMCA, NAU, Navsari (Gujarat) – 396 450

*Corresponding author: shinde.3112@nau.in

Abstract

The fig-fig wasp mutualism is an obligate and highly specialized interaction. Figs possess a unique syconium, an enclosed inflorescence, and access to this chamber is regulated by the ostiole, a selective barrier equipped with secretory structures and species-specific volatile cues that ensure attraction and entry of appropriate pollinating wasps. Pollinator wasps exhibit complementary adaptations, including specialized head morphology, pollen pockets, and behaviourally synchronized life cycles. Their reproduction depends on oviposition within short-styled flowers, while long-styled flowers develop into seeds. Pollination occurs through active or passive mechanisms, with synstigmata enhancing pollen distribution across flowers. Evolutionary diversification is driven by floral scent differentiation and host-specific olfactory recognition. However, climate-induced shifts in temperature and parasitoid pressure threaten stability by altering community structure and reducing pollinator dominance. Together, these integrated mechanisms illustrate how structural, behavioural, and ecological processes maintain this long-standing mutualism.

Keywords: Fig wasp, mutualism, complementary adaptations and behavioural adaptations, etc.

Introduction

The mutualism between figs (*Ficus* spp.) and their pollinating wasps (Agaonidae) is one of the most specialized plant-insect interactions. Central to this relationship is the syconium, an enclosed inflorescence that houses pollination, oviposition, gall development, and seed formation. Its structure, particularly the ostiole composed of overlapping bracts and secretory tissues, regulates access and ensures that only behaviourally and morphologically adapted wasps can enter. Correspondingly, pollinating fig wasps possess specialized features including flattened heads, mandibular appendages, pollen pockets, and olfactory sensitivity that enable successful entry, pollination, and reproduction inside the syconium. Host specificity is reinforced by species-specific volatile cues that guide female wasps to receptive figs. Evolutionary diversification within the mutualism is strongly influenced by chemical differentiation and morphological compatibility. However, the system remains sensitive to ecological disruptions; climate-driven temperature shifts and parasitoid pressure can reduce pollinator dominance and alter community structure. Together, these biological and environmental factors shape the persistence and vulnerability of the fig-fig wasp mutualism.

Biology of Fig

The syconium is a specialized inflorescence that defines the genus *Ficus* and underlies the obligate mutualism with pollinating fig wasps. Morphologically, it is an enclosed, urn-shaped receptacle (Fig. 1). This architecture creates a protected chamber where pollination, oviposition, gall development, and seed formation occur. The inner wall is densely packed with pistillate or staminate flowers depending on developmental stage and species. The distribution and style-length variation among flowers are crucial, as short-styled flowers allow gall induction by pollinators, whereas long-styled flowers develop into seeds. A defining component of the syconium is its ostiole, a narrow passage composed of overlapping bracts that regulate access to the internal chamber. These bracts are supported by periostiolar tissues containing secretory structures such as osmophores, colleter, and specialized trichomes. Osmophores release species-specific volatile compounds that attract the appropriate pollinating wasps during the receptive phase, while secretory trichomes and mucilage-producing cells lubricate the passage to facilitate wasp entry. The ostiole act as a selective filter, permitting only behaviourally adapted wasps to enter the syconium while excluding non-mutualists and predators (Castro-Cárdenas et al., 2022).

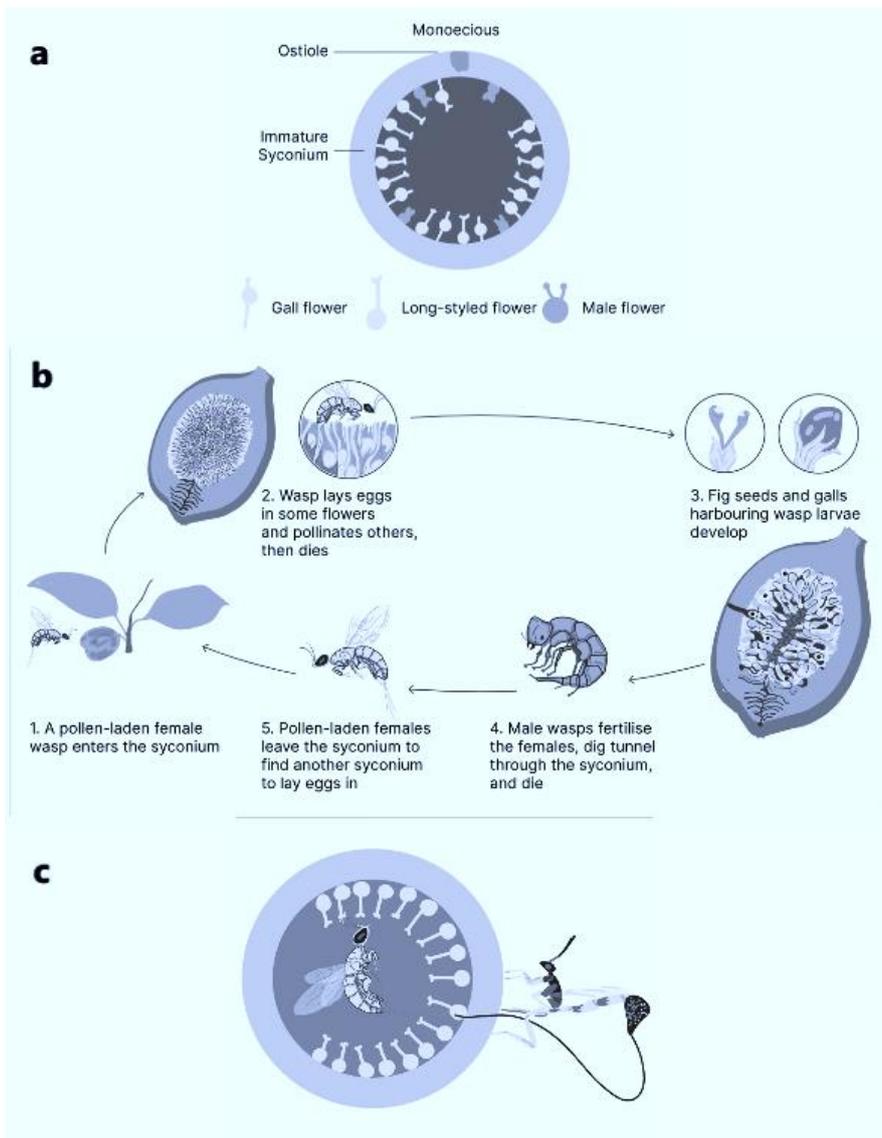


Fig. 1: (a) Cross section of a monoecious syconium, (b) Life cycle of fig and fig wasp, and (c) Pollinator and non-pollinator fig wasps laying eggs. (Credit: iThink Biology. Interactions between organisms-Figs. <https://ithinkbiology.in/book/text/d2-figs>).

Biology of Fig Wasp

Pollinating fig wasps (Agaonidae) exhibit morphological and behavioural adaptations shaped by their obligate association with *Ficus* species. Their biology is tightly integrated with the fig's enclosed inflorescence, where all major stages of their life cycle occur (Fig. 1). Female pollinating wasps possess functional wings, well-developed eyes, and specialized head morphology that enables them to force passage through the narrow ostiole. Features such as flattened heads, mandibular appendages with tooth-like structures, and modified antennae facilitate movement between the tightly arranged bracts during entry. Many pollinators also possess thoracic pollen pockets or abdominal grooves for transporting pollen, reflecting the importance of pollination for larval nutrition in the next generation. Inside the syconium, female wasps oviposit into the ovules of short-styled flowers, where larvae develop by feeding on endosperm within galled tissues. Males are wingless, blind, and remain inside the fig for their entire lifespan. They emerge earlier than females, chew holes into galls to access mates, and later dig exit tunnels that allow pollen-laden females to leave the fig. After emergence, females disperse rapidly, often aided

by wind currents above the forest canopy. Host specificity is extremely high, mediated by species-specific volatile cues that guide female wasps to appropriate hosts (Weiblen, 2002).

Pollination Mechanism

Two major pollination modes occur: active pollination, where wasps collect and deposit pollen from pollen pockets, and passive pollination, where wasps become coated with pollen in male figs and transfer it unintentionally. Active pollination is associated with highly efficient fertilization, and presence of synstigmata. Passive systems rely on abundant pollen and longer stigmas that brush against the wasps (Kjellberg et al., 2022).

Reproductive Strategies

Figs contain hundreds of pistillate flowers enclosed within the syconium; in many species, these stigmas become physically interconnected, forming synstigmata that serve as a shared receptive platform for pollen deposition. The synstigma is a key reproductive adaptation in actively pollinated figs. Because pollinating wasps typically deposit pollen only on flowers used for oviposition, non-oviposited flowers risk remaining unfertilized. Synstigmata mitigate this by allowing pollen placed on one flower to fertilize multiple adjacent flowers, increasing total seed output (Teixeira et al., 2021).

Life Cycle Synchronization

Life cycle synchronization between figs and their pollinating wasps is essential for maintaining the obligate mutualism. Fig development proceeds through discrete, predictable phases, and the timing of wasp emergence is tightly matched to pollen availability and fig receptivity. Adult wasps emerge during the male-flower phase of fig development, when pollen is released inside the syconium. Male wasps emerge first, mate with females still inside their galls, and create exit tunnels through the fig wall. Female wasps then collect pollen actively or passively depending on species and exit the fig shortly thereafter (Fig. 1). Adult female fig wasps are extremely short-lived, often surviving less than 24-48 hours. After emergence, females disperse immediately, frequently ascending above the forest canopy where wind currents facilitate long-distance movement. At the population level, figs exhibit asynchronous fruiting among individuals, ensuring that receptive figs are available throughout the year. Chemical cues released by receptive figs, particularly species-specific volatile blends emitted from ostiolar tissues, guide dispersing females to appropriate hosts (Weiblen, 2002).

Evolutionary Aspects

Because fig wasps rely heavily on olfactory cues to locate receptive syconia, floral scent composition is a primary isolating mechanism preventing cross-attraction among co-occurring species. Morphological similarity may impose selective pressure for stronger chemical differentiation to avoid pollinator confusion. It reinforces the role of chemical ecology as a critical axis of coevolution in the fig-fig wasp mutualism, ensuring precise host recognition and reproductive success (Okamoto & Su, 2021).

Factors Threatening the Mutualism

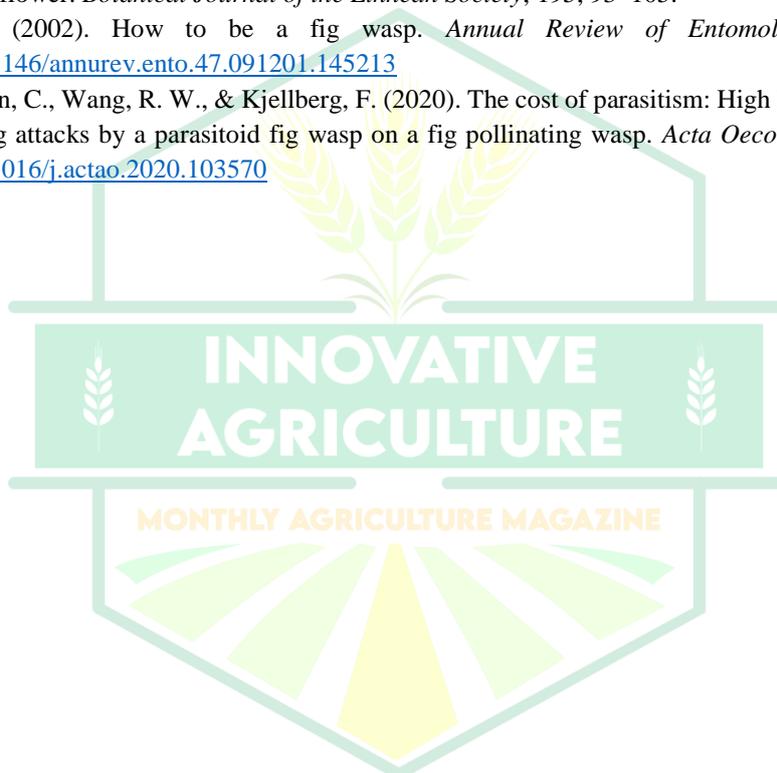
Under suboptimal temperature conditions, dominant pollinating wasps decline, allowing non-pollinating wasps to increase. Because fig-fig wasp mutualism depends on pollinator population persistence, excessive parasitoid pressure could destabilize the interaction if not counterbalanced by host fig traits. Reduced pollinator performance triggered shifting dominance toward non-pollinating wasps and altering trophic balance. These changes demonstrate that climate change can destabilize mutualisms indirectly via altered competition and parasitism (Aung et al., 2022; Zhang et al., 2020).

Summary

The fig-fig wasp mutualism persists through structural, chemical, and behavioral mechanisms that ensure pollinator specificity and reproductive success. The syconium and ostiole function as selective filters, while wasp morphology and life cycle synchronization reinforce mutual dependence. Active and passive pollination strategies, supported by synstigmata, maximize fertilization efficiency. However, the mutualism is vulnerable to environmental disturbances. Climate-driven changes in temperature and increased parasitoid pressure can shift community structure toward non-pollinating wasps, reducing pollinator performance and threatening system stability.

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CRISPR in the Wild: How Precision Gene Editing Could Help Crops Adapt to Extreme Climates by 2030



Ms. Suvidha Mishra

Assistant Professor
Institute of Agriculture Sciences, SAGE University, Indore

Introduction

Climate change is no longer a distant concern; it is an immediate and pressing challenge reshaping agriculture worldwide. Rising temperatures, unpredictable rainfall, prolonged droughts, floods, and soil degradation are creating conditions in which traditional farming methods often struggle. Farmers are facing declining crop yields, increased vulnerability to pests and diseases, and higher costs for maintaining productivity.

To meet the growing demand for food, humanity must find solutions that allow crops to thrive in these new environmental realities. One of the most promising tools in this effort is **CRISPR**—a gene-editing technology that allows scientists to precisely modify DNA sequences in plants. With CRISPR, crops can potentially gain traits that help them survive heat, drought, floods, and other environmental stresses while maintaining high yields and nutritional quality.

By 2030, CRISPR has the potential to revolutionize agriculture, enabling farmers to grow resilient crops that adapt to a changing climate. This article explores how CRISPR works, its current and potential applications, ethical considerations, and the global impact of gene editing in agriculture.

The Urgent Need for Climate-Resilient Crops

Food security is under severe threat due to climate change. Staple crops such as **rice, wheat, and maize** are particularly vulnerable to environmental stress. Rising temperatures, irregular rainfall patterns, and extreme weather events have already caused significant crop losses in Africa, Asia, and Latin America. For instance, a prolonged drought in East Africa in 2019 led to widespread maize crop failure, affecting millions of people.

Experts predict that without intervention, yields of these critical crops could decline by up to 25% in some regions by 2050. Crop failures not only threaten food availability but also increase food prices, push small-scale farmers into poverty, and exacerbate global inequalities.

Traditionally, plant breeding has been the primary method of developing resilient crops. Breeders select plants with desirable traits over multiple generations to produce improved varieties. While effective, this process is slow, often requiring **10 to 20 years** to develop a single new variety. In contrast, CRISPR allows precise changes to specific genes, shortening the time needed to produce resilient crops.

Climate-resilient crops can provide **economic stability** for farmers, reduce dependency on chemical inputs, and contribute to environmental sustainability. In the context of a rapidly changing climate, developing such crops is no longer optional—it is essential.

A Brief History of Crop Improvement

Understanding CRISPR's significance requires a look at the evolution of crop breeding. For thousands of years, farmers have selected plants with the best traits, gradually shaping modern agriculture. Early domestication focused on traits such as seed size, flavor, and yield.

The 20th century introduced **hybrid breeding** and **genetic modification (GMOs)**, allowing scientists to combine traits more rapidly and introduce characteristics like pest resistance and herbicide tolerance. While these methods significantly increased productivity, they often involved introducing foreign DNA into plants, which led to public concerns about safety and environmental impact.

CRISPR represents the next stage in this evolution. Instead of relying on random mutation or inserting foreign genes, it enables scientists to make precise changes within the plant's own genome. This precision has made CRISPR a highly promising tool for rapidly developing crops that are adapted to climate stress while addressing many of the concerns associated with traditional GMOs.

How CRISPR Works in Agriculture

CRISPR can be compared to a highly accurate pair of molecular scissors. Scientists can guide it to a specific location in a plant's DNA and make precise edits. These edits may involve removing a gene, modifying it, or switching it off entirely. Unlike older genetic engineering techniques, CRISPR often works without adding foreign DNA, making it more acceptable to regulators and consumers.

CRISPR can enhance several key traits in crops:

- **Drought tolerance:** By adjusting genes that regulate water retention or root development, plants can survive longer periods without rain.
- **Heat resistance:** Crops can be modified to cope with high temperatures during critical growth stages.
- **Disease resistance:** Genes that make plants susceptible to fungi, bacteria, or viruses can be altered to reduce crop losses.
- **Efficient nutrient use:** Modifying genes responsible for nutrient uptake can lower fertilizer needs and reduce environmental impact.
- **Improved nutrition:** CRISPR can increase levels of vitamins, minerals, and antioxidants, addressing malnutrition in vulnerable populations.

Beyond these traits, CRISPR enables scientists to study how plants respond to stress, accelerating research and allowing targeted breeding for multiple environmental challenges simultaneously.

Real-World Applications

CRISPR is not confined to laboratory research; it is increasingly being applied in field trials around the world. Some notable examples include:

1. **Drought-Resistant Cereals:** Researchers have developed maize and rice with deeper root systems and improved water retention. These crops maintain yields even under low rainfall.
2. **Heat-Tolerant Wheat:** By modifying heat-shock genes, wheat can endure higher temperatures during sensitive growth stages, reducing losses during heatwaves.
3. **Flood-Resistant Rice:** Certain rice varieties can survive weeks of submergence, providing a lifeline to farmers in flood-prone regions of Southeast Asia.
4. **Salt-Tolerant Vegetables:** Tomatoes, spinach, and other vegetables are being edited to tolerate high salinity soils caused by irrigation and rising sea levels.

Additional research focuses on crops that require fewer pesticides, legumes that fix nitrogen more efficiently, and plants optimized to capture carbon from the atmosphere. These innovations illustrate that CRISPR can address not only climate challenges but also broader environmental sustainability goals.

Integration with Technology

CRISPR's potential is enhanced when combined with **digital agriculture technologies**. Soil sensors, drones, satellite imagery, and AI analytics allow farmers to monitor crop health in real time and make precise adjustments. For example, drought-resistant crops can be paired with smart irrigation systems that water only when necessary. Similarly, disease-resistant varieties can reduce pesticide use, promoting environmentally friendly farming.

This integration represents a **holistic approach** to modern agriculture, where biotechnology and digital technology work together to improve productivity, reduce environmental impact, and ensure resilience against climate extremes.

Ethical and Regulatory Considerations

Despite its promise, CRISPR raises important questions about safety, regulation, and equity.

- **Off-target effects:** Sometimes, unintended genetic changes occur. Rigorous testing and monitoring are essential to ensure safety.
- **Regulatory frameworks:** Policies vary worldwide. Some countries classify CRISPR-edited crops as GMOs, while others adopt more lenient approaches if no foreign DNA is introduced.
- **Public perception:** Transparent communication about the risks and benefits of CRISPR is vital to gaining consumer trust.
- **Equitable access:** Ensuring that smallholder farmers in developing countries can benefit from CRISPR is critical to avoid widening global inequalities.

Successful implementation will require **collaboration between scientists, policymakers, and local communities** to ensure safe, responsible, and equitable use of gene-editing technology.

Economic and Environmental Impacts

CRISPR-edited crops have the potential to:

- Reduce crop losses caused by extreme weather.
- Stabilize incomes for small-scale farmers.
- Reduce the need for fertilizers and pesticides, lowering costs and environmental damage.
- Support local food security in regions vulnerable to climate change.

These impacts could reshape global agriculture by increasing resilience and efficiency while supporting environmental sustainability. Communities that adopt CRISPR technology could also stimulate local research and innovation, allowing for crop varieties tailored to regional climates and soils.

Future Prospects

The coming decade is likely to see major advances in **gene editing techniques**, including base editing and prime editing, which allow even more precise and subtle changes. Scientists are exploring crops that can withstand multiple stresses simultaneously—such as heat, drought, and disease—while also improving nutritional content and reducing environmental impact.

Other exciting prospects include:

- **Carbon-sequestering plants:** Crops that store more carbon in the soil, contributing to climate mitigation.
- **Customized nutrition:** Crops designed to address local nutritional deficiencies.
- **Adaptive crops:** Plants capable of adjusting to changing conditions, effectively “learning” to survive in different environments.

By combining CRISPR with traditional breeding, local agricultural knowledge, and sustainable farming practices, the next decade could usher in a **new agricultural revolution**.

Conclusion

CRISPR represents a powerful tool for addressing the challenges of climate change in agriculture. By precisely editing plant genes, scientists are helping crops withstand heat, drought, flooding, and other environmental stresses, while maintaining productivity and nutritional quality.

The coming years will be critical for ensuring that CRISPR technology is used responsibly and equitably. If implemented thoughtfully, it has the potential to strengthen global food systems, support smallholder farmers, and contribute to sustainable agriculture.

In the face of a rapidly changing climate, CRISPR offers hope: crops that not only survive, but thrive, securing food and livelihoods for generations to come.

Advances in Molecular Approaches for Biotic Stress Tolerance in Oilseeds



Lalita Kumari¹, Anshu Panwar², Barish Patel¹, Jagat Singh³, Priyanka Jeetarwal⁴

¹Department of Genetics and Plant Breeding, B. A. College of Agriculture, Anand Agricultural University, Anand (Gujarat), India - 388110

²Department of Plant Pathology, College of Agriculture, Jodhpur Agriculture University, Jodhpur - 342304

³Msc. Degree Holder in Department of Genetics and Plant Breeding

⁴Department of Agronomy, B. A. College of Agriculture, Anand Agricultural University, Anand (Gujarat), India - 388110

Abstract

Biotic stresses caused by pathogens and insect pests significantly limit oilseed productivity and quality worldwide. Conventional breeding approaches, though successful to some extent, are often constrained by environmental influence, complex inheritance of resistance traits and rapidly evolving pest populations. Advances in molecular approaches have revolutionized oilseed improvement by enabling precise, efficient and durable biotic stress tolerance. Techniques such as marker-assisted breeding, germplasm screening using genomic tools, genetic engineering and genome editing facilitate rapid identification, transfer and manipulation of resistance genes. Integration of these molecular strategies with conventional breeding offers sustainable solutions for enhancing oilseed resilience and ensuring long-term productivity.

Keywords: Oilseed crops, Biotic stress, Molecular breeding, Marker-assisted selection, Genetic engineering, Genome editing, Disease resistance

1. Introduction

Oilseed crops are among the most important agricultural commodities, supplying edible oils, industrial raw materials and nutritional security to a rapidly growing global population. In India, crops such as groundnut, mustard, soybean, sunflower, sesame, linseed, safflower and castor play a vital role in the agricultural economy and farmers' livelihoods. Despite large cultivation areas, oilseed productivity often remains low due to multiple constraints, among which biotic stresses are particularly damaging. Diseases and insect pests cause substantial yield losses and reduce oil quality, thereby widening the gap between domestic production and demand. Changing climatic conditions further intensify these problems by favouring the emergence of aggressive pathogens and pest populations. To ensure sustainable oilseed production, there is an urgent need to develop varieties with durable biotic stress tolerance using advanced molecular approaches integrated with conventional breeding strategies.

2. Importance of Oilseed Crops and Biotic Stress Challenges

Oilseed crops contribute significantly to food security by providing dietary fats, essential fatty acids and protein-rich meals. They also support agro-based industries and rural employment. However, oilseed productivity is highly vulnerable to biotic stresses caused by fungi, bacteria, viruses, phytoplasma, nematodes and insect pests. These stresses affect crops at all growth stages, from seedling emergence to post-harvest storage, leading to heavy economic losses.

Major diseases such as white rust, Alternaria blight, rust, downy mildew, stem rot, head rot and viral infections are widely prevalent in oilseed crops. Insect pests including aphids, caterpillars, borers, grubs and leaf miners further aggravate crop damage. The combined effect of multiple stresses often results in reduced plant vigour, poor seed filling, lower oil content and inferior seed quality. Conventional control measures, including chemical pesticides, are costly, environmentally unsafe and often ineffective due to resistance development in pests and pathogens.

**Edible
Oilseeds**



Groundnut
(*Arachis hypogaea*)



Soybean
(*Glycine max*)



Safflower
(*Carthamus tinctorious*)



Linseed
(*Linum usitatissimum*)



Sesame
(*Sesamum indicum*)



Indian mustard
(*Brassica juncea*)



Niger
(*Guizotia abyssinica*)



Sunflower
(*Helianthus annuus*)

**Non-Edible
Oilseeds**



Castor
(*Ricinus communis*)

3. Plant Responses to Biotic Stress

Plants possess innate defence mechanisms that allow them to perceive and respond to biotic stress. The initial recognition of pathogens or pests triggers a cascade of defence responses at cellular and molecular levels. One of the earliest responses involves changes in membrane permeability and calcium ion signalling, which activate downstream defence pathways. Reactive oxygen species are rapidly produced at infection sites, serving as both antimicrobial agents and signalling molecules.

Localized defence responses such as the hypersensitive response restrict pathogen spread by inducing programmed cell death in infected cells. Systemic responses, including systemic acquired resistance and induced systemic resistance, enhance whole-plant immunity against a broad range of pathogens. These defence mechanisms are regulated by complex networks involving phytohormones, transcription factors and defence-related genes. Understanding these responses has provided valuable insights for developing molecular strategies to enhance biotic stress tolerance in oilseed crops.

4. Limitations of Conventional Breeding for Biotic Stress Tolerance

Conventional breeding methods such as selection, hybridization and backcrossing have played a crucial role in oilseed improvement. However, breeding for biotic stress tolerance using traditional approaches faces several limitations. Screening for disease or pest resistance is often influenced by environmental conditions, pathogen variability and inconsistent disease pressure. As a result, reliable selection of resistant genotypes becomes difficult.

Many resistance traits are quantitatively inherited and controlled by multiple genes, making phenotypic selection slow and inefficient. Additionally, the continuous evolution of pathogens frequently leads to the breakdown of resistance in newly released varieties. Long breeding cycles and limited availability of resistance sources further restrict the effectiveness of conventional breeding. These challenges highlight the need for molecular tools that can improve selection efficiency and resistance durability.

5. Molecular Breeding Approaches for Biotic Stress Tolerance

Molecular breeding integrates genomic information into conventional breeding programmes to improve precision and efficiency. Marker-assisted selection is one of the most widely used molecular breeding tools for biotic stress tolerance. It involves the use of DNA markers tightly linked to resistance genes or quantitative trait loci to identify desirable genotypes at early growth stages.

Marker-assisted backcrossing accelerates the transfer of resistance genes from donor parents into elite cultivars while minimizing linkage drag. Foreground selection ensures the presence of the target resistance gene, while background selection helps recover the recurrent parent genome rapidly. Gene pyramiding through molecular markers enables the combination of multiple resistance genes into a single genotype, thereby enhancing

the durability and spectrum of resistance. Marker-assisted recurrent selection and genomic selection further increase genetic gain by exploiting genome-wide marker information for complex traits.

6. Role of Germplasm Screening and Genomic Tools

Efficient utilization of genetic diversity is fundamental to improving biotic stress tolerance. Germplasm collections, landraces and wild relatives of oilseed crops serve as valuable sources of resistance genes. Molecular tools facilitate precise screening of large germplasm sets through marker-based and genomic approaches.

Genome-wide association studies and linkage mapping enable the identification of genomic regions associated with resistance traits. These approaches help dissect complex traits and identify candidate genes involved in plant defence. The integration of high-throughput genotyping and phenotyping platforms has significantly improved the resolution and reliability of resistance mapping. Such genomic tools provide a strong foundation for molecular breeding and targeted improvement of oilseed crops.

7. Genetic Engineering for Enhancing Biotic Stress Tolerance

Genetic engineering allows the direct introduction of specific resistance genes into oilseed crops, bypassing the limitations of sexual compatibility. This approach has been particularly useful where natural resistance sources are scarce or ineffective. Genes conferring resistance to insects, fungi and viruses have been successfully deployed in several oilseed crops.

Agrobacterium-mediated transformation is the most commonly used method due to its efficiency and stable gene integration. Other techniques such as particle bombardment have also been explored. Transgenic oilseed crops expressing insecticidal proteins, antifungal genes, or antiviral sequences have shown improved resistance and reduced dependence on chemical pesticides. Genetic engineering thus offers a powerful complementary approach to conventional and molecular breeding strategies.

8. Genome Editing: Precision Breeding for the Future

Genome editing technologies, particularly CRISPR-Cas systems, have ushered in a new era of precision breeding. These tools enable targeted modification of specific genes involved in plant-pathogen and plant-insect interactions. By editing susceptibility genes or regulatory elements, resistance can be enhanced without introducing foreign DNA.

Genome editing offers several advantages, including high precision, speed and reduced regulatory complexity compared to transgenic approaches. In oilseed crops, editing genes related to disease susceptibility and defence regulation holds great promise for developing durable resistance. As genome editing protocols become more efficient, this technology is expected to play a central role in future oilseed improvement programmes.

9. Integration of Molecular Approaches for Sustainable Oilseed Production

The effective management of biotic stress in oilseeds requires an integrated approach combining molecular breeding, genetic engineering and genome editing with conventional practices. Such integration ensures the development of high-yielding, resilient varieties while maintaining environmental sustainability.

Capacity building, investment in genomic resources and strengthening of breeding infrastructure are essential for the successful adoption of molecular approaches. Collaboration between breeders, molecular biologists and pathologists will further accelerate progress. The use of molecular tools not only enhances resistance breeding but also reduces production costs and pesticide usage, benefiting both farmers and the environment.

10. Future Prospects and Research Thrust

Future management of biotic stresses in oilseed crops will rely on integrating molecular breeding, genome editing and advanced genomic tools with conventional breeding strategies. Emphasis will be placed on identifying novel resistance genes from diverse germplasm, strengthening gene pyramiding and deploying CRISPR-based editing to enhance durable resistance. High-throughput phenotyping, bioinformatics and precise manipulation of plant defence pathways will further support the development of resilient, high-yielding oilseed varieties with reduced dependence on chemical pesticides.

11. Conclusion

Molecular approaches have significantly advanced the development of biotic stress tolerant oilseed crops. By improving selection accuracy, reducing breeding time and enabling precise manipulation of resistance traits, these tools complement conventional breeding effectively. The identification and deployment of resistance genes, combined with gene pyramiding and genome editing, offer durable solutions to complex biotic stress challenges. Continued integration of molecular technologies with traditional breeding will be crucial for achieving sustainable oilseed production, improving self-sufficiency and ensuring long-term agricultural resilience.

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Alternative Protein in Indian Diets: Plant and Insect-Based Innovation



Kaliraj K and Loganathan M*

Department of Food Packaging and Storage Technology,
National Institute of Food Technology, Entrepreneurship and Management, Thanjavur
(NIFTEM-T), Tamil Nadu, India

*Corresponding author: E-mail: logu@iifpt.edu.in

1. Introduction

India seems to be at nutritional crossroads; it ranks among the top in food grain and pulse production worldwide, but at the same time, there exists a large population herein that is not meeting its daily protein requirements. Though cereals form the staple food for Indian, protein intake is lacking in adequate quantities due to their cost, availability, and awareness of these items. This “protein gap” is seen in all age groups and results in hidden hunger, weak muscles, and low immunity.

However, the country's population is also expected to reach 1.5 billion by the coming years, and this will put tremendous pressure on the existing food system. The existing sources of protein available in the country will not be enough to cater to the needs that are expected while still exerting more pressure on the environment. Raising livestock requires huge space, water, and feed, but climate change could also affect agricultural production.

In this context, alternative proteins are also gaining popularity. Plant proteins and insect proteins are some of the alternative proteins that have shown great promise in terms of being rich in nutrients and sustainable. These alternative proteins were considered niche or unconventional, but now they are also emerging as a viable alternative to fill the protein gap in India.

2. Protein Consumption Patterns in India.

In the case of India, the basis for the consumption of protein is tradition, culture, and food habits. For the majority of Indians, protein such as lentils, chickpeas, pigeon peas, and green gram is available as the main source of protein. Other such sources of protein that are available in large quantities are dairy products such as milk, curd, paneer, and buttermilk. Grains such as rice and wheat are also readily available as a part of the daily consumption of protein in most Indian homes, even though they do not contain a large amount of protein. Protein such as eggs, fish, and meat is readily available but is unevenly distributed due to cultural and religious differences.

The food habits of India are quite varied. Fish and sea foods are more in coastal areas, dairy products are more in the Northern parts of the country. But the Southern and Eastern parts of the country have more of staple foods such as rice and pulses. In the Northeastern parts of the country, indigenous foods such as insects and fermented foods have been a part of the diet for a long time.

However, the presence of various protein sources, yet the total consumption is not adequate for many Indians. Pulses are generally consumed in small quantities; grains constitute the main component of their diet, and good proteins are either expensive or beyond the reach of the poorer sections of society. Moreover, the plant proteins may be poor in some essential amino acids, and hence their effectiveness.

3. What Is Alternative Protein?

Alternative proteins are protein sources that are developed or marketed as alternatives to traditional animal proteins such as meat, poultry, and fish. In short, they are designed to provide the nutritional benefits of protein in a sustainable manner. This protein source can be produced from plants, insects, or microorganisms and is designed to be consumed in a familiar form such as powder, snacks, and ready-to-eat meals.

Plant-based proteins are the most popular form of alternative proteins. They are produced from pulses, oil seeds, cereals, and millets and are increasingly being developed into protein-rich foods such as Meat analogues, beverages, and fortified foods. Insect proteins, although less popular, are highly efficient protein sources with

high protein content and low environmental impact. Microbial proteins, developed through fermentation using fungi, algae, or bacteria, are a new form of protein that is gaining popularity worldwide, although it is still in its infancy stage in India. The alternative proteins from various sources are shown in Fig. 1.

Globally, alternative proteins have moved from being niche innovation in the food industry to mainstream innovation due to health, climate change, and food production ethics. In India, the shift is more gradual and is associated with vegetarianism, affordability, and acceptance. Rather than replacing traditional food, alternative proteins in India are increasingly viewed as a complementary strategy to improve nutritional security. There are various forms of proteins, which was substituted for normal protein as alternative protein (Table 1.)

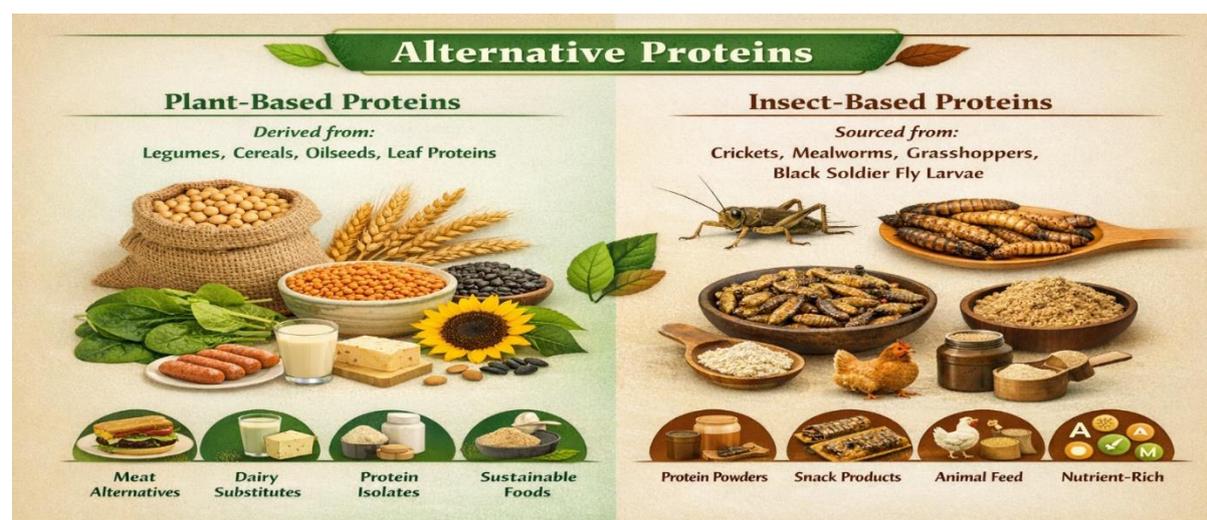


Fig 1. Alternative protein of plant-based protein and insect-based protein

Table 1. Classification of Alternative Proteins, Their Sources, and Applications

Alternative Protein Type	Plant / Animal / Microbial Based	Primary Source	Major Uses / Applications
Legume proteins	Plant-based	Soybean, pea, lentil, chickpea	Meat analogues, protein isolates, dairy alternatives, nutritional supplements
Cereal proteins	Plant-based	Wheat (gluten), rice, maize, oats	Bakery products, textured vegetable protein, protein fortification
Oilseed proteins	Plant-based	Groundnut, sunflower, sesame, rapeseed	Protein concentrates, functional food ingredients, emulsifiers
Algal proteins	Microbial-based	Spirulina, Chlorella	Nutraceuticals, functional foods, protein supplements
Mycoprotein	Fungal-based	Fusarium venenatum	Meat substitutes, ready-to-eat foods, high-protein foods
Insect protein	Animal-based (Invertebrate)	Crickets, mealworms, black soldier fly larvae	Protein powders, animal feed, snack foods
Single-cell protein (SCP)	Microbial-based	Yeast, bacteria, fungi	Animal feed, protein fortification, food ingredients
Cultivated (cell-based) meat	Animal-based (cell culture)	Muscle cells from livestock or poultry	Meat substitutes, sustainable meat products
Fermentation-derived proteins	Microbial-based	Precision fermentation using yeast or bacteria	Dairy proteins (casein,

4. Plant-Based Proteins: The Indian Advantage

Given its vegetarian culture and agricultural diversity, India already has a natural advantage in plant protein. For centuries on end, the main sources of protein-variability in the Indian diet have been pulses such as lentil, chickpeas, blackgram, and pigeon pea. Added to these are millets like sorghum, pearl millet, and finger millet with their moderate levels of protein combined with fiber and nutrients. Oilseeds such as groundnut, sesame, and soybean also add to the protein intake of meals. These are combined to form the staple of a sustainable and accepted protein diet.

Another major innovation that has occurred is the use of protein isolates and concentrates derived from plant sources such as pea, soy, chickpea, and rice. These highly refined protein products are mixed to produce protein powders, fortified drinks, nutrition bars, and conventional foods like rotis and snacks. Through these foods, nutrient deficiencies have been overcome through improved digestibility and protein/amino acid profiles.

The startup system related to food products in India has played an important role in this transition. The vast majority of the startup businesses in India are working towards creating plant-based protein foods that can be consumed by India's taste buds. For instance, there is development towards creating high protein-containing snacks, meals, and even dishes such as ready-to-cook, apart from being a healthy source of protein. Another important thing associated with this source of protein is that, apart from being healthy, it also contains several advantages related to the environment. For instance, it needs fewer resources such as water and even land, thereby creating fewer amounts of greenhouse gases. Furthermore, pulses and millet have also been discovered to have favorable impacts on the soil, thereby creating climate-resilient agriculture. Besides that, this source of protein contains no amounts of cholesterol, besides being filled with fiber, antioxidants, and bioactive constituents.

5. Insect-Based proteins: Ancient practice, modern Innovations

Although the food insect is found to be exotic, even strange, to most Indians, the food habit of having insect-based food is stated to have a long history in various sections of the Indian geography, especially in the North-East. Stated as an integral part of the food culture of the original inhabitants of Nagaland, Manipur, Mizoram, and Arunachal Pradesh, the locals have always had an inclination towards having insect-based food such as silkworm pupae, crickets, termites, grasshoppers, etc. The insect-based food is not stated as a novelty food but as a seasonal food, which is relished for its taste as well as nutritional value. There is no doubt that the consumption of insect-based food is not alien to India; it is a part of the food culture of India.

From a nutritional perspective, insects are a very efficient source of protein. Most edible insects have a protein content of 50-70% dry weight, along with essential amino acids. They also have high quantities of other key micronutrients like iron, zinc, calcium, and vitamin B12, which are absent in the Indian diet. Apart from this, they also have healthy fats and bioactive compounds, which are very important from a nutritional perspective and make them a potential answer to the problem of malnutrition and protein deficiency.

Insects also have some environmental benefits. Some species of insects can be reared on agricultural by-products or food waste, which is in sync with the concept of the circular economy. With the increase in climate change and resource scarcity, insect rearing can be a sustainable answer to produce high-quality protein with a much smaller ecological footprint.

Innovation is also bringing with itself a change in the packaging of insect-based proteins for consumption. Instead of consuming them in whole form, new forms are being innovated for consumption in the form of insect flour or protein powder, which can be mixed with baked food items, snacks, energy bars, and even regular food products. Therefore, by packaging the insect-based proteins in a conventional way for consumption, the psychological barrier for food consumption can be removed while retaining the nutrient benefits associated with them. These are being used for sports nutrition and even animal feed segments across the globe.

However, with this advantage in mind, insect protein technologies remain a controversial subject in mainstream India. Some of the inhibiting factors contributing to this may include the cultural inhibitions of the people of India, lack of awareness, lack of a regulatory mechanism in place, and the perspective of the people of India regarding the consumption of insects as pests and not as food items. Education and awareness need to be raised concerning this technology.

6. Safety, Regulation and Consumer Acceptance

With alternative proteins poised on the brink of entering the mainstream, the concerns of food Safety and consumer trust are becoming increasingly relevant. For plant-proteins as well as insect-proteins, there are concerns related to contamination, allergens, proper processing, and hygienic production practices. For insect-proteins, there are certain concerns related to microbial safety and allergens, especially in individuals with shellfish allergies, owing to their close biological relatives.

In India, the regulation of food safety is the mandate of the Food Safety Standard Authority of India (FSSAI). At present, plant-proteins are governed by existing food regulations such as protein supplements, fortified foods, and novel food ingredients. Insect-proteins, on the other hand, are in a state of regulatory flux as they have not yet been classified under existing mainstream food regulations. Although international debates on edible insect-proteins are in progress, India is only in the early stages of developing appropriate guidelines, and therefore, there is a need for regulatory clarity for commercialization.

Apart from regulatory issues, health-related issues, and other challenges, the first challenge is related to consumers. Taste, texture, and appearance were important determining factors. The appearance of plant-based protein foods, similar to normal food, has been more appreciated by consumers, whereas insect protein food has received challenges owing to cultural issues that perceive them to be unhygienic and inedible by the vast majority of the population, psychological issues.

To overcome these issues, education and awareness are important. Labeling of foods in terms of their origin and safety, along with discussions, may help to reduce these apprehensions. Processed foods, with the help of their education and usage, can also help to improve acceptance of these alternative protein sources. Trust and confidence can also help to ensure the acceptance of novel foods in the Indian diet.

7. Environmental And Economic Impact

Alternative proteins provide environmental grievance because India is also facing challenges of climate change, water scarcity, and land scarcity. When compared to conventional animal protein production and the environmental consequences of the same, the environmental impact of plant protein production and insect protein production is less water and land-consumptive, along with a lower amount of carbon emissions. In addition to this, pulses and millets are hardy crops that can also grow in poor soil with low inputs, and insect production causes less greenhouse emissions and requires fewer feed stocks to raise them for providing a sustainable alternative to the increasing protein requirements.

Alternatively, alternative protein products offer a further opportunity of making some money along the value chain. In the first place, farmers will be able to take advantage of the increasing demand for pulses, millets, and oil seeds. On the other hand, small-scale insect farming will offer a new source of money, primarily among the people living in the countryside. However, the new sector of food technology has provided a new opportunity for MSMEs and start-ups to come up with innovative food products rich in proteins and tailor-made to suit the taste of the Indians. This is a further opportunity of ensuring that the indigenous industries of food production will be retained. Alternative proteins can be a compelling opportunity to create a new business that buttresses and underpins the concept of the circular economy. In the first place, there is the opportunity of insect farming, which will depend on food waste and underutilized crops as a source of protein. As a result of its ability to offer a synergy of nutrition, sustainability, and sustainable business opportunity, there is no doubt that alternative proteins will be the agents of a new and sustainable revolution in the Indian food system.

8. Challenges

However, there are also some challenges facing India at the moment despite the promising alternative protein development. To begin with, one challenge is that of cost, as most of these alternative protein sources, like plant-based and insect-based proteins, are still cost-prohibitive compared to traditional protein sources. Secondly, issues affecting scalability and supply chains in most of these alternative protein sources, like the storing of coal in alternative proteins, and also issues affecting insect-based protein sources, like lack of clarity in their regulation and production methodologies, also pose some challenges.

There are specific gaps to be addressed with particular attention to research in the areas that require further refinement of alternatives in terms of taste, texture, and digestibility and in terms of making the present technology

more accommodating to the Indian climate and culture. There is also a need to address the requirement in terms of investment in pilot plant facilities and quality testing facilities and training the farmers in the areas of farming. In the future, it is expected that in India, the future protein scenario will be diverse and inclusive, and by adding traditional dishes with model innovation, it can be possible to add other protein sources to the diet of the extinct, thereby making it more nutrient-rich.

9. Conclusion

The path to Protein security in India is not to go against Tradition but to build upon it. Pulses, Millet, and Traditional foods have been the bedrocks of Indian nutrition for centuries now, and the latest developments in Plant Protein and Insect Protein technology are a great opportunity to build upon these bedrocks. When Tradition meets innovation, Nutritional security, Sustainability, and Acceptability can walk together in parallel.

Ensuring the transition to Alternative Protein will require the collective efforts of every stakeholder involved. This implies that consumers must be willing to learn and be ready for new food options. Equally, the government will need to provide education on matters touching on regulation and research in sustainable food systems. Nevertheless, the food industry and innovators will have to strive towards making learning safe and acceptable cultural options for protein consumption part of the equation altogether.

With the right amalgamation of knowledge, innovation, and government backing, Alternative Protein has tremendous potential in filling this present gap in India, thus offering a solution to the deteriorating environment. Even though the future holds tremendous problems, it also holds prospects of hope, thus resulting in a healthy and robust country.



Plant Quarantine as a Biosecurity Strategy in Indian Agriculture



Sukhjot Singh

PhD Scholar, Department of Genetics & Plant Breeding, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India

Numerous economically significant crops are known to be attacked by insects, mites, nematodes, fungi, bacteria, viruses, MLOs, and other organisms. These diseases and pests significantly degrade the quality of the food in addition to lowering its quantity. E.C. Stakman, a renowned wheat pathologist, stated in 1969 that "plant diseases, insect pests, and weeds reduce the potential agricultural production in the U.S. by 23 percent." At least 75 million people could be fed with the potential food that has been destroyed. It's possible that things are still worse in the majority of countries that are developing. Therefore, we must make every effort to at least minimise these losses by managing crops properly and controlling pests and diseases.

Quarantine of plants as a national service

From time to time, the introduced pests/pathogens have devastated crops and even created famine conditions in different parts of the world. The Ireland famine of 1845 was the result of an almost total failure of the potato crop due to the introduction of the late blight pathogen (*Phytophthora infestans*) from Central America. A number of disease and pests were also brought to India as well; some of these, such as banana bunchy top, bacterial blight, late blight of potatoes, and paddy streak diseases, have subsequently spread widely. Others, such as downy mildew of onions, wart disease of potatoes, and golden nematode, are still restricted to specific regions of the nation. plant quarantine, in real sense, serves as a national service by preventing the introduction of exotic pests/pathogens/weeds and their further spread. However, such endeavours could succeed only with the active support of all-the administrators, general public, farmers, scientists, communication media, customs and others.

Pest/pathogen detection techniques

1. Generalized tests

Examining dry seeds with the naked eye or with a low-power microscope is a highly popular technique. A variety of free-moving insects, their eggs and larval stages, mites on or with the seed, weeds, soil, infected or infested plant debris, fungal fructifications such as sclerotia, smut, and bunt balls, nematode galls, malformed or discoloured seeds mixed with seed, bacterial crusts, acervuli, pycnidia, sclerotia, and even free spores of rusts, smuts, and numerous other fungi on the seed surface would all be visible using this method. Most commonly used incubation methods for the detection of fungi are the common moist blotter and agar tests wherein seeds are incubated on these media for a specific length of time (generally about a week) at a suitable temperature under alternating light and dark cycles.

2. Specialized tests for insects, nematodes, Fungi, bacteria and viruses

For Insects- worldwide, X-ray radiography has proven to be a highly effective method for identifying insect infestations that are hidden from view, especially chalcids and bruchids that infest seeds. The seed transparency test, which involves boiling the seeds in lactophenol to turn them transparent, can also be used to identify insects and find concealed infestations. Additionally, infested seed lots can be successfully salvaged using X-ray radiography. On the seed surface, there are free spores of rusts, smuts, and numerous other fungi.

For nematodes- detection of seed-borne nematodes, seeds are soaked in water for about 24 hours. This makes the nematodes active, which then come out of the seed into the water, or the seeds may be teased out with the help of forceps and a needle and examined for detection of nematodes under a stereo microscope. In rooted plants, the accompanying soil and plant debris may similarly be soaked in water and nematodes may be extracted for identification using nematological sieves or tissue paper.

Fungi, bacteria and viruses- Serological assays are frequently used in plant quarantine stations and are highly successful in detecting and identifying bacterial and viral diseases. Even bacterial strains can be recognised using the phage-plague approach, making it more sensitive to bacterial infections. Because they may identify harmful races within a species of a bacterium, fungus, or virus, indicator test plants are also very useful.

3. Chemical treatments

Chemicals may be applied as dust, slurry, spray or as dip. It should be ensured that dosage of chemical should be enough to eradicate the inoculum but should not kill the host and the chemical should not be hazardous to personnel handling the treated seed.

Table 1. Important pathogens and pests intercepted on introduced seeds/planting materials at NBPGR*

Pathogens/pests	Crop species	Sources
Fungi		
<i>Alternaria brassicae</i>	<i>Brassica</i> spp.	Italy, Sweden, Taiwan
	<i>Phaseolus vulgaris</i>	USA
	<i>Spinacea oleracea</i>	Netherlands
<i>A. helianthi</i>	<i>Daucus carota</i>	France, Poland, USA, UK
<i>Colletotrichum acutatum</i>	<i>Lycopersicon esculentum</i>	USA
	<i>Medicago</i> spp.	Australia
	<i>Panicum maximum</i>	Australia
<i>C. falcatum</i>	<i>Saccharum</i> spp.	USA
<i>C. graminicola</i>	<i>Glycine max</i>	Taiwan
<i>Colletotrichum acutatum</i>	<i>Lycopersicon esculentum</i>	USA
Nematodes		
<i>Anguina</i> sp.	<i>Stylosanthes</i> (seeds)	Australia
<i>A. tritici</i>	<i>Triticum aestivum</i>	Turkey, UK, Italy
<i>Aphelenchoides besseyi</i>	<i>Digitaria smutsii</i> , <i>Oryza sativa</i> , <i>Oryza glaberrima</i> , <i>Guiljelma gasipee</i>	Philippines, USA, Brazil, Madagascar, Burma, UK, Indonesia, Australia, Costa Rica
<i>A. composticola</i>	Orchids	Australia
<i>A. fragariae</i>	Strawberry plants (soil), <i>Dahlia</i> sp. (soil), Orchid seedlings, <i>Fragaria</i> sp. (plants)	USA, Netherlands, Australia
<i>Ditylenchus angustus</i>	<i>Oryza sativa</i>	Madagascar
<i>D. destructor</i>	<i>Humulus lupulus</i> (rooted cuttings), <i>Solarium tuberosum</i> (tubers)	Australia, W. Germany, Peru
<i>D. dipsaci</i>	Alfalfa (<i>Medicago sativa</i>) seeds, Flower bulbs, Hops (rooted cuttings), <i>Hyacinthus</i> sp., <i>Tulipa</i> sp., <i>Narcissus</i> sp.	USA, Netherlands
<i>Heterodera goettingiana</i>	<i>Pisum sativum</i> (soil clods)	UK
Insects		
<i>Acanthoscelides obtectus</i>	<i>Cajanus cajan</i> , <i>Phaseolus vulgaris</i> , <i>Vigna</i> sp.	Brazil, Colombia, Italy, Nigeria, USA
<i>Anthonomus grandis</i>	<i>Gossypium</i> sp., <i>Hibiscus</i> sp., <i>Sesamum</i> sp., <i>Vigna unguiculata</i>	USA Italy, Zambia
<i>A. fasciculatus</i>	<i>Allium</i> sp., <i>Cajanus cajan</i> , <i>Leucaena diversifolia</i> , <i>L. leucocephala</i> , <i>Psophocarpus</i> sp., <i>Vigna radiata</i> , <i>Zingiber officinale</i>	Fiji, Indonesia, Italy, Philippines, Thailand, USA

*Adopted from 'Research achievements - A decade' Scientific Monograph No. 11, 1987, National Bureau of Plant Genetic Resources, New Delhi-110 012 (Eds., K. P. S. Chandel and B. M. Singh).

Plant quarantine system in India

In India, plant quarantine operations are conducted according to with the Destructive Insects and Pests Act (DIP Act) of 1914 and the guidelines periodically established by the Indian government (Anonymous, 1975). Until the Government of India introduced the comprehensive 'Plants, Fruits and Seeds (Regulation of Import into India) Order, 1984' in 1984, seeds were not included by the DIP Act. This order went into effect in June 1985

(Anonymous, 1985). With a view to provide the farmers the best planting materials available in the world for maximising productivity per unit area and to encourage the private seed industry in India not only to meet the internal requirements but also to develop export potential for high quality planting materials, the Government of India announced a 'New Policy on Seed Development' in September 1988. The new policy covers the import of seeds/planting materials of wheat, paddy, coarse cereals, oilseeds, pulses, vegetables, flowers, ornamentals and fruit crops.

This policy also states that absolutely no compromise shall be made with the requirements of plant quarantine procedures to prevent entry into the country of exotic pests, diseases and weeds detrimental to Indian agriculture.

Coordination at the national level

The majority of plant material is brought into the nation by air mail or air cargo. Additionally, passengers travelling overseas carry planting materials and seeds. Under "Open General Licence," the New Seed Policy now allows private companies to add more content in specific circumstances. Ships deliver bulk consignments for consumption or planting, whereas the postal service or air freight deliver tiny research consignments. As a result, the Indian Port Authority, International Airport Authority, Customs Department, and Postal Service are all involved. The final users of the introduced germplasm material in crop improvement programs are state departments of agriculture, agricultural universities, private individuals/agencies, and various research institutes under the Indian Council of Agricultural Research (ICAR) and the Council of Scientific & Industrial Research (CSIR) systems.

Summary

Various plant pests and pathogens inflict heavy crop losses both under field as well as under storage conditions. Plant quarantine regulations promulgated by governments of different countries are designed to regulate the introduction and movement of plants, planting materials, plant products, etc. with a view to prevent the introduction of associated pests, pathogens and weeds exotic to a country or a region and which are harmful to its agriculture. Plant quarantine is effective only against such pests which have no natural means of transport. Plant quarantine as a national service and its complementary role have been briefly discussed. Techniques for the detection of pests and pathogens, and salvaging of infested/infected material have been described.

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Innovative Microbial Consortia for Sustainable Agriculture in Manipur



Mahesh Kumar Dhakar

M.Sc. Scholar, Department of Agricultural Chemistry and Soil Science, College of Agriculture, CAU, IMPHAL, 795004, MANIPUR.

Abstract

Agricultural sustainability in Manipur is under growing pressure from soil acidity, declining organic matter, nutrient imbalances and climate variability. Long-term dependence on chemical fertilizers has accelerated soil degradation and weakened beneficial microbial communities. Microbial consortia-multi-strain biofertilizer formulations composed of compatible indigenous microorganisms-offer an innovative and eco-friendly solution for restoring soil health and strengthening climate resilience. These synergistic microbial systems enhance nutrient availability, improve soil structure, promote plant growth and increase tolerance to environmental stress. This article highlights soil-related challenges in Manipur and discusses the scientific basis, application methods and future prospects of indigenous microbial consortia for sustainable agriculture.

Keywords: Soil microbiome, Native rhizobacteria, Nutrient efficiency, Agroecological resilience.

Introduction

Soil health is fundamental to sustainable agricultural productivity. In Manipur agricultural systems are dominated by paddy cultivation in valley regions and mixed cropping systems in hill districts. However long-term fertilizer dependency, soil erosion and climatic variability have negatively affected soil structure, nutrient balance and microbial diversity. Microbial biofertilizers have emerged as eco-friendly alternatives to chemical fertilizers (Vessey 2003). More recently microbial consortia-combinations of compatible beneficial microorganisms-have shown greater potential due to synergistic interactions that enhance nutrient availability and plant growth (Bashan *et al.* 2014). Indigenous strains adapted to local agroecological conditions are particularly promising for sustainable soil management.

This study explores innovative microbial consortia as a strategic solution for soil restoration and climate resilience in Manipur.

Soil Constraints in Manipur

2.1 Soil Acidity and Nutrient Fixation

Upland soils of Manipur are predominantly acidic, limiting phosphorus availability and increasing aluminum toxicity. Acidic conditions restrict microbial activity and nutrient cycling (Brady and Weil 2016).

2.2 Low Soil Organic Carbon

Declining organic carbon reduces soil aggregation, water retention and microbial biomass. Soil organic matter is critical for sustaining nutrient transformations and long-term fertility (Lal 2004).

2.3 Climate Variability

High rainfall and erratic climatic patterns influence nutrient leaching and microbial survival. Climate-induced stress further reduces crop productivity and soil biological stability (IPCC 2022).

Microbial Consortia: Concept and Functional Basis

Microbial consortia consist of multiple compatible microbial strains designed to function synergistically. Unlike single-strain inoculants, consortia integrate complementary nutrient-transforming activities (Timmusk *et al.* 2017).

3.1 Nitrogen Fixation

Biological nitrogen fixation reduces dependence on synthetic fertilizers and improves nitrogen use efficiency (Glick 2012).

EX.- *Rhizobium spp.*, *Azotobacter spp.*, *Azospirillum spp.*

3.2 Phosphate Solubilization

Phosphate-solubilizing microorganisms convert insoluble phosphates into plant-available forms particularly beneficial in acidic soils (Sharma *et al.* 2013).

EX.- *Bacillus megaterium*, *Pseudomonas fluorescens*, *Aspergillus niger*, *Penicillium spp.*

3.3 Potassium and Micronutrient Mobilization

Certain bacteria mobilize potassium and micronutrients, enhancing balanced nutrition (Bashan *et al.* 2014).

EX.- *Bacillus mucilaginosus*, *Frateuria aurantia*, *Thiobacillus spp.*

3.4 Plant Growth Promotion

Production of phytohormones such as indole acetic acid stimulates root growth and nutrient absorption (Glick 2012).

EX.- Gibberellic acid (GA₃), Cytokinins, Abscisic acid (ABA), Salicylic acid

Indigenous Microbial Resources of Manipur

Indigenous microorganisms possess ecological adaptability to local soils and climatic conditions. Native strains demonstrate improved survival, colonization efficiency and stress tolerance under field conditions (Timmusk *et al.* 2017).

Isolation of rhizosphere microorganisms from paddy and upland cropping systems can facilitate development of region-specific microbial consortia. Compatibility testing and functional screening ensure synergistic interactions among selected strains.

Climate Resilience through Microbial Innovation

Microbial consortia enhance agroecosystem resilience by:

- Improving soil aggregation and moisture retention
- Increasing nutrient use efficiency
- Enhancing plant tolerance to abiotic stress
- Supporting soil carbon sequestration.

Soil carbon enhancement through biological processes contributes to climate mitigation and long-term fertility (Lal 2004).

Application Strategies in Manipur

Paddy-Based Systems

Seed treatment and root dipping methods ensure effective rhizosphere colonization in flooded conditions.

Hill Agriculture

Application of acid-tolerant indigenous consortia improves nutrient availability and reduces leaching losses.

Integrated Nutrient Management

Combining microbial consortia with organic amendments and balanced fertilizers maximizes benefits (Vessey 2003).

Challenges and Future Perspectives

Adoption barriers include limited awareness, quality control issues and insufficient field validation. Future research should focus on:

- Molecular characterization of indigenous strains
- Long-term field trials
- Integration with precision agriculture tools
- Establishment of microbial resource centers in Manipur

Advances in metagenomics and systems biology can further optimize consortium development.

Conclusion

Innovative microbial consortia offer a scientifically robust and environmentally sustainable strategy for soil health management in Manipur. By harnessing indigenous microbial diversity and integrating modern formulation technologies agriculture in the region can transition toward climate-resilient and sustainable production systems. Continued research, policy support and farmer engagement are essential for large-scale adoption.

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INNOVATIVE PACKAGING APPROACHES TO MINIMIZE VEGETABLE LOSSES



Sristi¹ and Anuj Sohi^{1*}

¹Department of Vegetable Science, College of Horticulture, Dr Yashwant Singh Parmar
University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh (173 230), India

*Corresponding author: anujssohi@gmail.com

Abstract

Vegetables are highly perishable commodities, prone to losses from physiological deterioration, microbial contamination, mechanical damage and poor storage conditions. Traditional passive packaging provides limited protection, prompting the adoption of advanced technologies that actively interact with produce and its environment. Modified Atmosphere Packaging (MAP) adjusts oxygen and carbon dioxide levels to slow respiration, while active and intelligent packaging systems incorporate antimicrobial agents, gas scavengers and freshness indicators. Biodegradable and edible films offer eco-friendly alternatives, reducing reliance on plastics. Additionally, sensor-based monitoring integrated with Internet of Things (IoT) platforms enables real-time tracking of quality, temperature and humidity, ensuring timely interventions. These innovations collectively extend shelf life, maintain nutritional value and minimize waste, contributing to more sustainable supply chains. Future research will focus on cost-effective scalability, consumer acceptance and integration of smart technologies to enhance efficiency and environmental responsibility in post-harvest management.

Keywords: Vegetable packaging, Modified atmosphere packaging, Intelligent packaging, biodegradable films, Smart sensors.

Introduction

Vegetables are among the most perishable agricultural commodities, beginning to deteriorate immediately after harvesting due to high respiration, moisture loss, ethylene-induced senescence and microbial contamination. Their elevated water content, active metabolism and susceptibility to mechanical damage accelerate biochemical changes that compromise quality. Globally, post-harvest losses remain a major concern, with estimates ranging from 20–40% in developing countries depending on crop type and supply chain efficiency (Dwivedi *et al.*, 2024). These losses not only represent economic setbacks but also contribute to food insecurity, highlighting the urgent need for improved preservation strategies. Conventional packaging systems-plastic films, crates and sacks function-mainly as passive barriers, offering limited protection while failing to regulate the internal microenvironment. As a result, physiological disorders, microbial growth and quality degradation continue during storage and transportation.

Driven by consumer demand for fresh, safe, minimally processed vegetables and growing concerns over food waste and plastic pollution, researchers and industry innovators have advanced packaging technologies (Zheng *et al.*, 2018). Modified Atmosphere Packaging (MAP) regulates oxygen, carbon dioxide and humidity to slow respiration and microbial activity. Active packaging incorporates agents that scavenge ethylene, absorb excess moisture or release antimicrobial compounds. Intelligent packaging employs indicators and biosensors to provide real-time feedback on freshness and safety, enhancing supply-chain transparency. Biodegradable and edible films offer eco-friendly alternatives to plastics, sometimes with added antimicrobial properties (Du *et al.*, 2025). Sensor-based monitoring integrated with Internet of Things (IoT) platforms further enables continuous tracking of quality parameters, ensuring timely interventions.

Collectively, these innovations move beyond passive containment, creating dynamic systems that interact with produce and its environment. They extend shelf life, preserve nutritional quality and reduce waste, while future research must address cost-effective scalability, consumer acceptance and digital integration to strengthen sustainable supply chains.

1. Modified Atmosphere Packaging (MAP)

Concept and Mechanism

Modified Atmosphere Packaging (MAP) is widely applied to extend the freshness of vegetables (Fig. 1). It functions by altering the gas composition inside the package, generally reducing oxygen (O_2) and increasing carbon dioxide (CO_2) compared to normal air. These controlled conditions slow respiration, inhibit ethylene production and decelerate enzymatic activity, thereby delaying aging and limiting quality deterioration (Zheng *et al.*, 2018). MAP can be achieved either actively, by introducing a specific gas mixture or passively, through the natural balance between vegetable respiration and the permeability of the packaging materials.

Its success depends on maintaining a precise gas equilibrium, since excessive oxygen reduction can lead to anaerobic respiration, causing off-flavors and tissue damage.

Application to Vegetables

Vegetables vary in their ideal storage atmospheres due to differences in respiration rates and ethylene sensitivity. Leafy greens such as spinach and lettuce benefit from reduced oxygen levels, which slow respiration and help prevent wilting. In contrast, cruciferous crops like broccoli and cauliflower maintain better quality under elevated carbon dioxide concentrations that suppress microbial growth (Dwibedi *et al.*, 2024). Advances in polymer engineering have enabled the development of selectively permeable films that regulate gas exchange according to the physiological requirements of each type of produce, thereby enhancing preservation and extending shelf life.

Benefits and Challenges

Benefits:

- **Extended shelf life:** Innovative packaging technologies, such as Modified Atmosphere Packaging (MAP) and active systems, slow down respiration and microbial activity, thereby prolonging the freshness and usability of vegetables.
- **Reduced enzymatic browning:** By regulating oxygen levels and incorporating antioxidant or antimicrobial agents, these packaging methods minimize enzymatic reactions that cause discoloration, helping maintain visual appeal and nutritional quality.
- **Improved moisture retention:** Selectively permeable films and biodegradable coatings reduce water loss, preventing wilting and textural degradation, which is particularly important for leafy greens and high moisture produce.

Challenges:

- **Need for precise control for each vegetable type:** Different crops have unique respiration rates and ethylene sensitivities, requiring carefully tailored atmospheric conditions to avoid quality loss.
- **Initial cost of film design and packaging machinery:** Advanced packaging systems demand significant upfront investment in specialized films and equipment, which can limit widespread adoption, especially in resource-constrained settings.

2. Active Packaging Technologies

Concept of Active Packaging

Active packaging systems go beyond the scope of Modified Atmosphere Packaging (MAP) by integrating components that actively interact with the package's internal environment. These systems utilize oxygen scavengers, ethylene absorbers, moisture regulators, antimicrobial agents and carbon dioxide emitters or absorbers to directly counter the main causes of spoilage (Dwibedi *et al.*, 2024). By targeting these critical factors,



Figure 1: Smart MAP Packaging

active packaging significantly improves the shelf life of vegetables. Ethylene management is particularly important, as this gas accelerates aging, promotes yellowing and causes softening. Packaging materials designed to capture or neutralize ethylene effectively delay these processes, thereby maintaining freshness and quality for longer periods.

Functional Mechanisms

Active packaging operates through multiple mechanisms:

- **Gas scavenging:** Involves the removal of oxygen or ethylene within the package to reduce respiration rates and delay ripening.
- **Antimicrobial activity:** Utilizes incorporated antimicrobial agents that suppress or inhibit the growth of spoilage-causing microorganisms.
- **Moisture control:** Maintains appropriate humidity levels to minimize dehydration and prevent condensation, thereby preserving texture and quality.

These mechanisms help maintain freshness, color, texture and nutritional quality of vegetables. **Recent Innovations**

Recent studies have explored the use of advanced materials such as metal–organic frameworks (MOFs) and nanocomposites for improving ethylene removal and providing antimicrobial benefits. Thanks to their extremely high surface area, these materials exhibit strong efficiency even at relatively low concentrations. Alongside this, nanotechnology-based active films have gained attention as innovative packaging solutions, delivering enhanced barrier performance while maintaining product safety and quality.

2. Intelligent and Smart Packaging Systems

Concept of Intelligent Packaging

Intelligent packaging systems focus on providing information rather than directly extending product preservation. They integrate sensors, indicators and data carriers that monitor key internal conditions such as temperature, humidity, gas composition and freshness markers (Vanderroost *et al.*, 2019). Unlike active packaging, which alters the storage atmosphere to slow deterioration, intelligent packaging delivers real-time insights that enable stakeholders throughout the supply chain to make informed decisions. This transparency enhances quality control, improves logistics and supports timely interventions to maintain product safety and freshness.

Types of Indicators and Sensors

Common intelligent packaging tools include:

- **Time–temperature indicators (TTIs):** Detect and signal temperature abuse during storage and transportation.
- **Freshness indicators:** Monitor biochemical changes linked to spoilage, providing a visual cue of product quality.
- **Gas sensors:** Measure oxygen (O₂) and carbon dioxide (CO₂) levels to verify optimal Modified Atmosphere Packaging (MAP) conditions.

These indicators enhance transparency and quality assurance throughout the supply chain.

Integration with IoT Technologies

The combination of intelligent packaging and Internet of Things (IoT) technologies enables remote monitoring, digital recordkeeping and instant alert mechanisms. Smart labels connected to cloud-based systems allow distributors and retailers to receive immediate notifications of unfavorable conditions, ensuring rapid corrective actions to maintain product quality (Du *et al.*, 2025).

Advantages

Intelligent packaging contributes to sustainability by minimizing avoidable waste, strengthening traceability and enhancing food safety. In addition, it facilitates quality-based pricing by providing reliable information on product condition. The implementation of such systems is especially advantageous in long-distance vegetable supply chains, where maintaining freshness and quality throughout extended distribution networks is critical.

3. Biodegradable and Edible Packaging Materials



Figure 2: Eco-Smart Bio Packaging

Need for Sustainable Packaging

Concerns over the environmental consequences of petroleum-derived plastic packaging have stimulated growing interest in biodegradable options. These sustainable packaging approaches are designed to minimize plastic waste while simultaneously maintaining or even enhancing, the preservation efficiency of fresh produce (Dwibedi *et al.*, 2024).

Biodegradable Packaging Materials

Biodegradable packaging is derived from renewable sources such as starch, cellulose, chitosan and polylactic acid (PLA) (Fig. 2). These materials can naturally break down, helping to reduce environmental pollution. Ongoing research focuses on improving their mechanical strength, enhancing barrier properties against moisture and gases and integrating antimicrobial functions to boost their effectiveness in preserving food quality and safety.

Edible Coatings and Films

Edible coatings are applied as thin films directly on the surface of vegetables, acting as semi-permeable barriers that slow respiration, minimize moisture loss and reduce microbial contamination. Materials such as alginate, proteins and lipid-based films are frequently studied due to their biodegradability and safety (Sharma *et al.*, 2024). Beyond these protective functions, edible coatings can also be enriched with natural antimicrobial and antioxidant compounds, which further enhance preservation and extend the shelf life of fresh produce.

Challenges and Future Research

While biodegradable and edible packaging materials present significant sustainability benefits, they still face challenges such as high production costs, limited scalability and inconsistent consumer acceptance. To overcome these barriers, ongoing research is focusing on the use of plant-based by-products and agricultural residues as alternative raw materials. This approach not only helps reduce manufacturing expenses but also enhances functional characteristics, making these packaging solutions more effective for food preservation and environmentally responsible (Sharma *et al.*, 2024).

4. Integrated Packaging Strategies

Synergy with Cold Chain Management

Innovative packaging solutions reach their full potential only when paired with strong cold chain management. Temperature fluctuations can rapidly accelerate deterioration, even in the presence of advanced packaging

systems. Therefore, integrating these technologies with consistently controlled storage and transportation environments is essential to safeguard quality and reduce post-harvest losses (Dwivedi *et al.*, 2024).

Hybrid Packaging Systems

Future advancements in packaging technology are increasingly focused on hybrid systems that combine Modified Atmosphere Packaging (MAP), active elements and intelligent sensors into a single unit. These multifunctional designs can address multiple spoilage pathways at once, offering stronger protection and more holistic quality management. By integrating gas regulation, antimicrobial activity and real-time monitoring, such systems provide comprehensive control over storage conditions and product safety. This convergence of technologies enhances shelf life, reduces waste and supports more sustainable supply chains (Du *et al.*, 2025).

Consumer and Market Trends

Increasing consumer awareness of food safety and sustainability is driving demand for innovative, eco-friendly packaging solutions. Modern vegetable markets increasingly prefer packaging that not only protects produce but also communicates key information about freshness, traceability and environmental responsibility. Such smart packaging aligns with consumer expectations for transparency and sustainability, reinforcing trust while supporting waste reduction and greener supply chains.

5. Cold Chain Synergy

Packaging innovations are most effective when combined with a reliable cold chain. Because temperature variations are a leading factor in spoilage, solutions that control internal conditions while maintaining stable external temperatures can greatly reduce post-harvest losses.

Combining Technologies

The future of vegetable packaging is moving toward hybrid systems that combine Modified Atmosphere Packaging (MAP) with active scavenging agents and integrated freshness sensors. These multifunctional designs are engineered to address multiple spoilage pathways at once, ensuring stronger preservation and more reliable quality control. By regulating gas composition, neutralizing harmful compounds and providing real-time monitoring, such packaging offers a comprehensive approach to maintaining freshness, extending shelf life and reducing waste across the supply chain.

Sustainability and Consumer Trends

Growing consumer emphasis on transparency in food quality and sustainability is pushing manufacturers toward adopting smart, eco-friendly packaging solutions. These systems convey information on freshness while showcasing reduced environmental impact, aligning closely with shifting consumer preferences. As a result, such trends are reshaping industry priorities and directing future research efforts.

Table 1: Major Spoilage Factors in Vegetables and Packaging-Based Interventions

Spoilage Factor	Effect on Vegetables	Packaging Intervention
High respiration rate	Rapid senescence and quality loss	Modified Atmosphere Packaging (reduced O ₂ , elevated CO ₂)
Microbial growth	Decay and food safety risks	Active packaging with antimicrobial agents
Moisture loss	Wilting and texture deterioration	Moisture-regulating films and absorbers
Temperature abuse	Accelerated spoilage during transport	Intelligent packaging with time–temperature indicators
Environmental impact	Plastic waste accumulation	Biodegradable and bio-based packaging materials

Conclusion

Innovative packaging has transformed vegetable preservation, shifting from simple passive barriers to advanced active, dynamic and intelligent systems. Modified Atmosphere Packaging (MAP) manages internal gas levels, active components reduce spoilage, sensor-based intelligent systems enable real-time monitoring, and biodegradable materials lessen environmental impact. Collectively, these approaches form a rapidly evolving set

of solutions that extend shelf life, enhance food safety, cut post-harvest losses and increase transparency throughout supply chains. Moving forward, interdisciplinary research, industry implementation and supportive regulatory measures will be crucial to unlocking their full potential. By tackling multiple spoilage factors at once and aligning with sustainability objectives, next-generation packaging technologies can significantly reduce global food waste and contribute to building resilient, eco-friendly food systems.

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IMPACT OF CLIMATE CHANGE ON FRUIT CROPS



Dr. N.V.S. SUPRIYA

Dr.YSR Horticultural University

INTRODUCTION

Climate plays a significant role in plant growth and productivity. The term “Climate Change” commonly refers to influences on climate resulting from human practices. An increase in the concentration of greenhouse gases in the atmosphere like carbon dioxide, nitrous oxide, ozone and methane may cause an impact in terms of increased temperature, more demand for water and an increase in biotic and abiotic stresses resulting largely from the burning of fossil fuels and deforestation, have led to an observed and projected warming of the earth known as the greenhouse effect. It has a direct impact on agriculture and horticulture. Due to climate change, low production of horticultural crops is featured. Recent climate changes have had widespread impacts on human and natural systems. The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85°C (0.65 to 1.06°C) over the period 1880 to 2012, for which multiple independently produced datasets exist. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78°C (0.72 to 0.85°C), based on the single longest dataset available.

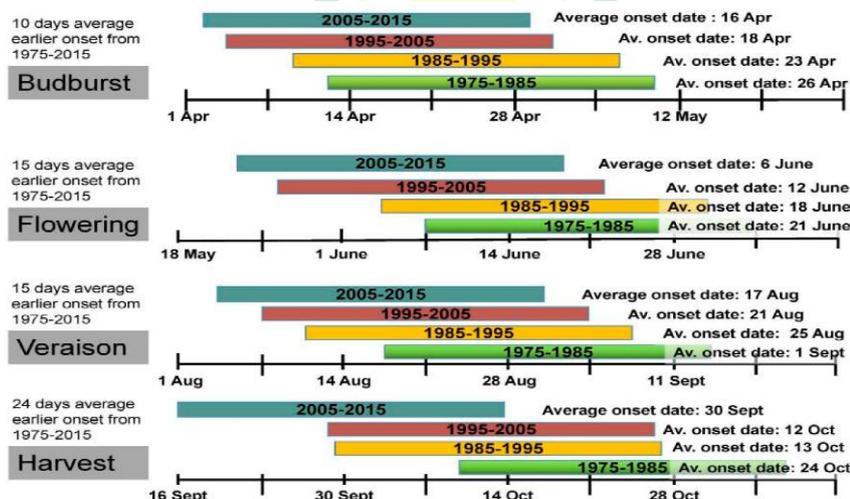
CLIMATE CHANGE IMPLICATIONS IN FRUIT CROPS

- Given that long generation species (perennial trees, shrubs, and herbs) would be less able to respond to new selective pressures than short generation species, fruit crops need to get special attention in the case of climate change. (Rosenheim *et al.*, 1991).
- In comparison to annuals, developing a new variety in fruit crops takes 15 to 20 years, making it more difficult for it to compete with obstacles brought on by climate change.
- Fruit crops are challenging to re-establish since they are high value crops that produce quality yield with increased productivity and necessitate the utmost caution in a changing climatic environment.
- Production of fruit crops is significantly impacted by climate, an important environmental variable.
- Poor fruit quality and low fruit production were the results of changes to plant physical characteristics like vigour, canopy development, and reproductive traits like fruiting ability and reduction in fruit size, as well as quality characteristics like less colour development, low juice content, decreased shelflife, and higher pest attack (Jangra *et al.*, 2013).
- The ability of temperate crops to adapt to sudden changes in the weather at a certain time of the growing season in any historically inhabited areas of temperate crops is at risk, and this could result in serious production issues in the near future (Ameglio *et al.*, 2004)
- In terms of the models used to predict how crops will respond to a changing climate, currently there are more than two dozen crop models available.
- The majority of these models consider crop response to only one climatic variable, such as CO₂ concentrations, temperature, or water stress, and they all generally agree on the general direction of the altered response but disagree on the magnitude of the changes predicted for the future.
- However, as was already indicated, the majorities of these techniques were developed for annual crops or were only tested on a few crops (Hoogenboom *et al.*, 2018).
- Due to anticipated changes in temperature and rainfall, changes in enterprise structure and location are likely to have an impact on tropical fruits and regions. In a changing climate, increased irrigation demand as well as altered irrigation scheme efficiency and water supply are likely to be important concerns for tropical fruit.
- The spread of current pests, illnesses, and weeds, as well as the increased threat of invasions into new crops, as well as the incidence of minor pests, diseases, and physiological conditions including sunburn, fruit cracking, and tipburn (Kumar *et al.*, 2007).

- In temperate fruit species, adequate cooling hours are crucial for healthy vegetative growth and fruiting. In temperate fruit crops, insufficient chilling hours results in inconsistent bud break and fruiting (Viti *et al.*, 2010).
- According to numerous recent modelling attempts that include long-term temperature measurements, a large portion of the recent trend of global warming can be linked to increasing minimum temperatures, which have augmented at a quicker rate than mean or maximum temperatures (Lobell *et al.*, 2007).
- Since their production depends on consistently cold temperatures during the growing season, perennial fruit trees are particularly susceptible to climate change.

IMPACT OF CLIMATE CHANGE ON PHENOLOGY OF FRUIT CROPS

The shift in the time of plant growth activity, or change in phenology, is one of the well-known impacts of climate change. Fruit trees' vegetative and reproductive stages were altered due to climate change. Flowering is a critical stage in fruit development that has an effect on production and productivity. The flower primordia in pome fruits may totally or partially abscise in mild winters, (Brown *et al.*, 1952) producing smaller flower bud clusters that resemble leafy spurs. Climate change has resulted in alterations in flowering, fruiting, and eventually yield. The absence of early cold in December and January has a detrimental impact on the amount of chilling requirement. (Sharma, 2012) In apple, lack of chilling time led to incomplete blossoms and poor fruit set. (Jackson *et al.*, 1980) The blossoming and subsequently fruit set were both qualitatively and quantitatively affected by chilling hours. An increase of 0.45°C/decade (1973–2009) in early spring temperature led to an advance in apple and pear blooming by 1.6 days/decade. At various locations around the world, the following crops also had similar outcomes. In Alsace, France, an increase in the average growing temperature of 2–3°C (1964–2009) accelerated flowering, veraison, and harvest by 13–19 days in grape. Veraison for the cultivars "Riesling" and "Gewurtztraminer" will be advanced by up to 23 days by 2100. The peak flowering date of the cherry tree has shifted to early by 5.5 days in the past 25 years due to temperature fluctuations in February and March. There has been a 1.8°C increase in temperature during the past 25 years. Insufficient chilling requirements during warm seasons cause some phenological disturbances, including late flowering, prolonged flowering times, and a longer time between flowering and harvest in apple. A substantial correlation found between flowering progress and changes in maximum and minimum temperature over time in several sites throughout Iran (Kerman, Shiraz).²⁰ In citrus fruits, it was discovered that flowering advances at rates of 3.15–3.39 days/°C for Kerman and 4.3–4.47 days/°C for Shiraz. In Junagadh, India, flowering was delayed in the majority of mango varieties due to temperatures that were over the ideal day/night temperature range and in part because of cloudy weather. After flower initiation, hermaphrodite flowers were more closely associated with greater temperatures. Undeveloped pistils were a result of the warm (15.9°C) temperature, which is 3–5°C higher than typical.



Phenological shifts based on average onset dates for bud break, flowering, veraison and harvest of four grapevine varieties (“Pinot Gris”, “Pinot Noir”, “Riesling” and “Muller Thurgau”) grown in Hainfeld (Southwest Germany) from 1975 to 2015. (Venioset *et al.*, 2017)

IMPACT OF CLIMATE CHANGE ON FRUIT CROP'S PHYSIOLOGY

TEMPERATURE EFFECT

Temperature regulates the physiological functions of the plants. Imbalanced temperatures causes to following impacts. viz.,

1. Heat stress
2. Inadequate chilling for temperate crops
3. Disruption in pollination activity.

Heat stress increases evaporation, which leads to stomatal closure and a reduced influx of CO₂, which ultimately drives respiration and reduces photosynthesis.

Mango

- Mango has a vegetative tendency and when temperature rises it bears more number of leaves thus impacting the phenology of flowering.
- It may be noted that the hermaphrodite flowers (having both stamen and carpel) percentage in late emerging panicles was higher which also coincided with extreme temperatures (Balogoun *et al.*, 2016).
- In bearing or non-bearing trees of mango, scorching of leaves and the dying of twigs are the main symptoms of heat stroke.
- In mango, the major effects observed during climate change were multiplication of reproductive flushes, early flowering or delayed flowering, poor fruit set, reproductive buds transformation into vegetative ones, changes in the fruit maturity *etc* (Rajan *et al.*, 2011).

Banana

- In general, higher temperature of 31-32 °C increases the maturity rate in banana plant thus shortens the period of bunches development (Turner *et al.*, 2007).
- High temperature of more than 38 °C cause choking of bunches in banana (Stover, 1972).
- In Cavendish bananas, the development of the golden yellow color on leaves at high temperatures (Friend, 1981).

Grape

- Although the grape originated in temperate regions, advances in production method have enabled it to adjust to subtropical and tropical region. Availability of growing degree-days (GDD)/temperature under climate change will lead to speeding up of the phenological processes (Wolfe *et al.*, 2005; Webb *et al.*, 2007).
- In grape vines, the development of **anthocyanin pigment is influenced by the day and night (15-20 °C)** temperatures with high variation.
- Extreme temperatures for prolonged periods in grapes usually **delay fruit ripening and decreases quality of fruit** (Kadir, 2005). Temperature fluctuations lead to changes in stages of growth and ultimately the maturation phase of the grapes. At the period of fruit growth, fruit firmness, TSS and dry weight percentage were negatively related with temperature and it also differ with cultivars (Hoppula *et al.*, 2006)
- No. of cluster/shoots increases with the increase in temperature but number of flower/cluster get reduced (Subedi, 2019).

Papaya

- Higher temperatures in papaya led to flower drop in female and hermaphrodite plants and also responsible for changes in sex in hermaphrodite plants.
- If flowering occurs under extremely low temperatures, flower drops in papaya are relatively normal (Reddy *et al.*, 2017).

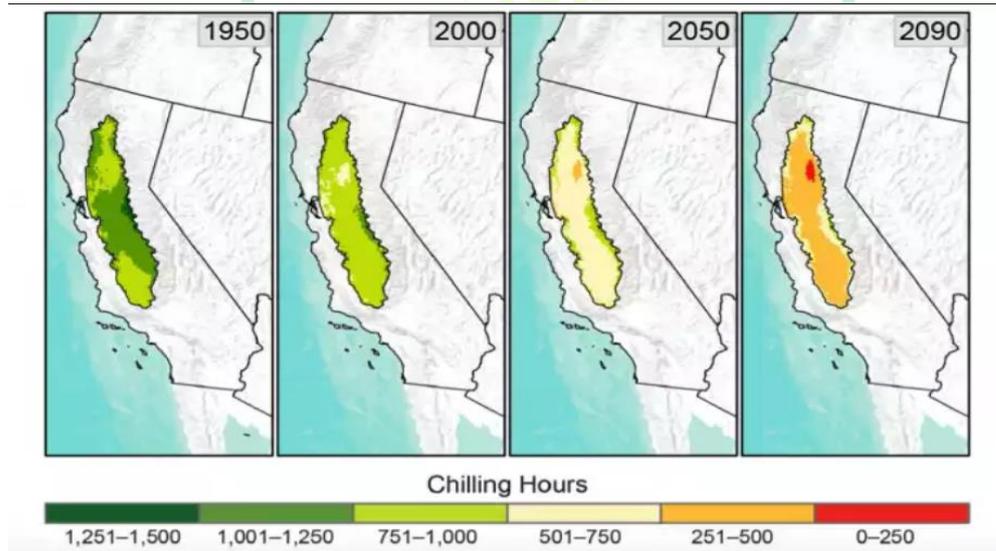
LOW TEMPERATURE

- Horticultural crops suffer a 10-100 percent return loss which depends on the crops and varieties because of the extremely cold waves (Hazarika, 2013).

- Potential flower buds have deeper dormancy than vegetative buds and the first stages of flower initiation seem to occur before the winter rest period (Reddy *et al.*, 2017).
- Inadequate chills can reduce pollination for cross-pollinated fruits such as pistachios and walnuts and thus reduces the crop yields.
- Optimum temperature in temperate fruits such as plum, apples, cherry, pears etc. for pollination and fertilization is between 20° and 25 °C. During pollination in USA in sour cherry conditions like foggy, rainy or low temperatures were found to have a negative impact (Haokipet *et al.*, 2020).
- In longan fruit, overwinter develops problems like severe fruit drop, reduction in fruit size, and fruit cracking. In the young fruit phase, temperatures of less than 15°C reduce the potential and final size of fruit growth. Stressful colds or sudden changes in temperature cause severe fruit drop. Cold or dry weather during the young fruit stage is linked to extreme fruit cracking (Yang *et al.*, 2010).
- The low temperature in the case of mandarins has dual effects, inducing flowering as well as breaking bud dormancy.

Inadequate chilling for temperate crops

According to National Climate Assessment 2014, chilling hours will decrease by 30 to 60 % by 2050 and by up to 80 % by 2100. The In peach cultivars, flowering, fruit set, yield and quality all were proved to be significantly influenced by warmer climatic conditions. Due to lack of chilling, peach tree develop irregular patterns of phenological stages including late flowering and prolonged flowering period. These traits are directly associated with chill accumulation in stone fruit species. Flower abortion occurs in warm winter years, resulting in lower fruit yield.



Carbon dioxide effect

- ✓ Increased CO₂ concentration affects a plant's physiological state. It performs a key role in photosynthesis, which produces the biomass of the plant. However, a rise in temperature and a shift in rainfall pattern may cancel out the positive effects.
- ✓ Increasing net photosynthetic rate in grapes while decreasing stomatal conductance in response to increasing CO₂ improves innate water use efficiency in Portugal (Pereira *et al.*, 2009) In general, they discovered that raising the atmospheric CO₂ level enhances the yield regardless of any good or negative impacts on grape maturity.
- ✓ Sour orange trees were particularly sensitive to the higher CO₂ levels even though they were well into middle-age reproductive maturity (17 years). At the time of final harvest, the root biomass, leaf biomass, branch biomass, fruit biomass and total biomass was significantly higher in the trees with CO₂ enrichment (350-650 ppm of CO₂) than that of the trees grown in ambient conditions (Kimball *et al.*, 2007).

Climate Change Impact on Quality

- ✓ Fruits quality parameters are of essential concern in order to fetch a lucrative price in export market.
- ✓ Changing climatic scenarios are impacting the ideal situations of proper pigmentation and secondary metabolites production which are of integral necessity to produce quality fruits.
- ✓ Temperature variability might also synergist to ideal conditions based on growing areas. Higher antioxidant activity was reported in 'Kent' strawberries under warm days (25°C) & warm nights (18–22°C).
- ✓ Changes in climate have also been recorded to have negative consequences such as earlier ripening by the end of this century in California which may result in lower quality grapes in the region.
- ✓ Incidental heat shocks (over 35°C) caused the loss of 50 % of the berries due to browning and berry burn.

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Nutrient Dynamics and Management Challenges in Conservation Agriculture Systems



Jayashree Dey Sarkar¹, Amrita Kumar Sarkar²

¹Department of Soil Science and Agricultural Chemistry, U.B.K.V., Pundibari, Coochbehar, West Bengal-736165, India

²Department of Agricultural Extension, Faculty of Agriculture, Guru Kashi University, Bathinda, Punjab-151302, India

Abstract

Conservation Agriculture (CA), based on the principles of minimal soil disturbance, permanent soil cover, and diversified cropping systems, has emerged as a key strategy for achieving sustainable agricultural intensification. While CA offers substantial benefits in terms of soil health improvement, resource conservation, and climate resilience, it also fundamentally alters soil nutrient dynamics, necessitating a reorientation of conventional nutrient management practices. This article examines the changes in nutrient availability, distribution, and transformation under CA systems, highlighting key challenges such as nutrient stratification, nitrogen immobilization, temporal mismatches between nutrient release and crop demand, and increased risks of nutrient losses. Emphasis is placed on integrated, site-specific, and precision-based nutrient management approaches to address these constraints. Strategies including Site-Specific Nutrient Management (SSNM), residue recycling, enhanced-efficiency fertilizers, and the use of decision-support tools such as Leaf Colour Chart, SPAD meter, GreenSeeker, and Nutrient Expert are discussed in detail. By integrating 4R Nutrient Stewardship with precision nutrient technologies, CA systems can significantly enhance nutrient use efficiency, sustain soil health, and contribute to long-term food security and climate-smart agriculture, particularly in smallholder-dominated agroecosystems.

Keywords: Conservation Agriculture, nutrient use efficiency, site-specific nutrient management, precision agriculture tools, 4R nutrient stewardship, soil health

1. Introduction

During the Green Revolution, agricultural intensification was largely driven by the widespread adoption of intensive soil disturbance, energy-intensive technologies, substantial capital inputs, and high-yielding crop varieties (Sarkar et al., 2026). Although these interventions resulted in a manifold increase in food grain production, the post Green Revolution period witnessed a complex phase marked by significant gains in food productivity occurring alongside escalating land values and growing pressure on limited land resources (Sarkar et al., 2023). Over time, however, the dominance of intensive tillage practices combined with inadequate crop and soil management has adversely affected soil health, leading to increased runoff, soil erosion, and associated land degradation (Sarkar et al., 2025a). Moreover, the persistent practice of monocropping on the same land parcels has contributed to declining soil fertility, raising serious concerns regarding the long-term sustainability of such production systems. Ensuring food security for an expanding population, reducing poverty, and maintaining the productive capacity of agricultural systems under conditions of diminishing natural resources remain major challenges across many Asian countries (Sarkar et al., 2025b). Addressing the rising food demand in a sustainable manner therefore necessitates a careful balance between agricultural productivity, natural resource conservation, and environmental protection.

In this context, the alignment of food production goals with ecological sustainability requires the adoption of alternative production systems capable of sustaining high yields while preserving environmental integrity. Consequently, a fundamental transformation in farming practices focused on phasing out unsustainable components of conventional agriculture has become imperative to achieve future productivity gains without compromising natural resources. Conservation agriculture (CA) has thus emerged as a viable alternative to traditional tillage-based systems.

Conservation agriculture represents a holistic approach to crop production that emphasizes sustained productivity alongside environmental stewardship. CA enhances soil structural stability through improved aggregate formation, reduces erosion losses, and facilitates better water infiltration and groundwater recharge (Sarkar and Sarkar, 2025c). The system also alleviates soil compaction by encouraging biological tillage, increases soil organic carbon (SOC) stocks, moderates soil temperature regimes, and supports greater microbial diversity, which collectively contribute to improved nutrient cycling and weed suppression. In addition, CA practices help lower production costs, save labour and time, enable timely crop establishment, suppress pests and diseases through enhanced biological interactions, and mitigate greenhouse gas (GHG) emissions, thereby strengthening the overall sustainability and resilience of agricultural systems (Sarkar and Sarkar, 2025d).

2. Best Practices for Nutrient Management under Conservation Agriculture

Effective nutrient management in Conservation Agriculture (CA) systems requires a comprehensive, location-specific, and flexible strategy that is firmly aligned with the fundamental principles of minimal soil disturbance, continuous soil cover, and diversified cropping systems. Unlike conventional input-intensive approaches, nutrient management under CA emphasizes optimizing nutrient cycling within the soil-plant system, enhancing nutrient use efficiency, and sustaining soil health to ensure long-term productivity and environmental sustainability. The following practices are widely recognized as key components of efficient nutrient management in CA-based production systems.

2.1. Conservation Tillage to Improve Soil Organic Matter and Nutrient Retention

Reduced tillage and Zero tillage forms the cornerstone of Conservation Agriculture, with soil disturbance restricted primarily to operations essential for seed placement and crop establishment. Historically, intensive tillage was practiced accelerating organic matter decomposition and nutrient mineralization (Dumanski et al., 2006). However, prolonged reliance on excessive tillage has resulted in deterioration of soil structure, depletion of soil organic matter, heightened erosion, and disruption of soil biological processes.

By minimizing disturbance, reduced tillage systems help conserve soil organic carbon and enhance the soil's capacity to retain nutrients. Lower soil disturbance reduces nutrient losses through volatilization, runoff, and leaching, thereby improving nutrient retention and decreasing the dependence on external synthetic fertilizers. Conservation tillage practices such as zero tillage (ZT) preserve soil aggregates, maintain pore continuity, and promote stable soil structure, which are essential for efficient water and nutrient movement within the root zone. Furthermore, reduced tillage supports beneficial soil organisms that regulate organic matter turnover, improve aggregation, and facilitate biological nutrient transformations. The absence of repeated soil inversion also limits weed seed exposure, contributing to natural weed suppression and reducing nutrient competition (Kassam & Friedrich, 2009).

2.2. Incorporation of Cover Crops and Diversified Crop Rotations

Maintaining continuous soil cover through crop residues and cover crops is a critical strategy for enhancing nutrient dynamics in CA systems. Residue retention protects the soil surface from erosive forces, moderates soil temperature fluctuations, and creates a favourable habitat for soil microorganisms and fauna (Ghosh et al., 2010). Decomposing residues contribute significantly to soil organic carbon buildup, improve nutrient availability, and stimulate microbial-mediated nutrient cycling processes, thereby strengthening soil resilience and productivity.

The integration of cover crops, particularly legumes, into diversified crop rotations provides additional nutrient-related advantages. Leguminous cover crops contribute biologically fixed nitrogen to the soil, reducing the need for external nitrogen inputs and improving nitrogen availability for subsequent crops. Diverse crop rotations also enhance nutrient balance by exploiting varying rooting depths and nutrient uptake patterns, which promote more efficient nutrient recycling within the soil profile. Moreover, crop diversification disrupts pest, disease, and weed cycles, improves crop nutritional quality, and alleviates the adverse effects associated with continuous monocropping especially in intensive systems such as rice–wheat rotations. Collectively, residue management, cover cropping, and crop diversification reinforce CA as a systems-based approach that integrates nutrient management with ecological sustainability and long-term resource conservation.

2.3. Integrated Nutrient Management (INM) for Balanced Soil Fertility

INM plays a pivotal role in maintaining balanced fertility under Conservation Agriculture. INM involves the combined use of organic nutrient sources such as farmyard manure, compost, green manures, and retained crop residues alongside carefully calibrated, site-specific applications of inorganic fertilizers. This integrated approach ensures the immediate availability of essential nutrients to crops while simultaneously improving soil physical, chemical, and biological properties over time. Organic inputs enhance soil organic matter content, stimulate microbial diversity, and support nutrient mineralization and immobilization processes that regulate nutrient supply. When integrated with mineral fertilizers, these organic amendments improve nutrient synchronization with crop demand, reduce nutrient losses, and enhance overall nutrient use efficiency. In CA systems, INM contributes to sustained soil fertility, improved nutrient buffering capacity, and long-term productivity while minimizing environmental risks associated with excessive fertilizer use.

2.4. Precision Nutrient Application Using Advanced Technologies

The adoption of precision nutrient management technologies is increasingly important for optimizing nutrient use under Conservation Agriculture (Sarkar and Sarkar, 2025e). Tools such as soil testing, geographic information systems (GIS), remote sensing, decision support systems, and variable-rate fertilizer application enable more accurate assessment of spatial and temporal nutrient variability within fields. These technologies facilitate the precise matching of nutrient inputs with crop requirements, reducing over-application and minimizing nutrient losses to the environment. Precision nutrient application enhances fertilizer use efficiency, lowers production costs, and mitigates adverse environmental impacts such as groundwater contamination and greenhouse gas emissions. In CA systems, where nutrient stratification and residue-mediated nutrient dynamics are common, precision tools are particularly valuable for ensuring that nutrients are applied at the right rate, time, and place to support optimal crop growth and soil health.

2.5. Nutrient Recycling through Strategic Residue Management

Strategic management of crop residues is a vital mechanism for nutrient recycling in Conservation Agriculture systems. Retaining residues on the soil surface serves as a continuous source of nutrients that are gradually released during decomposition, supporting sustained nutrient availability throughout the cropping cycle. Residues also enhance microbial activity, improve soil moisture retention, and protect against erosion, thereby creating favourable conditions for nutrient transformation and uptake. Over time, residue retention promotes the development of a self-reinforcing nutrient cycle, wherein nutrients are efficiently recycled within the soil-plant system rather than lost from the field. This practice reduces reliance on external nutrient inputs, enhances soil biological functioning, and contributes to the formation of a resilient, nutrient-rich agroecosystem. When combined with reduced tillage, diversified cropping, and integrated nutrient inputs, residue management strengthens the overall sustainability and productivity of Conservation Agriculture systems.

3. Nutrient Dynamics and Management Challenges in Conservation Agriculture Systems

Nutrient management under Conservation Agriculture (CA) represents a significant departure from conventional soil and crop nutrient management paradigms. The combined implementation of minimal soil disturbance, continuous soil cover, and diversified cropping systems fundamentally modifies soil physical, chemical, and biological processes. As a result, nutrient availability, spatial distribution, transformation pathways, and crop uptake behaviour in CA systems differ markedly from those observed under conventional tillage. These altered dynamics introduce a set of interconnected challenges that require system-oriented, knowledge-intensive, and adaptive nutrient management strategies.

3.1. Nutrient Stratification: A Persistent and Systemic Constraint

One of the most consistently reported challenges in CA systems is the vertical stratification of nutrients within the soil profile, particularly for relatively immobile nutrients such as phosphorus (P), potassium (K), and micronutrients like zinc (Zn). Under reduced or zero tillage conditions, the absence of soil mixing leads to the accumulation of applied fertilizers and decomposing crop residues in the upper soil layers. Field-based evidence from Southern Telangana indicates that conservation agriculture practices result in distinct stratification ratios, with P and Zn showing pronounced enrichment in surface horizons (Nthebere et al., 2025). While surface enrichment can enhance nutrient availability during favourable moisture conditions, it simultaneously restricts

nutrient access to deeper soil layers. This becomes particularly problematic during periods of moisture stress, when crop roots rely on subsoil moisture and nutrient reserves. In such situations, shallow nutrient concentration limits effective uptake, potentially leading to hidden hunger or yield penalties. Addressing nutrient stratification in CA systems therefore requires strategic nutrient placement, crop root system diversification, and improved synchronization between nutrient supply and root activity across soil depths.

3.2. Nitrogen Management Complexities under Reduced Disturbance

Nitrogen (N) management remains one of the most challenging aspects of CA-based nutrient management due to its high mobility and sensitivity to soil-climate interactions. Surface application of nitrogenous fertilizers, particularly urea, without soil incorporation substantially increases the risk of ammonia volatilization, especially under conditions of high temperature, alkaline soils, and limited rainfall following application. Globally, it is estimated that less than 50% of applied nitrogen is recovered by crops, underscoring the inefficiencies associated with conventional N management approaches.

In CA systems, improved soil structure and enhanced infiltration capacity although beneficial for water conservation can increase the potential for nitrate leaching beyond the root zone, particularly during high rainfall events. Simultaneously, the retention of crop residues with wide carbon-to-nitrogen (C: N) ratios promotes microbial immobilization of available nitrogen during early decomposition stages. This temporary immobilization often leads to early-season nitrogen deficiency, adversely affecting crop establishment, vigour, and initial biomass accumulation.

These interacting processes necessitate modified nitrogen management strategies under CA, including split fertilizer applications, the use of starter nitrogen at planting, deep placement techniques, and adoption of enhanced-efficiency fertilizers such as slow-release formulations and nitrification or urease inhibitors. Such approaches aim to improve nitrogen synchronization with crop demand while minimizing environmental losses.

3.3. Biological Regulation of Nutrient Cycling

Conservation Agriculture intensifies biological activity within the soil by promoting organic matter accumulation, improving habitat continuity, and enhancing soil structural stability. Elevated microbial biomass and diversity under CA systems play a central role in regulating nutrient transformations and long-term nutrient retention. However, increased biological regulation also alters the timing and rate of nutrient release, often slowing mineralization processes compared to conventionally tilled systems. Key microbial-mediated processes including mineralization-immobilization turnover, redox-driven nutrient transformations, and sorption-desorption reactions operate under distinct temporal and environmental controls in CA soils. While these processes enhance nutrient conservation and reduce losses over the long term, they can also result in asynchronous nutrient availability relative to peak crop demand. Consequently, nutrient supply may not always coincide with critical growth stages, necessitating management strategies that integrate biological timing, residue quality, and climatic conditions to optimize nutrient availability.

3.4. Microclimatic Modulation of Nutrient Dynamics

The maintenance of surface residues and reduced soil disturbance under CA creates a modified soil microclimate characterized by moderated temperature regimes and improved soil moisture retention. These changes generally favour root growth, microbial activity, and nutrient uptake efficiency. However, under certain conditions, enhanced soil moisture particularly in poorly drained or fine-textured soils can stimulate anaerobic processes such as denitrification, leading to gaseous nitrogen losses. Additionally, cooler soil temperatures under residue-covered surfaces may delay nutrient mineralization during early cropping stages, affecting nutrient availability for young seedlings. These microclimatic influences highlight the importance of optimizing nutrient application timing, fertilizer form, and placement to align with soil temperature and moisture dynamics unique to CA systems.

3.5. Contemporary Challenges in CA Nutrient Management

Despite its long-term agronomic and environmental benefits, the complexity of nutrient dynamics under CA remains a major barrier to widespread adoption. Nutrient stratification, nitrogen losses, biological immobilization, and microclimate-induced variability collectively increase the management intensity required for successful CA implementation. The conceptual framework presented in Fig. 1 illustrates the multidimensional nature of these constraints, emphasizing the interactions among soil processes, crop requirements, and environmental conditions.

A comprehensive understanding of nutrient behaviour in CA systems is therefore essential for developing context-specific, resilient nutrient management strategies. Such approaches must integrate soil biology, climate variability, cropping system diversity, and economic considerations to ensure sustained productivity and resource-use efficiency. Addressing these challenges is critical for enabling CA to fulfill its potential as a climate-resilient and economically viable pathway for sustainable agricultural intensification under conditions of increasing climatic and resource uncertainty.

Challenges in Nutrient Management in Conservation Agriculture

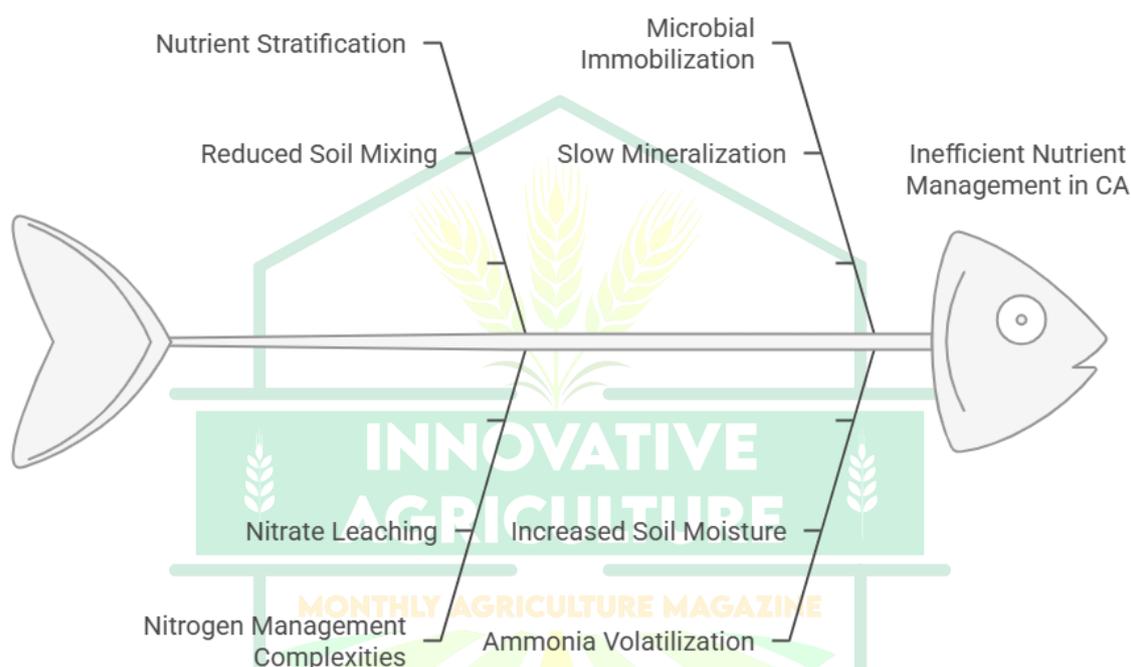


Fig 1: Fishbone Diagram of Challenges in CA Nutrient Management

4. Strategies to Overcome Nutrient Management Challenges in Conservation Agriculture

Conventional agriculture often relies on generalized or uniform nutrient management strategies, such as blanket fertilizer recommendations, without considering site-specific variability. In contrast, nutrient management under Conservation Agriculture (CA) demands a more holistic and knowledge-intensive approach. It requires an understanding of various interrelated factors including the existing soil fertility status, the nutrient uptake and removal patterns of different crops, crop-specific nutrient response, and the critical growth stages where nutrient demand is highest. Achieving effective and efficient nutrient use in CA systems therefore calls for an integrated and adaptive nutrient management framework that incorporates these elements. The following strategies (Fig. 2) provide effective solutions to overcome nutrient-related constraints in CA systems:

4.1. Site specific nutrient management

Site-Specific Nutrient Management (SSNM) is a precision agriculture approach that optimizes nutrient use efficiency by tailoring fertilizer applications to the spatial and temporal variability of soil fertility and crop nutrient demand. Under Conservation Agriculture (CA) systems, where reduced tillage, residue retention, and diversified cropping significantly modify nutrient dynamics, SSNM becomes an essential strategy to address the challenges of nutrient stratification, delayed mineralization, and potential losses. Unlike blanket fertilizer recommendations, SSNM recognizes that fields are heterogeneous and that nutrient needs can vary across seasons, soil types, and management practices. Therefore, SSNM emphasizes applying the right amount of nutrients, at the right time, in

the right place, and from the right source the core philosophy behind the 4R Nutrient Stewardship (Fig.3). In CA systems, SSNM is particularly valuable for managing nitrogen (N), phosphorus (P), and potassium (K), which are highly influenced by residue cover, minimal disturbance, and microbial activity. Tools such as the Leaf Colour Chart (LCC), SPAD chlorophyll meter, GreenSeeker sensor, and decision-support systems like Nutrient Expert enhance the effectiveness of SSNM by enabling real-time monitoring and informed nutrient application. The following are major tools and techniques for implementing SSNM under CA systems.

Strategies for Nutrient Management in Conservation Agriculture



Fig 2. Strategies to Overcome Nutrient Management Challenges in Conservation Agriculture

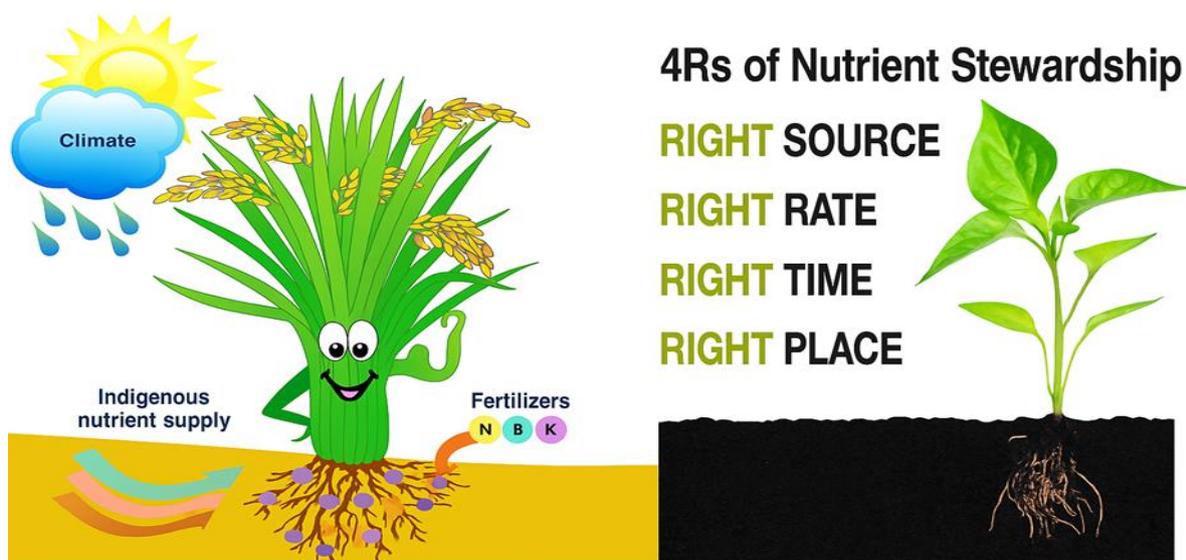


Fig. 3. 4Rs of Nutrient stewardship

4.2. Precision Nutrient Management in Conservation Agriculture (CA) Systems

Precision nutrient management is a critical component of Conservation Agriculture (CA), as the reduced soil disturbance and residue-retained environment fundamentally alter nutrient behaviour, availability, and loss pathways. By integrating residue management, advanced nitrogen loss mitigation strategies, enhanced-efficiency fertilizers, and farmer-centered extension mechanisms, precision nutrient management aims to optimize nutrient use efficiency (NUE), improve crop productivity, and minimize environmental externalities. The following sub-sections elaborate on the key dimensions of precision nutrient management under CA systems.

4.2.1. Crop Residue Management

Retention of crop residues on the soil surface is a defining feature of CA systems and plays a pivotal role in regulating nutrient dynamics (Sarkar and Sarkar, 2025c). As residues gradually decompose, they contribute organic matter to the soil, improving its physical, chemical, and biological properties. The quantity and quality of soil organic matter (SOM) derived from residue decomposition directly influence essential soil functions, including enhanced soil aggregation, improved moisture retention, increased water infiltration, and greater nutrient-holding capacity.

Residue-derived organic matter also serves as a substrate for soil microorganisms, stimulating biological activity and facilitating nutrient transformation processes such as mineralization and immobilization. Over time, these processes contribute to improved nutrient availability and buffering capacity, enabling soils to supply nutrients more consistently across cropping cycles. Additionally, surface residues reduce soil temperature fluctuations and protect against erosion, creating a favourable microenvironment for root growth and nutrient uptake. Effective residue management, therefore, is integral to sustaining soil health, improving nutrient cycling, and enhancing crop resilience under CA systems.

4.2.2. Nitrogen Loss Management

Nitrogen management under CA systems is particularly challenging due to surface fertilizer application and limited soil incorporation. Nitrogen losses commonly occur through three primary pathways—denitrification, nitrate leaching, and ammonia volatilization—each of which is influenced by soil moisture, temperature, residue cover, and fertilizer form. These losses not only diminish nitrogen use efficiency but also contribute to environmental concerns such as groundwater contamination and greenhouse gas emissions.

To mitigate nitrogen losses and enhance NUE in CA systems, several precision-oriented strategies are recommended. Splitting nitrogen applications across key crop growth stages helps synchronize nitrogen supply with crop demand, reducing the risk of excess nitrogen at any given time. Banded application of liquid fertilizers, such as urea-ammonium nitrate (UAN), is widely practiced in no-till systems, as it concentrates nutrients in localized zones and limits surface exposure.

Sub-surface placement of nitrogen fertilizers beneath crop residues further reduces volatilization losses while improving nutrient availability in the root zone. Increasing the basal nitrogen dose at planting can help overcome early-season nitrogen deficiencies associated with residue-induced immobilization and slow mineralization under CA conditions. Strategic placement of fertilizers near active root zones enhances nutrient access and uptake efficiency, particularly during critical growth stages.

4.3.3. Use of Enhanced-Efficiency Fertilizers (EEFs)

Enhanced-efficiency fertilizers represent an important advancement in precision nutrient management for CA systems. These fertilizers, which include slow-release, controlled-release, and stabilized formulations, are designed to synchronize nutrient availability with crop uptake patterns. By regulating nutrient release rates or inhibiting microbial processes responsible for nitrogen loss, EEFs significantly reduce leaching, volatilization, and denitrification losses. The use of EEFs improves nutrient use efficiency (NUE), enhances crop productivity, and reduces the environmental footprint of fertilizer use.

4.3.4. Farmer Capacity Building and Extension Services

The successful implementation of precision nutrient management in CA systems ultimately depends on farmer awareness, knowledge, and adaptive capacity. Capacity-building initiatives such as targeted training programs, on-farm demonstrations, and participatory learning platforms play a crucial role in translating scientific recommendations into practical field-level actions. Modern extension approaches, including digital advisory

tools, mobile-based nutrient decision support systems, and remote sensing-based recommendations, can help farmers better understand nutrient dynamics and implement precision practices tailored to their specific agro-ecological conditions. Strengthening farmer-research-extension linkages ensures continuous knowledge exchange and feedback, enabling refinement of nutrient management strategies over time. Enhanced farmer capacity not only accelerates CA adoption but also ensures the long-term sustainability and effectiveness of precision nutrient management interventions.

5. Conclusion and way forward

Conservation Agriculture (CA) provides a robust framework for sustainable agricultural intensification by harmonizing productivity enhancement with natural resource conservation. Its core principles-minimal soil disturbance, permanent soil cover, and diversified cropping systems promote improved soil health, efficient nutrient cycling, and enhanced ecosystem resilience. However, these practices also alter nutrient dynamics, leading to challenges such as nutrient stratification, microbial immobilization, and increased risks of nitrogen losses through volatilization and leaching. Addressing these challenges requires adaptive, site-specific precision nutrient management that aligns nutrient supply with crop demand, soil characteristics, and climatic variability. Decision-support tools such as the Leaf Colour Chart, SPAD meter, GreenSeeker, and Nutrient Expert play a vital role in improving nutrient use efficiency while minimizing losses. The integration of 4R Nutrient Stewardship-right source, rate, time, and place is fundamental to the long-term sustainability of CA systems. Future progress will depend on strengthened farmer capacity building, customized nutrient advisories, expanded use of digital decision-support technologies, and supportive policy frameworks. Together, these efforts can enhance productivity, protect environmental resources, and ensure long-term food security for smallholder-dominated agroecosystems.

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MORINGA: The Tree of Health and Wealth

Tusar Ranjan Sahoo, A. Bhaskaran & Shaik N. Meera

ICAR-ATARI Zone-X, Hyderabad-500059

Introduction:

Moringa *oleifera*, known as the "miracle tree", grows well in tropical and subtropical regions and is believed to have originated in **India, Pakistan, Bangladesh, and Afghanistan**. It's a fast-growing tropical deciduous plant of the Moringaceae family, has tuberous roots, light green leaves, abundant flowers, and pendulous fruits with seeds. It belongs to a family of 13 species, but *M. oleifera* is the most well-known for its **nutritional, medicinal, and agricultural uses**. It grows well in dry areas and can survive in different types of soil, especially **well-drained sandy or loamy soil** with a pH between 5 and 9. This plant is often called the "Miracle Tree" because almost every part like leaves, roots, seeds, bark can be used for food, medicine, or household products. This drought-tolerant tree is one of the most affordable sources of essential nutrients and plays a crucial role in combating malnutrition, particularly among infants and lactating mothers. Moringa is a fast-growing, drought-tolerant plant rich in essential nutrients and widely used for food, medicine, and agriculture, especially in tropical regions. Due to its low cost, high nutritional value, and multi-purpose uses, it plays a vital role in combating malnutrition and supporting food security and sustainable livelihoods.



Nutritional Composition of Moringa oleifera (Drumstick Tree):

1. Moringa Leaves

- **Fresh leaves** are rich in protein, vitamins (especially A and C), calcium, iron, and antioxidants.
- **Dried leaves and leaf powder** are more concentrated, offering higher amounts of protein (up to 30%), calcium (over 2000 mg), and iron (up to 28 mg).
- Leaves provide **all essential amino acids** and contain healthy unsaturated fatty acids like omega-3 and omega-6.
- The calorific value is low, making moringa leaves suitable for weight-conscious diets.
- They also contain **important phytochemicals** (e.g., flavonoids, phenolics, isothiocyanates) that support immune and anti-cancer functions.

2. Moringa Pods (Drumsticks)

- Commonly used as a vegetable.
- Rich in **dietary fiber**, helping in digestion and preventing colon-related diseases.
- Immature pods contain up to **46% fiber** and **20% protein**.
- High in **vitamin C**, moderate in potassium and phosphorus.
- Contains beneficial fatty acids and minor amounts of essential minerals.

3. Moringa Seeds

- Seeds are a **rich source of edible oil** (up to 40%), primarily made of **oleic acid** (a heart-healthy monounsaturated fat).

- High in **protein (up to 36%)** and contain good amounts of calcium, magnesium, and iron.
- Also used for **water purification** due to natural coagulant properties.
- Seeds contain **antioxidants** and natural compounds with potential medicinal uses.

4. Moringa Flowers

- Less commonly consumed, but rich in **essential amino acids, healthy fatty acids, and antioxidants**.
- Contain linoleic, linolenic, and oleic acids—important for heart and brain health.
- Flowers have potential for use in **functional foods**, herbal teas, and traditional remedies.

Nutritional Benefits

- **Leaves** are the most nutrient-dense part, especially rich in **protein, calcium, iron, and vitamins A, C, and E**. **Pods are excellent for fibre and vitamin C, ideal for digestive health**, while seeds offer healthy fats, protein, and are useful for water purification. **Flowers** offer a balanced mix of **amino acids and plant-based fats**, with antioxidant benefits. **Low in Calories**: Especially leaves and pods, beneficial for weight control.
- **Phytochemical-Rich**: Contains antioxidants, flavonoids, tannins, alkaloids, and anti-cancer agents like glucosinolates and isothiocyanates.
- **Safe Anti-nutrients**: Small amounts of phytates and oxalates are present but are not harmful in normal consumption; drying or cooking further reduces them.

Health Benefits of Moringa oleifera:

Moringa oleifera, known as the "Miracle Tree", is rich in antioxidants, vitamins, minerals, and medicinal compounds. It supports prevention and management of many diseases.

1. Diabetes Management

- Helps control both Type 1 and Type 2 diabetes.
- Lowers blood sugar and improves insulin activity.
- Protects pancreatic cells and prevents diabetic complications.

2. Cancer Prevention

- Contains isothiocyanates and niazimicin with anti-cancer properties.
- Slows tumor growth and promotes natural death of harmful cells.
- Protects normal cells while targeting cancer cells.

3. Other Health Benefits

Condition	Benefit
Brain health	Improves memory and protects against stroke and dementia
Kidney health	Reduces urea/creatinine; prevents kidney damage
Stomach ulcers	Reduces acidity and promotes healing
Arthritis	Relieves joint pain and inflammation
Infections	Fights bacteria and fungi; natural antibiotic
Immunity (HIV/AIDS)	May help boost immune strength (research ongoing)

4. Medicinal Uses by Plant Part

Plant Part	Uses
Leaves	Anti-diabetic, anti-cancer, antimicrobial, antioxidant, brain-protective
Seeds	Treats arthritis, infections, epilepsy, and inflammation
Roots	Ulcer relief, heart stimulant, muscle relaxant
Flowers	Supports cholesterol control, joint and urinary health
Pods	Aids digestion, liver function, and joint pain relief



Value-Added Products from *Moringa oleifera*:

Moringa oleifera is used to develop a wide range of nutritional, medicinal, and commercial products from its different parts—leaves, seeds, pods, flowers, and roots.

1. From Moringa Leaves

Product Type	Description/Use
Leaf Powder	Used as a dietary supplement for vitamins and protein
Herbal Tea	Made from dried leaves; rich in antioxidants
Capsules/Tablets	Health supplements for boosting immunity and energy
Moringa Juice	Nutrient-rich drink with medicinal benefits
Animal Feed	High-protein additive for livestock and poultry

2. From Moringa Seeds

Product Type	Description/Use
Moringa Oil (Ben Oil)	Edible oil rich in oleic acid; used in cooking and cosmetics
Water Purifier	Crushed seeds used as a natural coagulant in water treatment
Seed Cake	Fertilizer and animal feed after oil extraction

3. From Moringa Pods

Product Type	Description/Use
Vegetable Products	Used in soups, curries, pickles, and frozen mixes
Ready-to-Cook Mixes	Dried pod-based food products for quick preparation

4. From Moringa Flowers

Product Type	Description/Use
Edible Delicacies	Used in traditional dishes and herbal recipes
Medicinal Tinctures	Used for anti-inflammatory and urinary health

5. From Moringa Roots & Bark

Product Type	Description/Use
Herbal Extracts	Used in traditional medicine for digestive and cardiac benefits

6. Cosmetic and Personal Care Products

Product Type	Description/Use
Face Creams & Lotions	For skin hydration and antioxidant protection
Hair Oils & Shampoos	Promote hair growth and scalp health
Soaps	Herbal cleansing with antibacterial properties

Industrial Uses of *Moringa oleifera*:

Moringa oleifera is not only valuable for nutrition and medicine but also plays a significant role in various industries due to its unique bioactive compounds and functional properties.

1. Pharmaceutical Industry

- **Herbal Medicines:** Leaves, seeds, and roots are used to make capsules, tablets, and syrups.
- **Natural Antioxidants:** Extracts are used in formulations for anti-aging, immunity, and diabetes control.
- **Cancer Research:** Compounds like niazimicin and isothiocyanates are studied for anti-cancer potential.

2. Nutraceutical Industry

- **Dietary Supplements:** Leaf powder and extract are used in protein powders, health drinks, and energy bars.
- **Functional Foods:** Fortified flours, soups, snacks, and beverages enriched with moringa.

3. Cosmetic & Personal Care Industry

- **Skincare Products:** Moringa oil is used in creams, lotions, soaps, and anti-aging serums.
- **Hair Care:** Shampoos, conditioners, and oils contain moringa for scalp health and hair strengthening.
- **Soap Manufacturing:** Due to its antimicrobial and moisturizing properties.

4. Food Processing Industry

- **Natural Preservative:** Leaf and seed extracts are used for their antioxidant and antimicrobial effects.
- **Flavor Enhancer:** Dried leaf powder adds nutritional and sensory value to food products.
- **Edible Oil:** Moringa seed oil (Ben oil) is stable, odorless, and used in high-quality cooking oil blends.

5. Water Purification Industry

- **Natural Coagulant:** Crushed moringa seeds are used to clarify turbid water by settling impurities.
- **Eco-Friendly Alternative:** Offers a biodegradable, low-cost replacement for alum and other chemicals.

6. Agriculture and Animal Feed

- **Green Manure and Biofertilizer:** Seed cake (after oil extraction) is rich in nutrients.
- **Plant Growth Promoter:** Moringa leaf extract acts as a natural biostimulant.
- **Animal Feed Supplement:** High-protein leaf and pod meals enhance livestock health and productivity.

7. Textile and Dyeing Industry

- **Natural Dye Source:** Bark and roots are used in traditional dyeing.
- **Fabric Finishing:** Moringa seed extract may be used for antibacterial finishing in fabrics.

8. Biofuel and Lubricant Industry

- **Biofuel Potential:** Moringa seed oil can be converted into biodiesel.
- **Industrial Lubricants:** Due to its high oleic acid content, moringa oil can be used in machines and precision instruments.

Moringa in Animal and Fish Sector:

Moringa oleifera is increasingly used in livestock and aquaculture due to its high nutritional value, medicinal properties, and growth-promoting effects.

1. Animal Feed Supplement

As an animal feed supplement, moringa leaves and pods are excellent sources of protein, vitamins A, B, and C, as well as calcium and iron. Their inclusion in the diets of cattle, poultry, goats, and pigs has been shown to improve weight gain, increase milk yield, and enhance egg production. Moringa also acts as a natural dewormer and boosts immunity in livestock. Dairy cows fed moringa leaf meal show higher milk yield and butterfat, while poultry produce more and better-quality eggs.

2. Fodder and Silage

Moringa leaves also serve as a valuable source of fodder and silage, either in fresh form or as preserved feed. Their high digestibility and palatability make them ideal for ruminants such as cows, goats, and sheep. When combined with conventional fodder crops, moringa enhances the overall nutritional content of livestock diets.

3. Moringa Seed Cake

Furthermore, the **seed cake**, which remains after oil extraction, is rich in protein and can be used as a supplemental livestock feed. This by-product also serves as an effective **natural fertilizer**, adding value to both animal husbandry and crop cultivation systems.

4. Moringa in Aquaculture (Fish Farming)

In aquaculture, moringa leaf meal is added to fish and shrimp feed to help them grow faster, survive better, and use feed more efficiently. It also improves their immunity and disease resistance, reducing the need for antibiotics, and works well for fish like tilapia, catla, rohu, and common carp.

5. Health and Medicinal Benefits

It acts as a natural antibiotic and antioxidant, helping to lower stress levels and disease incidence. Bioactive compounds in moringa support gut health, reduce inflammation, and enhance metabolic functions, contributing to the overall well-being of farm animals and aquatic species.

6. Environmental Benefits

Moreover, *Moringa oleifera* offers environmental benefits in livestock systems by reducing methane emissions when used as a ruminant feed additive. Its ability to grow on dry, degraded lands makes it a sustainable option for year-round fodder production in climate-stressed regions.

Agricultural Uses of *Moringa oleifera*

Moringa oleifera has multiple applications in agriculture due to its antifungal, growth-promoting, and stress-reducing properties:

Natural Fungicide:

- Extracts from Moringa leaves, roots, seed oil, and pods showed antifungal activity against pathogens like *Fusarium*, *Alternaria*, *Rhizoctonia*, *Sclerotium*, and *Macrophomina*, reducing spore germination and growth.
- Moringa seed oil and leaf extract effectively controlled early blight (*Alternaria solani*) in potatoes and improved tuber yield.

Crop Growth Enhancer:

- **Apples:** Foliar spray (6%) improved growth, fruit set, yield, and resistance to climate stress in ‘Anna’ apples.
- **Plums:** Spraying enhanced yield, fruit weight, quality, and antioxidant levels in “Hollywood” plums.
- **Lettuce:** Seed drenching (5%) and foliar spray (10%) improved growth under salt stress, increased chlorophyll and nutrient levels (N, P, K), and reduced nitrate content.
- **Potatoes and lettuce:** Moringa leaf extract and seed cake improve plant growth, increase chlorophyll, and keep plants healthier.

Soil and Microbial Health:

- Moringa application increased soil microbial activity, leaf nutrient content, fruit quality, and yield across different crops.

Soil Amendment:

- Mixing Moringa seed cake with vermicompost (50:50) improved apple tree growth and productivity.

Moringa as a Climate-Resilient Crop:

Moringa (Moringa oleifera) is recognized as a climate-resilient crop due to its ability to thrive in challenging environments, making it ideal for sustainable farming in drought-prone and resource-limited regions.

1. Drought Tolerant

Moringa oleifera is a climate-resilient crop well-suited for drought-prone and resource-poor regions due to its ability to thrive in harsh conditions. Once established, it requires minimal water, survives long dry spells, and can grow in areas receiving as little as 250–300 mm of annual rainfall.

2. Heat Resistant

Moringa is also **highly heat resistant**, growing well in temperatures ranging from 25°C to 48°C while continuing to produce leaves and pods even under intense heat and sunlight. Its adaptability extends to poor soil conditions as well.

3. Grows in Poor Soils

The plant can grow in marginal, sandy, or rocky soils with low fertility and is tolerant of both slightly acidic and slightly alkaline soils. It can produce well with little or no fertilizer input.

4. Fast Growing and Perennial

As a fast-growing and perennial tree, moringa can reach heights of 3 to 5 meters in its first year alone. It allows for multiple harvests of leaves and pods throughout the year and can be coppiced and regenerated easily, ensuring year-round availability of food and fodder.

5. Low Input, High Output

It is a low-input, high-output crop, requiring minimal agrochemical use and is easy to manage, especially for small and marginal farmers. Its compatibility with agroforestry and mixed cropping systems makes it even more valuable in sustainable agriculture.

6. Soil and Environmental Benefits

Moringa also offers important soil and environmental benefits. Its deep root system helps prevent soil erosion and improves soil structure. Additionally, it contributes to carbon sequestration, playing a role in mitigating climate change. The tree is frequently used in reforestation and wasteland reclamation efforts.

7. Livelihood Support under Climate Stress

Most importantly, moringa serves as a source of livelihood support under climate stress. It provides nutritious food, animal fodder, and a potential source of income during periods of drought, acting as a reliable safety-net crop in the face of increasing climate uncertainties.

Conclusion

The Moringa tree, renowned globally as the "miracle tree", represents nature's ideal combination of health, wealth, and sustainability. Each part of the tree possesses extraordinary value—its leaves and pods are rich in nutraceuticals and food, while its seeds and extracts serve various purposes in agriculture, veterinary medicine, and fisheries. Beyond being merely a crop, Moringa is a climate-smart option for farmers. It protects soil and water, enhances ecosystems, and simultaneously increases farm income through fresh produce and value-added products that create opportunities for new businesses and livelihoods. So, it is a **natural gift of resilience and abundance**, a true companion for a healthier life, stronger farms, and a greener Earth.

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When Banned Chemicals Find New Homes: PFAS Production and Environmental Risk in Maharashtra



Dr. Ramesh N. Dhawale

Assistant Professor

V. D. College of Agril. Biotechnology, Latur,

Vasantrao Naik Marathwada Agricultural University, Parbhani, Maharashtra, India

Per- and polyfluoroalkyl substances (PFAS) are a large group of **synthetic fluorinated chemicals** produced since the mid-20th century. Their **carbon-fluorine bonds** are among the strongest in chemistry, making these compounds highly resistant to degradation in the environment earning them the nickname “*forever chemicals.*” PFAS include legacy compounds such as **PFOS** (perfluorooctane sulfonic acid) and **PFOA** (perfluorooctanoic acid), as well as thousands of emerging derivatives designed as alternatives to phased-out chemicals. Globally, PFAS have been used in **non-stick cookware**, stain- and water-repellent fabrics, grease-proof food packaging, firefighting foams, and in a variety of industrial processes because of their **water/oil repellency and heat stability**. However, these same properties drive their environmental persistence and capacity to **bioaccumulate and biomagnify** through ecosystems and human food chains.

The PFAS Problem in India: Growing Evidence of Widespread Contamination

1. Environmental Distribution

Research on PFAS in India remains limited compared to Western nations, yet emerging data show that these contaminants are **already ubiquitous across environmental matrices**:

- A **nationwide road dust study** found 21 PFAS compounds in samples collected from 12 states and a union territory, with concentrations highest in **urban areas** and correlated with population and vehicular activity. PFOS was the dominant compound detected. This suggests urbanization and traffic may contribute to PFAS presence in dust potentially exposing both children and adults.
- Groundwater contamination has been documented in the **Kamrup region of Assam**, where 12 different PFAS were detected in drinking water sources. Risk assessments indicated that certain PFAS, especially **PFBS**, pose higher relative hazard to **children and adolescents**. The study also revealed cellular level disruptions in lipid metabolism linked to PFAS exposure.
- In **Chennai**, both surface and groundwater samples showed significant levels of PFAS (e.g., PFOA and PFBS), with concentrations increasing after conventional water treatment, indicating typical treatment plants are **ineffective at removing these contaminants**. Industrial emissions and untreated wastewater appear to be significant sources.
- Coastal regions along the east coast of India (including Tamil Nadu and West Bengal) showed measurable levels of PFAS in rivers and adjacent coastal waters, with PFOA levels often exceeding PFOS - a worrying trend for aquatic ecosystems.

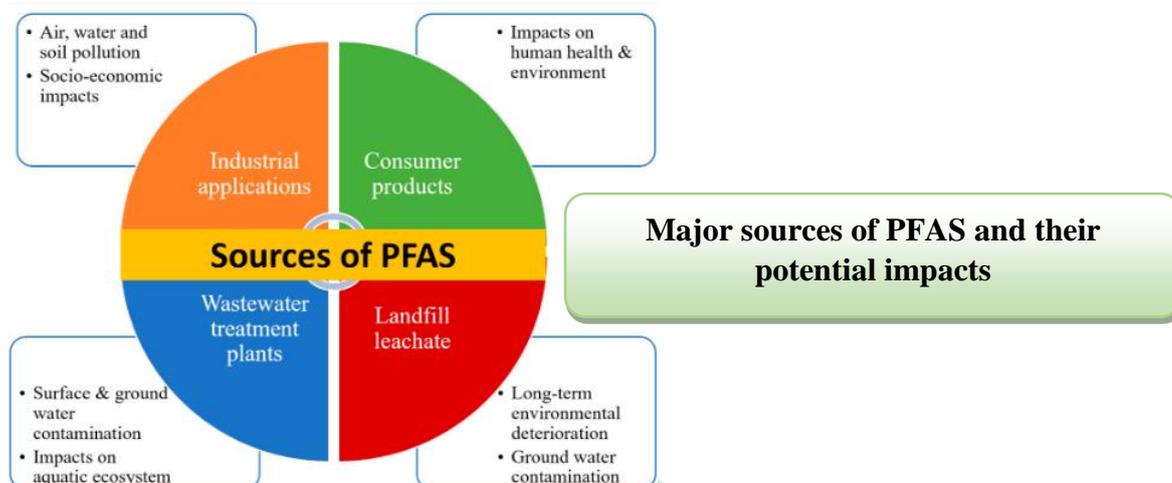
2. Human Exposure Indicators

Limited biomonitoring efforts show that PFAS exposure is not confined to the environment but reaches humans directly:

- A **preliminary nationwide hair-analysis survey** detected PFAS (including PFHxS, PFOS, and PFOA) in human hair samples across 14 Indian cities, suggesting widespread exposure across regions and demographic groups.
- These findings underscore that *PFAS are not isolated to industrial hotspots* but are present in both environmental media and human tissues - which raises concerns about chronic exposure effects.

Sources and Pathways of PFAS Pollution

PFAS enter the Indian environment from multiple and often interconnected sources:



1. Industrial Activities

PFAS are used in textile waterproofing, leather tanning, metal plating, paper coating, and plastics. Effluents from industries may discharge PFAS directly into **surface water, soil, and sediments**. Unregulated industrial discharge remains a critical gap in environmental protection.

Recent investigative reporting indicates that **PFAS production capacity has expanded in India** through acquisition of production assets from overseas firms. For example, machinery from a facility once responsible for one of Italy's worst PFAS water contamination scandals has been relocated to Lote, Maharashtra, causing environmental justice concerns over a potential new pollution source amid India's less stringent regulation.

2. Wastewater and Landfills

Municipal wastewater treatment plants in India typically **do not remove PFAS** effectively. As a result, treated wastewater - along with biosolids - becomes a pathway for these chemicals into rivers, soils, and coastal regions. Improperly managed landfills and open dumpsites also leach PFAS into groundwater and soils. This is crucial because many Indian towns and cities still rely heavily on unlined or poorly maintained dumping sites.

3. Urban Sources and Consumer Products

Everyday products like **food packaging, non-stick cookware, cosmetics, and textiles** contribute to PFAS loads. PFAS can enter waste streams when products are discarded or incinerated, eventually contaminating **air, water, and dust**- such as the road dust findings from Indian cities.

Health and Ecological Impacts:

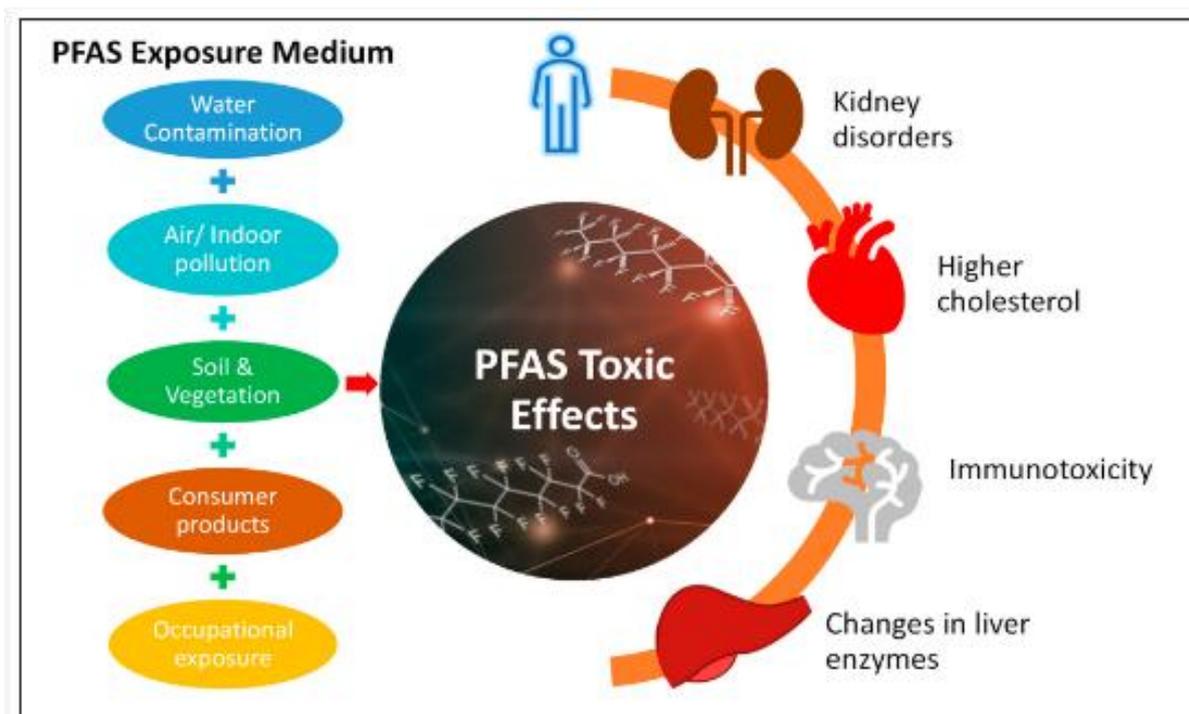
1. Human Health Concerns

PFAS are associated with a wide range of adverse health outcomes:

- PFAS exposure has been linked to **cancer, liver damage, thyroid disease, immune suppression, and developmental issues** in children, among other effects.
- New international studies suggest that PFAS exposure may correlate with dramatically increased **infant mortality rates**, highlighting the severe potential risk for vulnerable populations even at low exposure levels.
- Children are often more susceptible, particularly via environmental exposure pathways like hand-to-mouth contact with contaminated dust and soil.

2. Ecological Effects

PFAS in aquatic systems - as seen in coastal regions and river basins - may accumulate in **fish and shellfish**, posing long-term risks to wildlife and people dependent on these resources for food. Their persistence means ecosystems remain contaminated long after the initial release.



Overview of PFAS exposure media and toxic effects to humans

Regulatory Landscape in India – Gaps and Challenges

The regulatory response in India has lagged behind scientific evidence and global trends:

- India is a signatory to the **Stockholm Convention on Persistent Organic Pollutants (POPs)**, which includes some PFAS derivatives like PFOS for restriction. However, India has **not fully adopted all PFAS-related amendments or comprehensive domestic regulations** for emerging PFAS compounds.
- Unlike the United States and the European Union - where enforceable limits for PFAS in drinking water and broader chemical classes are being implemented - India *does not yet have PFAS-specific standards for drinking water, surface water, soil or air*. Regulatory frameworks such as the Water Act and Environment (Protection) Act allow for hazardous chemical regulation but **lack numeric PFAS criteria at this time**.
- In practice, industrial monitoring for PFAS is inconsistent, and enforcement is weak due to limited testing capacity, budget constraints, and inadequate awareness.

Remediation and Management – Scientific and Policy Solutions

1. Advanced Monitoring and Research

India needs a **nationwide monitoring network** for PFAS in water, soil, air, and biota to map contamination patterns. Emerging analytical tools - including ultra-sensitive sensors developed in Indian research labs - could support rapid and cost-effective detection. Further epidemiological and exposure studies are also needed to correlate environmental levels with health outcomes across populations.

2. Technological Remediation

Conventional water treatment plants are ineffective against PFAS. Advanced solutions include **granular activated carbon (GAC), reverse osmosis (RO), ion-exchange resins, and emerging photochemical or nanotechnology-based methods** (e.g., sunlight-driven degradation techniques being developed in Indian institutions).

3. Regulatory and Policy Actions

Adopting PFAS-specific standards for **drinking water and effluent discharge limits**, aligned with global best practices, will be critical. India could also restrict or phase out non-essential PFAS uses, parallel to actions taken in the EU and U.S. Policymakers may consider a **precautionary approach** that treats PFAS as a class, given

evidence of harm - rather than regulating individual compounds piecemeal. Public transparency, polluter-pays principles, and rigorous enforcement will form the backbone of effective regulation.

Public Awareness and Individual Actions

While regulatory frameworks evolve, **community awareness and individual actions** can mitigate exposure:

- Use **water filtration systems** that are effective for PFAS (e.g., RO units certified for PFAS removal).
- Minimize use of **non-stick cookware and PFAS-treated textiles** where feasible.
- Support local monitoring initiatives and demand transparent industrial discharge reporting.

Revised India–France Double Tax Avoidance Treaty (DTAA)

India and France have **finalized an updated version of their bilateral tax treaty**, originally signed in **1992**. The revision is designed to **modernize the treaty**, align it with contemporary tax-transparency standards, and rebalance taxing rights between the two countries.

Key elements of the updated treaty include:

- **Reduced dividend tax:** French companies holding more than 10 % equity in Indian firms will pay a reduced **5 % tax on dividends** instead of the earlier rate. For minority shareholders (below 10 % stake), the dividend tax will increase to **15 %** from 10 %.
- **Expanded capital gains taxation:** India will gain **full source-based taxation rights** on capital gains arising from share sales by French investors, removing the previous 10 % ownership threshold.
- **End of the MFN clause:** The treaty will remove France’s **“most favoured nation” (MFN)** status, which previously could allow France to claim benefits from India’s tax deals with other OECD countries.
- **Narrowed technical services tax:** Tax on technical services will apply **only when technical know-how is transferred**, excluding routine services like consultancy, market research, or design support.

The revised treaty is pending approval by India’s cabinet and is **expected to be signed soon, strengthening economic cooperation and investor certainty between the two nations**. This DTAA revision is currently the most significant treaty development between India and France as of late 2025, reflecting evolving economic relations. If you want, I can also summarize **security or strategic cooperation agreements** between the two countries.

Laxmi Organic Industries PFAS Facility - Lote Parshuram, Ratnagiri (Maharashtra):

- A chemical plant in **Lote Parshuram MIDC (Ratnagiri district), Maharashtra** - part of an industrial area managed by the Maharashtra Industrial Development Corporation - is **now operational producing PFAS and related fluorochemicals**.

The machinery, patents, and production processes at this facility were acquired by **Laxmi Organic Industries Ltd. (through its subsidiary Viva Lifesciences)** from the now-defunct **Miteni S.p.A.** plant in **Vicenza, Italy**. That Italian factory had been shut down following one of Europe’s most severe PFAS contamination scandals, where emissions polluted drinking water and exposed hundreds of thousands of people to these “forever chemicals.” Although the *factory structure is new*, much of the **equipment and chemical process know-how previously used in Italy** was transported to India and reassembled. It **started producing PFAS chemicals in early 2025**. The products made here - PFAS used in pesticides, dyes, cosmetics, pharmaceuticals, and other industrial applications - are controversial because PFAS compounds are environmentally persistent and often linked to serious health risks.

Environmental & Regulatory Concerns

- Local environmental advocates and independent researchers have raised concerns about the **potential for pollution** since PFAS compounds **do not break down in nature** and accumulate in soil and water.
- Critics argue that India currently lacks **robust PFAS-specific regulation**, and that such facilities could pose risks to local ecosystems and communities if not strictly monitored.

Why the PFAS Factory Was Shut Down (Miteni, Vicenza, Italy)

The former fluorochemical plant at **Trissino, near Vicenza in northern Italy**- operated for decades by **Miteni S.p.A.** and predecessor companies - was effectively closed after a *major environmental contamination scandal* involving PFAS “forever chemicals.” The shutdown was tied to **severe groundwater and drinking water contamination** affecting hundreds of thousands of people.

1. Long-Term PFAS Pollution of Water Supplies

Industrial production at the Miteni plant released wastewater containing high levels of **per- and polyfluoroalkyl substances (PFAS)** into local waterways and soils beginning in the 1960s. PFAS are highly persistent chemicals that do not break down easily and accumulate in the environment. In **2013**, regional environmental monitoring detected *widespread contamination* of groundwater, surface water, and drinking water supplies across the provinces of **Vicenza, Verona and Padova** - collectively home to about 350,000 residents. Investigators concluded that this contamination originated from PFAS discharges from the factory's processes over many years.

2. Corporate Knowledge and Concealment

One of the most critical findings in the **criminal prosecution** was that the company and some of its executives were *aware* of the contamination but **failed to notify authorities or take adequate measures to stop it**:

- Court documents state that Miteni *knew about the pollution* and nevertheless continued operations while **ignoring the environmental and public health implications**.
- This failure to disclose or mitigate the pollution was a central issue in the legal judgments.

3. Criminal Convictions for Environmental Crimes

In **June 2025**, the *Court of Assizes of Vicenza* handed down one of the largest environmental judicial rulings in Europe related to PFAS:

- **11 former managers and executives** of Miteni and its associated companies were convicted of **intentional water poisoning, environmental disaster, and related crimes**, receiving a **combined 141 years of prison sentences**.
- The court also imposed **fines totaling more than €57 million** and ordered compensation to governments and affected communities.

4. Bankruptcy and Plant Closure

By **2018**, the Miteni company had declared *bankruptcy* amid rising legal, financial, and regulatory pressures. The plant ceased operations as part of that process. After closure, much of its equipment and patents were *sold at auction* - later purchased by an Indian company and reassembled in Maharashtra, India - a move that has drawn controversy due to the very history that led to the Italian shutdown.

The factory was effectively banned/closed because:

1. It caused **widespread contamination** of groundwater and drinking water with persistent PFAS chemicals.
2. Evidence showed the company **knew about the contamination but did not act**, leading to criminal liability.
3. The legal process concluded with **criminal convictions and financial penalties**, and the company went bankrupt soon after, ending operations at that site.

Conclusion – PFAS Pollution Is an Urgent Emerging Issue in India

PFAS contamination in India - though still under-studied compared to other pollutants like particulate matter or lead - is an **emerging and systemic environmental challenge**. Scientific studies show that PFAS are already present in road dust, groundwater, surface waters, coastal ecosystems, and human tissues. The **persistence, bioaccumulation potential, and health risks** of PFAS call for immediate attention from scientists, policymakers, industry, and civil society. Without **comprehensive monitoring, regulation, and remediation**, PFAS pollution may continue to grow invisibly, posing long-term risks to Indian communities and ecosystems.

Peer-Reviewed Scientific Studies

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2. **Yamazaki, E., Lalwani, D., Ruan, Y., Tani, S., Hanari, N. J. I. Kumar, P. K. S. Lam, & Yamashita, N. (2023).** *Nationwide distribution of per- and polyfluoroalkyl substances (PFAS) in road dust from India.* **Science of the Total Environment**, 892, 164538 - First nationwide survey of PFAS in road dust across Indian states, including urban vs rural differences.

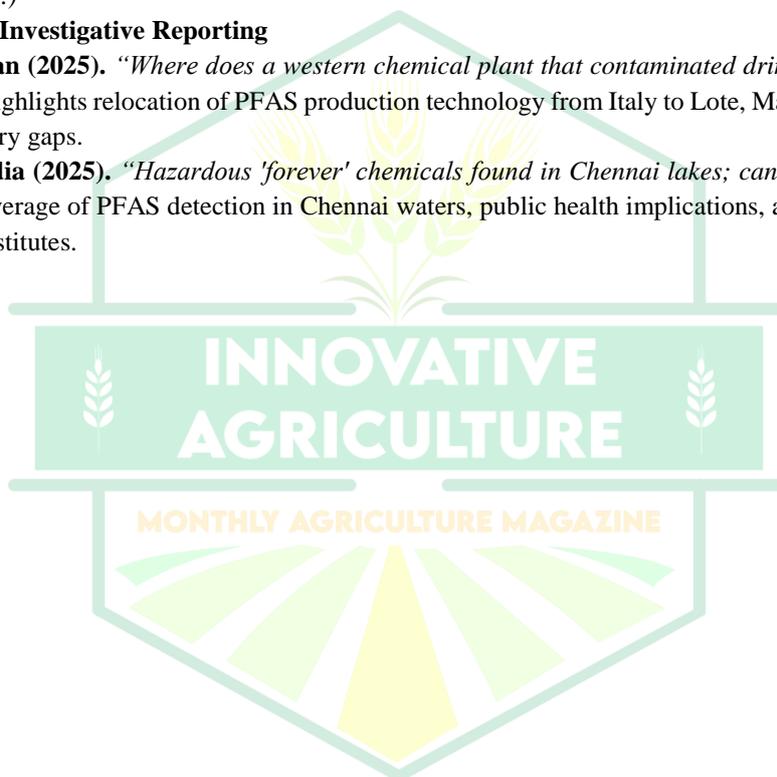
3. **Assessment of PFOA and PFOS in surface waters around Chennai and Tamil Nadu, India.** *Perfluoroalkyl compound levels in river and lake water (e.g., Noyyal, Cauvery).* **PubMed / Environmental Monitoring Publications** - Reports on PFOA and PFOS concentrations in southern Indian surface waters.
4. **Kurunthachalam, K., et al. (2019).** *Assessing exposure to legacy and emerging per- and polyfluoroalkyl substances via hair - first nationwide survey in India.* **Science of the Total Environment**, Hair biomonitoring for PFAS exposure across Indian cities.

Government & Institutional Sources

6. **Stockholm Convention on Persistent Organic Pollutants (POPs).** India's obligations as a Party, including listed PFAS compounds (e.g., PFOS). Convention documents and national implementation reports explain regulatory context for PFAS-related controls in India. (*Geneva: UN Environment Programme.*)
7. **Indian Environmental Monitoring Reports.** State Pollution Control Boards and Central Pollution Control Board (CPCB) monitoring reports (Water Quality, Hazardous Chemicals, Toxic Pollutants) often include data on fluorinated compounds, persistent pollutants, and industrial discharge. (*Government of India, various years.*)

Credible News & Investigative Reporting

8. **The Guardian (2025).** *"Where does a western chemical plant that contaminated drinking water go next? To India."* Highlights relocation of PFAS production technology from Italy to Lote, Maharashtra - concerns over regulatory gaps.
9. **Times of India (2025).** *"Hazardous 'forever' chemicals found in Chennai lakes; can cause liver damage, cancer."* Coverage of PFAS detection in Chennai waters, public health implications, and research findings from local institutes.



Biodegradable Grow Mats from Agricultural Fibers: Converting Farm Waste into a Sustainable Medium for Microgreens Production



Papitha P¹, Gowthaman R², Sanjeev B², Elancheliyan E², Sree Akshan C², Potri Selvan RS², Ezhil Selvan R²

¹Guest Faculty, Department of Agriculture, School of Agriculture and Animal Sciences, The Gandhigram Rural Institute (Deemed to be University), Dindigul, Tamil Nadu, India.

²IV Year B.Sc. (Hons.) Agriculture, Department of Agriculture, School of Agriculture and Animal Sciences, The Gandhigram Rural Institute (Deemed to be University), Dindigul, Tamil Nadu, India.

Introduction

The rapid expansion of urban agriculture and indoor farming has significantly increased the demand for microgreens, which are tender seedlings harvested at an early stage of growth. Microgreens are widely valued for their high nutritional density, containing concentrated levels of vitamins, minerals, antioxidants, and beneficial phytochemicals compared to their mature counterparts. Their short growth cycle, low resource requirement, and ability to be cultivated in small spaces make them ideal for households, restaurants, educational institutions, and commercial vertical farms. As interest in fresh, locally produced, and chemical-free foods is growing, microgreens production has emerged as an important component of modern sustainable food systems. Despite these advantages, conventional microgreens cultivation relies heavily on plastic trays, disposable synthetic growing pads, and peat-based substrates. These materials pose significant environmental concerns. Single-use plastics accumulate as persistent waste because they degrade very slowly in natural conditions, contributing to land and water pollution. Peat, commonly used as a growing medium, is harvested from peatlands that function as critical carbon sinks and biodiversity reservoirs; its extraction leads to ecosystem degradation and increased greenhouse gas emissions. Therefore, the search for biodegradable, renewable, and environmentally safe alternatives to conventional growing media has become increasingly important.

Agricultural residues offer a promising solution to this challenge. Large quantities of plant biomass such as banana pseudostem fiber, rice straw, sugarcane bagasse, and coconut husk fiber are generated annually after crop harvest and processing. These materials are often underutilized or disposed off through open-field burning, which contributes to severe air pollution and loss of valuable organic resources. Scientifically, these residues are rich in lignocellulosic components, including cellulose, hemicellulose, and lignin, which provide natural strength, porosity, and water-holding capacity. Such characteristics make them suitable candidates for developing biodegradable substrates capable of supporting seed germination and early plant growth. By processing these fibers into a composite structure and binding them with natural adhesives such as tapioca starch, it is possible to produce molded grow mats that can function as sustainable alternatives to synthetic media. This approach not only addresses environmental issues associated with plastic waste and peat extraction but also promotes the efficient utilization of agricultural by-products, supporting circular economy principles in agriculture. Consequently, biodegradable fiber-based grow mats represent an innovative and eco-friendly strategy for sustainable microgreens production, aligning modern food cultivation practices with environmental conservation goals.

In this article, a study-based approach utilizes abundant farm wastes banana fiber, rice straw, sugarcane bagasse, and coconut fiber blended and bound with tapioca starch to produce molded grow mats specifically designed for microgreens cultivation. By transforming low-value residues into a functional agricultural input, this method addresses both waste management and plastic reduction simultaneously.

Availability and Potential of Agricultural Residues

Agricultural residues are produced in enormous quantities worldwide. Rice cultivation alone generates hundreds of millions of tonnes of straw annually, much of which is burnt in open fields, contributing to severe air pollution

and greenhouse gas emissions. Similarly, sugarcane processing produces bagasse as a by-product, banana cultivation leaves behind bulky pseudostems, and coconut processing yields husk fibers. These materials are rich in lignocellulosic components—cellulose, hemicellulose, and lignin—which provide structural strength, flexibility, and water absorption capacity.

Studies on natural fiber composites (Mohanty et al., 2005; Satyanarayana et al., 2009) highlight that such fibers can replace synthetic materials in many applications due to their biodegradability, low density, and renewability. Rice straw's porous structure enhances aeration, bagasse contributes moisture retention, banana fiber provides tensile strength, and coconut coir offers durability and resistance to microbial degradation. When combined, these fibers create a balanced matrix suitable for plant growth media. Research on coconut coir as a horticultural substrate (Abad et al., 2002) demonstrates its excellent water-holding capacity and aeration, making it widely used as a peat substitute. Similarly, sugarcane bagasse fibers have been reported to possess high porosity and moisture retention (Sun et al., 2004). These characteristics are essential for seed germination, where both water availability and oxygen supply must be maintained.

Tapioca Starch as a Biodegradable Binder

Loose fibers alone cannot form a stable sheet; therefore, a binding agent is necessary. Tapioca starch, derived from cassava, is an ideal natural binder due to its biodegradability, low cost, and safety. When heated with water, starch undergoes gelatinization, producing a viscous paste that can coat fiber particles and create strong inter-particle bonding upon drying. Research on starch-based biodegradable materials (Tharanathan, 2003; Shogren, 1997) confirms that starch can form films and composites with sufficient mechanical strength for packaging and agricultural applications. Unlike synthetic adhesives, starch does not introduce toxic residues and decomposes naturally through microbial activity. This makes it suitable for products intended to contact soil and plants.

Preparation and Structural Design of the Grow Mat

- In the developed method, collected fibers are first cleaned to remove dust and contaminants.
- Then the fibers are ground by adding required amount of water until the fibers are uniformly separated. Tapioca starch paste is prepared separately and blended thoroughly with the fiber mixture to produce a homogeneous mass.
- The mixture is placed in a mold frame measuring approximately 15 × 15 cm. Before drying, ridge-like depressions are formed on the surface, creating four parallel raised sections across the mat.
- This structured design distinguishes the product from conventional flat grow pads.
- The molded material is then dried under solar dryer (52 to 56 °C) until a firm, lightweight sheet is obtained.
- The resulting mat possesses sufficient mechanical strength for handling while remaining porous and flexible.



Procedure of Biodegradable grow mat preparation

Functional Role of Ridge Design and Biochar Covering

The ridge pattern serves several agronomic purposes. Microgreen seeds are sown in the grooves between ridges rather than being broadcast randomly. This ensures uniform spacing, reduces seed clustering, and promotes even germination. Proper spacing minimizes competition among seedlings for water, oxygen, and light.

After sowing, seeds are lightly covered with biochar. Biochar, a carbon-rich material produced by pyrolysis of biomass, has been shown to improve soil water retention, nutrient availability, and microbial activity (Lehmann

& Joseph, 2015). Its porous structure helps maintain moisture around the seeds while providing a clean surface that reduces the risk of fungal contamination—an important consideration in dense microgreens cultivation.



Suitability for Microgreens Growth

Microgreens require only a shallow substrate that can support roots, retain moisture, and allow aeration. The fibre-based grow mat fulfills these requirements effectively. The interconnected pores absorb water rapidly and release it gradually, preventing both drought stress and waterlogging. Adequate oxygen diffusion through the porous structure supports healthy root respiration. Because the materials are organic and free from harmful chemicals, the mat provides a safe medium for edible crops harvested at an early stage. After harvest, the used mat can be composted or incorporated into soil, where it decomposes and contributes organic matter.

Environmental and Socio-Economic Benefits

The environmental advantages of this technology are significant:

- Reduction of single-use plastics in horticulture
- Productive utilization of agricultural residues
- Decrease in residue burning and associated air pollution
- Promotion of biodegradable materials
- Contribution to circular economy principles

From a socio-economic perspective, local production of grow mats can create new income opportunities for farmers and rural entrepreneurs. Agro-processing units can convert low-value waste into marketable products for urban agriculture and home gardening markets.

International agencies emphasize the importance of residue utilization for sustainability. Reports by FAO and UNEP highlight that converting biomass waste into useful products can reduce environmental degradation while supporting rural livelihoods.

Implications for Sustainable Agriculture

As global agriculture moves toward environmentally responsible practices, replacing petroleum-based inputs with renewable materials is essential. Biodegradable grow mats align with the goals of sustainable intensification, urban food security, and climate-smart agriculture. They demonstrate how locally available materials can be engineered into functional products without sophisticated technology. Such innovations are particularly relevant for developing countries, where agricultural residues are abundant but waste management infrastructure is limited. By integrating waste recycling into food production systems, these mats contribute to a more resilient and resource-efficient agricultural model.

Conclusion

The production of grow mats from banana fiber, rice straw, sugarcane bagasse, and coconut fiber bound with tapioca starch represents a practical and environmentally sound solution for microgreens cultivation. The ridge-designed structure improves seed placement and germination, while the natural materials ensure biodegradability and safety. This approach simultaneously addresses plastic pollution, residue management, and sustainable food production. With increasing demand for eco-friendly cultivation methods, biodegradable fiber grow mats have strong potential for widespread adoption in both urban and rural settings.

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Enhancement of income through high yielding newly introduced Groundnut variety TCGS1694 (Visishta)



I. Venkata Reddy¹, M. Ravi Kishore², P.N. Siva Prasad³ and N. Rajasekhar⁴

¹SMS (Extension), KVK, Garikapadu, NTR District, Andhra Pradesh

²Programme Coordinator, KVK, Garikapadu, NTR District, Andhra Pradesh, India

³SMS (Crop Production), KVK, Garikapadu, NTR District, Andhra Pradesh, India

⁴SMS (Plant Protection), KVK, Garikapadu, NTR District, Andhra Pradesh, India

INTRODUCTION

Groundnut (*Arachis hypogaea* L.) is a pivotal oilseed crop in India, yet its productivity is often hampered by traditional variety susceptibility to biotic stresses and poor adaptation to specific soil types. In the NTR District of Andhra Pradesh, farmers traditionally relied on older varieties like TAG 24, which often faced challenges with leaf spot diseases and sub-optimal yields in sandy river basin soils. To address these gaps, Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu, introduced the high-yielding variety TCGS-1694 (Visishta). This variety was specifically selected for its tolerance to leaf spots and its robust performance in coastal sands and irrigated red soils. Through Cluster Frontline Demonstrations (CFLD), KVK aimed to enhance farmer income by integrating improved genetics with scientific crop management practices.

Specific technology:- High yielding, tolerant to leaf spots and suitable for coastal sands

Name of KVK	:	Dr. K.L.Rao Krishi Vigyan Kendra, Garikapadu
Crop and variety	:	TCGS-1694 (Visishta)
Name of farmer & address	:	Karise Daveedu, S/o. Suleman, Kannevedu (Village), Vastavai (Mandal), NTR District, Pincode:-521190 Phone Number:- 7036319087 Adhar Number:- 760990233927
Background information about farmer field	:	Irrigated, the Available N-191Kg/ha, Available P-21 kg/ha, Available K- 179 kg/ha, PH :8.8, Electrical Conductivity -0.64%, Available Organic Carbon :0.51 %.
Details of technology demonstrated	:	Integrated Crop management Practices in Groundnut, High yielding variety with tolerance to leaf spots
Institutional involvement	:	Distributed quality seed of TCGS-1694 (Visishta), pre and post emergence herbicides, need based insecticides. Attended regular field visits, conducted field days and trainings to farmers
Success point	:	More enthusiasm in groundnut cultivation
Outcome of Yield		
Demonstration	:	25.84 Q/ha.
Potential yield of variety/technology	:	28 Q/ha.
District average (Previous year)	:	
State average (Previous year)	:	

Performance of technology vis-à-vis Local check (Increase in productivity and returns)

Used Practice	Yield (q/ha)	Gross cost (Rs/ha)	Gross income (Rs/ha)	Net income (Rs/ha)	B:C ratio
Farmer Practices	23	84,300	149500	65,000	0.77
Demonstration	25	79,150	162500	83,350	0.94
% Increase	8.69				

Farmer’s feedback

The variety performed very well under sandy soils of river basin. Farmer was satisfied with the variety. The pod size, color of testa, oil percentage and taste of kernel are good. Farmers was very happy with the service rendered by the KVK, Garikapdu.

Impact of the technology

Farmer got net income of Rs.83,350/- per hectare as against 65,000/- in case of local variety . The variety has spread to adjacent villages. Many farmers are interested in growing groundnut instead of other ID crops. Generated employment for the agricultural labour. The cost of cultivation has been reduced by 5,250/- per hectare with the timely interventions.



Field inspection of before sowing of Groundnut



Distribution of seed and literature on G. nut variety, TCGS-1694



Distribution of Bio fertilizers



Field visit



Field day at Kannevedu village



Suggestions on post harvest management

Success story:-2

Specific technology:- **High yielding, tolerant to leaf spots and suitable for coastal sands**

Name of KVK	:	Dr.K.L.Rao Krishi Vigyan Kendra, Garikapadu	
Crop and variety	:	TCGS-1694 (Visishta)	
Name of farmer & address	:	Athukuri Gopal Rao, S/o.A. Subba Rao Balusuapdu (Village), Jaggayapeta (Mandal), NTR (district)- 521185, Phone number;- 6304596123	
Background information about farmer field	:	Irrigated, the available N – 191 Kg/ha, available P-99.86 Kg/ha, available K – 82.22 Kg/ha, PH – 7.8, electrical Conductivity - 0.19%, available organic carbon – 0.89%.	
Details of technology demonstrated	:	High yielding, tolerant to leaf spots and suitable for coastal sands	
Institutional involvement	:	Distributed seed, chemical for seed treatment, need based insecticides, field visits and trainings	
Success point	:	<ul style="list-style-type: none"> Supply of Foundation Seed (F/S) of improved variety, chemical for seed treatment, post emergence herbicide and other Insecticides Identified the Demonstrated the best suitable variety to the location. Timely supply of inputs and suggestions by the Scientists 	
Outcome of Yield			
Demonstration	:	28 Qtl/ha	
Potential yield of variety/technology	:	25-28 Qtl/Ha	
District average (Previous year)	:		
State average (Previous year)	:		

Performance of technology vis-à-vis Local check (Increase in productivity and returns)

Used Practice	Yield (q/ha)	Gross cost (Rs/ha)	Gross income (Rs/ha)	Net income (Rs/ha)	B:C ratio
Farmer Practices	24.80	80,870	1,60,800	79,930	0.98
Demonstration	28.34	72,300	1,87,700	1,15,400	1.59
% Increase	14.27			35,470	

Farmer's feedback

Groundnut variety, TCGS-1694 (Visishta) gave more yield per hectare as compared to local groundnut variety, TAG 24. This variety performed well in sandy soils as well as red soils under Irrigated condition. Leaf spot incidence was low in this variety.

Impact of the technology

Dr. K L Rao KVK, Garikapadu procured TCGS-1694 F/S from RARS, Tirupathi and supplied to the farmers under CFLD (Oilseeds). Before introduction of this variety, very few farmers of Balusupadu village grow groundnut to an extent of 20 acres. At present TCGS 1694 has spread to more than 100 acres in this village alone. Farmers of neighboring villages are also showing interest in growing groundnut and few farmers three other villages are growing groundnut as it was not grown earlier.



Distribution of seed distribution



Method demonstration of seed treatment in groundnut



Diagnostic field visits to monitor crop condition



Training on Integrated Crop Management



Conclusion

The introduction of **TCGS-1694 (Visishta)** has proven to be a transformative intervention for groundnut farmers in the region. The data demonstrates that the variety not only yields higher but also offers better resilience against common pathogens like leaf spots, which are prevalent in irrigated environments.

The success of the technology is attributed to:

1. **Superior Genetics:** Better pod size, desirable testa color, and higher oil content.
2. **Resource Optimization:** Lowering the cost of cultivation through scientific seed treatment and herbicide application.
3. **Institutional Support:** The proactive role of KVK Garikapadu in providing Foundation Seed (F/S) and technical handholding.

The socio-economic impact is evident in the increased employment for agricultural labor and the shift in cropping patterns, where farmers are now preferring groundnut over other Irrigated Dry (ID) crops. TCGS-1694 stands as

a recommended variety for the sandy and red soil tracts of Andhra Pradesh to ensure sustainable oilseed production.

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Closer Spacing in Cotton: A New Pathway to Higher Productivity and Profitability in NTR District of Andhra Pradesh



N. Rajasekhar¹, M. Ravi Kishore², G. Shobhitha Rani³, Y. Sai Gopi⁴, B. Jagadeesh Naik⁵

¹Subject Matter Specialist (Plant Protection), ²Programme Coordinator, Young Professional-II³,
^{4&5}Young Professional- I

Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu

Abstract

Cotton cultivation in Andhra Pradesh has traditionally faced challenges such as low plant population, erratic rainfall, high pest pressure—especially pink bollworm—and rising labor costs. The Closer Spacing System (CS), also known as High-Density Planting System (HDPS), developed by ICAR–Central Institute for Cotton Research (CICR), offers a promising solution to these constraints. Successful demonstrations conducted under the guidance of Dr. K.L. Rao Krishi Vigyan Kendra, Garikapadu, in NTR district have clearly shown the advantages of this system. Three progressive farmers—Shri Mukkapati Venu, Shri Pilliboyina Jamalayya, and Shri Maddela Chittibabu—adopted closer spacing (90 × 30 cm) using the Aadhya (NCS-1134) BG II hybrid with improved agronomic management. The results showed a 30–35% increase in yield, early and synchronous boll bursting, reduced pest incidence, and higher net returns. These farmer-led demonstrations prove that HDPS is a viable, profitable, and scalable model for cotton cultivation under local soil and climatic conditions.

Key words: - High-Density Planting System (HDPS), Cotton, Yield Enhancement Closer Spacing (90 × 30 cm), Pink Bollworm Management, Net Returns

Introduction

Cotton is a major commercial crop in Andhra Pradesh, but its productivity often remains low due to traditional wide spacing, sub-optimal plant population, prolonged crop duration, and vulnerability to pests such as pink bollworm. In recent years, the Closer Spacing (CS) or High-Density Planting System (HDPS) promoted by ICAR-CICR has emerged as a farmer-friendly innovation. The system focuses on increasing plant density, managing crop growth through plant growth regulators, and achieving early, uniform harvesting. Recognizing its potential, Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu, introduced and demonstrated this technology in several villages of NTR district, resulting in remarkable success.

1. Shri Mukkapati Venu from Village: Keesara, Mandal: Kanchikacharla, Dist: NTR

Mukkapati Venu, a farmer from Keesara, Andhra Pradesh, successfully boosted his cotton yields by 30–35% by transitioning from traditional spacing to the Closer Spacing System (CS). Using the Aadhya (NCS-1134) hybrid and a higher seed rate, he achieved an optimal density of 14,814 plants per acre (90 cm x 30 cm) spacing. This High-Density Planting System (HDPS), developed by ICAR-CICR, addresses common regional challenges like unpredictable rainfall and pink bollworm infestations. Through superior agronomic techniques and supplemental irrigation, Venu harvested a record 10.5 quintals per acre. His success with early, synchronous harvesting has now become a model for neighboring farmers. The farmer's success has turned his farm into a demonstration plot for the region. By proving that the HDPS procedures from ICAR-CICR are viable in local soil conditions, he is actively encouraging fellow farmers in surrounding villages to adopt the system. This transition marks a "new way" for cotton in Andhra Pradesh moving away from low-density, high-risk farming toward a more controlled, intensive, and profitable agronomic model.

Details of the intervention:

Name of the hybrid/variety	Aadhya (NCS-1134)
Seed rate	4 packets/acre
Spacing	90 X 30 cm
PGR Spray	Mepiquat chloride-once
No.of Pickings	Three
Cost of production	34,500
Seed cotton yield	10.5 q/ac
Gross income	Rs.78,275.00/-



Crop cut demonstration conducted at the farmer's field



Training programme conducted at Keesara village on Closer spacing in cotton

2. Shri Pilliboyina Jamalayya from Village: Chandrala, Mandal: Mylavaram, Dist: NTR

Under the technical guidance of Dr. K.L. Rao Krishi Vigyan Kendra, Garikapadu, Shri Pilliboyina Jamalayya of Chandrala village has demonstrated the high-profit potential of the Closer Spacing (CS) system by optimizing cotton cultivation on heavy soil. By shifting from the traditional (120cmX60cm) spacing to a high-density (90cmX30cm) model using the Aadhya (NCS-1134) BG II hybrid, he successfully boosted his plant population to 14,815 per acre. This intensive approach was supported by a higher seed rate of four packets per acre and a sophisticated growth management strategy; specifically, the use of the growth regulator "Chamatkar" allowed him to redirect plant energy from vegetative growth to reproductive sympodial branching. These refined agronomic practices, bolstered by supplemental irrigation, resulted in a robust yield of 10.5 quintals per acre a 32% increase over conventional irrigated yields. Critically, the system's early boll maturation and synchronous ripening allowed Jamalayya to harvest before the onset of pink bollworm infestations while reducing labor expenses, ultimately shortening the crop cycle and freeing the land for a subsequent crop.

Details of intervention

Name of the hybrid/variety	Aadhya (NCS-1134)
Seed rate	4 packets/acre
Spacing	90 X 30 cm
PGR Spray	Mepiquat chloride-once
No. of Pickings	Three
Cost of production	Rs.36,500.00/-
Seed cotton yield	10.5 q/ac
Gross income	Rs.81,275.00/-



Field day conducted at farmer's field at Chandrala village



Training programme conducted at Chandrala village on Closer spacing in cotton

3. Shri Maddela Chittibabu from Village: Pedamodugapalli, Mandal: Jaggayyapeta, Dist: NTR

Shri Maddela Chittibabu, a dedicated farmer from Pedamodugapalli village, has successfully modernized his 1.5-acre cotton farm by adopting the Closer Spacing (CS) system. Under the technical guidance of Dr. K.L. Rao Krishi Vigyan Kendra (KVK), Garikapadu, Chittibabu moved away from traditional spacing (100cmX60cm), which typically resulted in sparse plant populations and lower returns, to a high-density (90cmX30cm) configuration. By utilizing the Aadhya (NCS-1134) BG II hybrid at an increased seed rate of four packets per acre, he achieved an optimal density of 14,815 plants per acre. His success was driven by a sophisticated agronomic strategy. Beyond the increased output, the CS method provided significant logistical advantages. The early boll bursting and synchronous ripening allowed for a faster harvest that avoided the peak window for pink bollworm attacks. This synchronization also addressed the local labor crisis by reducing picking costs and duration. Because the crop cycle was shortened, Chittibabu now has the opportunity to utilize his land for a second crop, maximizing his annual profitability and establishing a new standard for cotton cultivation in the NTR district.

Details of the intervention:

Name of the hybrid/variety	Aadhya (NCS-1134)
Seed rate	4 packets/acre
Spacing	90 X 30 cm
PGR Spray	Mepiquat chloride-once
No.of Pickings	Three
Cost of production	33,200
Seed cotton yield	10 q/ac
Gross income	78,200



Field Visit at Pedha Modhugupalli



Training programme conducted at Pedamodugapalli village on Closer spacing in cotton

Conclusion

The success stories from Keesara, Chandrala, and Pedamodugapalli villages clearly demonstrate that Closer Spacing / HDPS in cotton is a game-changing technology for NTR district. By increasing plant population, managing crop growth scientifically, and enabling early and synchronized harvesting, the system addresses major challenges such as pest pressure, labor scarcity, and climate uncertainty. With proven yield gains of 30–35%, higher gross returns, and strong farmer acceptance, HDPS represents a sustainable, profitable, and scalable model for cotton cultivation in Andhra Pradesh. The efforts of Dr. K.L. Rao KVK, Garikapadu, and progressive farmers are paving the way for a new era of high-density, low-risk cotton farming.

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Point-of-care assay based on Protein and Nucleic acid



Payal Sharma¹, Mohan Singh Thakur², Kush Shrivastava³, Bikash Ranjan Prusty³

¹Ph.D Scholar, ²Professor, ³Assistant Professor, Animal Biotechnology Centre, Nanaji Deshmukh Veterinary Science University, Jabalpur, M.P.

Abstract

Point-of-care (POC) diagnostics are revolutionising healthcare by allowing for quick and decentralised illness diagnosis outside of traditional laboratories. Protein-based assays are inexpensive and suited for mass screening, but their sensitivity may be lower, whereas nucleic acid-based tests (PCR, LAMP, RPA, CRISPR) provide high sensitivity and reliable early identification. Despite improvements, issues like standardisation, sample preparation, reagent stability, and regulatory hurdles persist. Future developments in automation, multiplexing, microfluidics, and digital integration are projected to improve precision diagnostics, especially in low-resource situations.

Introduction

Point-of-care (POC) diagnostics are transforming clinical testing by enabling rapid, decentralized, and easy disease detection at or near the patient site. Unlike traditional laboratory methods, POC tests provide results within minutes, supporting early treatment decisions and better outcomes. Guided by the WHO ASSURED criteria (Affordable, Sensitive, Specific, User-friendly, Rapid, Equipment-free, and Deliverable), POC technologies have rapidly advanced across infectious diseases, chronic disorders, reproductive health, oncology, and veterinary care. (Wang et al., 2021)(Chen et al., 2019). Based on the kind of biomarker found, POC tests may be roughly divided into two groups: nucleic acid-based assays and protein-based assays. Protein-based POC tests usually use immunological responses to identify antigens, antibodies, or host biomarkers. Lateral flow assays (LFAs) are the most extensively used types, having advantages such as simplicity, cheap cost, and rapid readout without apparatus (Koczula & Gallotta, 2016). These assays played a significant role during the COVID-19 pandemic, as antigen LFAs were deployed worldwide for quick screening, illustrating the scalability and feasibility of protein-based POC techniques (Lindner et al., 2021). However, their decreased sensitivity, especially in early illness with low viral loads, remains a serious constraint.

In contrast, nucleic acid-based POC tests identify pathogen DNA or RNA, genetic alterations, or gene expression patterns with excellent analytical sensitivity and specificity. Techniques such as loop-mediated isothermal amplification (LAMP), recombinase polymerase amplification (RPA), and CRISPR-based detection systems have enabled molecular testing outside centralised laboratories without the need for thermal cyclers (Notomi, 2000). These platforms can detect very low copy counts of nucleic acids, allowing early diagnosis, identification of drug-resistant strains, and high-precision detection in infectious and non-infectious disorders. During COVID-19, CRISPR-Cas12/13-based assays revealed great sensitivity (similar to RT-PCR) while being deployable at the point of care, thus pushing molecular POC usage (Broughton et al., 2020).

Reagent stability, cold-chain requirements, restricted multiplexing, and the demand for quantitative readouts are still major obstacles despite recent developments. Future developments are anticipated to concentrate on multiplexed assays, extraction-free molecular workflows, AI-enabled interpretation, and ultra-sensitive hybrid platforms that combine protein and nucleic acid detection. Together, these advances promise to improve the reach of precision diagnostics and address major gaps in global healthcare delivery.

Classification of POC Assays

1. Protein-based POC assays

I. Immunochromatographic tests (Lateral Flow Assays — LFAs)

The basic idea is that when a target antigen or antibody is present, a labelled detection reagent (colloidal gold, coloured latex or fluorescent nanoparticle) generates a visible test line by capillary flow of the sample across a nitrocellulose strip bearing capture reagents.

Formats/uses: antigen testing (infectious disease), antibody tests (serology), and small-molecule strips. Widely used for pregnancy, infectious illness screening (e.g., fast antigen tests).

Strengths: quick (minutes), affordable, instrument-free, field-deployable, easy to interpret.

Limitations: poor analytical sensitivity vs lab assays; semi-quantitative at best until connected to a reader; matrix effects and hook effect for very high analyte concentrations.

Recent innovations: nanoparticle engineering (fluorescent and SERS labels), multiplex strips, smartphone readers for semi-quantitation, better membrane chemistry and sample pretreatment to boost sensitivity (Vealan et al., 2023).

II. Immunoassays (ELISA-based POC devices)

The basic Principle is colourimetric/chemiluminescent signal amplification via enzyme-mediated antibody–antigen binding. POC variations miniaturise ELISA into cartridges or microplates that run outside central labs.

Formats/uses: cartridge ELISA readers, paper-ELISA, microplate-style benchtop POC analysers for biomarkers (cardiac, infectious, hormonal).

Strengths: well-characterised chemistry; greater sensitivity and quantitative output when compared to LFAs.

Limitations: Typically, longer time and need for numerous washes; POC ELISA equipment must handle fluidics and chemicals (cost/complexity).

Recent innovations: paper-ELISA and fully integrated microfluidic ELISA cartridges that automate wash/incubation procedures, including lyophilised reagents for room-temperature storage (Aydin et al., 2025).

III. Microfluidic immunosensors / Lab-on-chip protein sensors-

The basic idea is to do immunoassays with small quantities by integrating microchannels, mixers, and capture surfaces; detection can be optical, electrochemical, or electrochemiluminescent.

Formats and applications include pathogen antigens, cytokine panels, and sample-to-answer cartridges for proteins. useful when multiplexing is needed or sample capacity is constrained.

Strengths include the ability to multiplex, quicker kinetics (shorter incubation), and minimal sample/reagent usage.

Limitations: device fabrication and successful mass-manufacturing remain problems; integration of user-friendly sample input is nontrivial.

Recent innovations: passive fluidic control (capillary/valve designs), integration with electrochemical readouts and smartphone interfaces to develop tiny POC platforms (Yang et al., 2022).

IV. Electrochemical and optical biosensors (protein targets)

Principle: target binding (antibody/aptamer) creates detectable electrical (current, impedance) or optical (fluorescence, SPR) signal change.

Strengths: electrochemical sensors are particularly suitable for POC since they are sensitive, compact, low-cost and susceptible to miniaturised electronics; optical sensors can give high sensitivity and multiplexing.

Limitations: sensor fouling by complicated biological fluids, necessity for robust biorecognition layers and calibration.

Recent innovations: nanostructured electrodes for reduced limits of detection, integrated electronics and wireless readouts, and wearable protein sensors.

2. Nucleic-acid–based POC assays

I. Isothermal amplification platforms (LAMP, RPA, NASBA)

The basic idea is to amplify DNA and RNA at a steady temperature without thermal cycling. Examples include NASBA (nucleic acid sequence-based amplification), RPA (recombinase polymerase amplification), and LAMP (loop-mediated isothermal amplification).

Strengths: quick (10–60 minutes), water baths or basic warmers work well, tolerant to some sample contaminants, and great for field/POC. LAMP contains visible readouts (turbidity, colour change) and generates large copy numbers. RPA works at very low temperatures (~37–42°C) and is quick.

Limitations: primer design, particularly LAMP, can be complicated; if not adequately regulated, there is a possibility of nonspecific amplification or false positives; if not precisely constructed, the quantitative precision is lower than qPCR.

Current advances include colorimetric/fluorescent smartphone-compatible readouts, lyophilised master mixes for room-temperature transport, and LAMP integrated into microfluidic cartridges (Anupama et al., 2019).

II. CRISPR-based detection (Cas12, Cas13, Cas14)

Principle: CRISPR effectors (e.g., Cas12/Cas13) are programmed with guide RNAs to bind specific DNA/RNA targets; upon binding, some effectors exhibit collateral nuclease activity that cleaves reporter molecules (fluorogenic or lateral-flow reporters), producing a signal. Often combined with a pre-amplification step (LAMP/RPA) for sensitivity.

Strengths: extreme specificity (single-base discrimination possible), programmability to new targets, compatibility with simple readouts (fluorescent or lateral flow). Good for rapid development in outbreaks.

Limitations: still often needs upstream amplification for low-copy targets; reagent stability and standardisation for clinical deployment are evolving.

Recent innovations: single-step CRISPR assays (amplification and detection in one pot), freeze-dried CRISPR reagents, multiplexed CRISPR readouts, and integration into handheld devices (Kaminski et al., 2021).

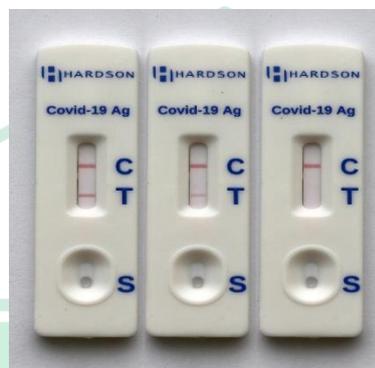


Fig 1: COVID-19 antigen rapid test cassettes showing control (C) and test (T) lines. The presence of both lines indicates a positive result, while the control line confirms test validity.

III. Paper-based molecular tests

The idea is to combine isothermal amplification or CRISPR detection with porous paper substrates (for sample flow and reagent storage); the results can be read via colour change, lateral-flow strips, or fluorescence.

Strengths: very inexpensive, readily disposable, suitable for mass production and use in environments with limited resources.

Limitations: regulating reaction conditions (temperature, humidity) and avoiding contamination require engineering; often single-use and often qualitative or semi-quantitative.

Recent innovations: integrated paper cartridges that incorporate dried reagents for LAMP/CRISPR and smartphone picture analysis for semi-quantitation (Jia et al., 2021).

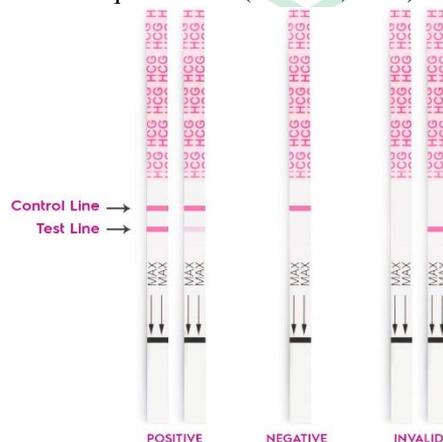


Fig 2: Interpretation of hCG pregnancy test strips showing positive, negative, and invalid results.

IV. Microfluidic nucleic-acid sensors and portable PCR devices

Microfluidic NA sensors (sample-to-answer): By automating extraction, amplification (PCR or isothermal), and detection in a closed cartridge, microfluidic integration minimises contamination and user steps. The ASSURED/REASSURED criteria (cheap, sensitive, particular, user-friendly, quick, robust, equipment-free, deliverable) are what these platforms strive to fulfil (Yang et al., 2022).

Portable PCR devices: improvements in miniaturised thermocyclers and lyophilised reagents have produced portable RT-PCR or qPCR tools for POC (some utilised in COVID-19 response). Portable PCR maintains the gold standard for sensitivity/specificity when thermal cycling is necessary, although power and equipment cost are issues. Recent lower-cost open-source and commercial portable PCR systems have achieved clinical performance approaching lab PCR in minutes to an hour (Sharma et al., 2023).

Applications of POC Assays

Table 1: Cover Protein-based and Nucleic-acid-based POC Case Studies / Applications.

Category	Application / Case Study	Assay Type	Target/Analyte	Readout Format	Key Advantages
Protein-based POC	COVID-19 Rapid Antigen Test	Lateral Flow Immunochromatographic Assay	SARS-CoV-2 Nucleocapsid (N) antigen	Visual colored line; smartphone quantitation	Fast (15–20 min), no instrumentation, ideal for mass screening
	Pregnancy Test Strip	Lateral Flow Immunoassay	hCG hormone in urine	Visual colored line	Highly sensitive and specific, affordable, widely available
	Malaria Rapid Test	LFA (HRP2, pLDH)	<i>Plasmodium</i> antigens	Visual line	Critical for remote malaria-endemic regions
	Dengue NS1 / IgM / IgG Rapid Test	LFA	Dengue NS1 antigen, anti-DENV antibodies	Visual	Early detection supports outbreak response
	HIV Rapid Screening Test	LFA / immunoassay	Anti-HIV antibodies	Visual/portable reader	Useful in community screening & antenatal programs
	Influenza Rapid Diagnostic Test (RIDT)	LFA	Influenza A/B nucleoproteins	Visual	10–15 min detection during flu outbreaks
Nucleic Acid-based POC	SARS-CoV-2 RT-LAMP	Isothermal LAMP assay	SARS-CoV-2 RNA	Colorimetric or fluorescent	Easy heating (60–65°C), rapid (20–30 min)
	CRISPR-based COVID-19 Tests (DETECTR/SHERLOCK)	CRISPR-Cas12/Cas13	Viral RNA (post-LAMP/RPA)	Fluorescent; LFA strip	High specificity (single-base mismatch), fast
	Tuberculosis POC Test	Recombinase Polymerase Amplification (RPA)	<i>Mycobacterium tuberculosis</i> DNA	Fluorescent or LFA	Works at 37–42°C; rapid diagnosis in low-resource settings
	HPV DNA Rapid Detection	LAMP / RPA / Portable PCR	High-risk HPV DNA	Fluorescent/colorimetric	Enables cervical cancer screening in rural areas
	Food Contamination Testing (Salmonella, E. coli, Listeria)	LAMP / RPA / CRISPR on paper or microfluidics	Foodborne pathogen DNA/RNA	Colourimetric, fluorescence, lateral flow	On-site testing in processing units and farms
	Animal Disease Diagnostics (ASF, FMDV, Avian Influenza)	LAMP / RPA NAATs	Viral RNA/DNA	Colourimetric/s trip	Field-deployable testing for rapid outbreak control

Advantages and Limitations

Protein-based point-of-care (POC) assays are ideal for settings with limited resources and large-scale screening programs because of their many benefits, which include quick turnaround times, low costs, ease of use, and the use of reasonably stable reagents. These procedures, including lateral-flow immunochromatographic testing, can provide results in a matter of minutes and require very little equipment. However, protein-based tests often suffer from lower analytical sensitivity, especially when antigen levels are low, resulting in reduced performance during the early stages of infection. Additionally, cross-reactivity with structurally identical antigens might decrease specificity, potentially leading to false-positive results (Wang et al., 2021).

High sensitivity and specificity are provided by nucleic acid-based POC assays (PCR, LAMP, RPA, and CRISPR), which enable early diagnosis and the identification of extremely low pathogen levels. But because they frequently include intricate processes, necessitate exact temperature control, and rely on the stability of the enzyme, their application in outdoor settings may be restricted. Widespread use in low-resource environments is further limited by their increased cost and requirement for specialised equipment (Caruana et al., 2020).

Challenges and Future Directions

Although point-of-care (POC) diagnostics are developing quickly, a number of obstacles prevent their broad clinical application. It is challenging to maintain laboratory-level accuracy in real-world situations because of user variability and environmental influences. Concerns about things like lack of standardised calibration, misleading results, and quality control still exist. One of the main bottlenecks is sample preparation, particularly for nucleic acid testing. Automated extraction technologies, integrated microfluidics, Internet of Things connectivity, and fully integrated sample-to-answer devices are essential for future advancement. Global standardisation and regulatory complexity continue to be major obstacles to wider adoption.

Conclusion

POC assays based on proteins and nucleic acids are revolutionising diagnostics by offering quick and convenient testing outside of conventional labs. While protein-based assays are economical and appropriate for large-scale screening, nucleic acid tests provide excellent sensitivity and specificity for precise early detection. Precision medicine will be supported by future POC systems that are more automated, multiplexed, and digitally integrated, particularly in distant and low-resource environments.

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Advancements in Seed Treatment Technologies for Enhanced Plant Disease Management



Dr. M. Madhavi¹, Mr. Shai Shareef¹, Dr. V. Swarnalatha¹, Dr. K. Kavitha¹ and Dr. G.S Madhu Bindu²

¹Agricultural College, Palem, Professor Jayashankar Telangana Agricultural University, Hyderabad.

²Agricultural College, Jagtial, PJTAU, Hyderabad.

Introduction

Seed-borne and soil-borne pathogens pose a major constraint to crop establishment and productivity worldwide. Fungal pathogens such as species of *Fusarium*, *Aspergillus*, *Rhizoctonia*, *Sclerotium*, and *Colletotrichum*, along with certain bacterial pathogens, are responsible for seed decay, damping-off, seedling blight, and early plant mortality. Effective management at the seed stage is therefore a critical strategy in plant disease control. Recent advances in seed treatment technologies have significantly improved the precision, efficiency, and sustainability of pathogen management during early crop growth.

Limitations of Conventional Chemical Seed Treatments

Conventional seed treatment primarily relied on contact or systemic fungicides to eliminate externally and internally seed-borne inoculum. While effective, repeated and indiscriminate use has raised concerns regarding pathogen resistance, environmental contamination, and non-target effects. Modern seed treatment approaches now integrate chemical, biological, and physical interventions to achieve broader and more sustainable disease suppression.

Biological Seed Treatments and Induced Resistance

Biological seed treatments have gained substantial attention in plant pathology. These formulations typically contain plant growth-promoting rhizobacteria (PGPR), antagonistic fungi such as *Trichoderma* spp., or microbial consortia capable of suppressing pathogens through competition, antibiosis, mycoparasitism, and induction of systemic resistance (ISR). Biopriming techniques combine seed hydration with microbial inoculation, allowing beneficial organisms to colonize the seed surface prior to sowing. Such colonization establishes a protective microbial barrier in the spermosphere and rhizosphere, thereby reducing infection by soil-borne pathogens. Biological seed treatments are increasingly considered essential components of integrated disease management programs.

Nanotechnology in Pathogen Suppression

Nanotechnology has introduced innovative possibilities for disease control at the seed level. Nano-encapsulated fungicides and antimicrobial agents enhance stability, improve solubility, and enable controlled release of active ingredients. Due to increased surface area and reactivity, nanoformulations often achieve effective pathogen suppression at lower application rates compared to conventional formulations. Research also indicates that certain metallic nanoparticles exhibit intrinsic antifungal properties. However, biosafety assessment and environmental impact evaluation remain important considerations before widespread adoption.

Advanced Polymer Coatings and Controlled Release Systems

Advances in polymer-based seed coatings have further strengthened disease management strategies. Controlled-release polymer matrices allow gradual diffusion of fungicides or biological agents in response to soil moisture conditions. This sustained release ensures prolonged protection against early-season pathogens. Furthermore, biodegradable polymers are being developed to minimize environmental persistence. Improved coating uniformity enhances adhesion of active ingredients and ensures consistent dosage across seed lots, which is critical for reliable disease control.

Physical and Non-Chemical Seed Treatments

Physical seed treatment methods have also expanded in recent years. Cold plasma technology has demonstrated potential in reducing surface microbial load while simultaneously enhancing seed germination. Thermal

treatments and ultraviolet irradiation are being refined to inactivate seed-borne pathogens without compromising seed viability. These non-chemical approaches offer promising alternatives where chemical usage is restricted or resistance development is a concern.

Integration with Precision Disease Management

Integration of seed treatment strategies with precision agriculture tools represents a further advancement. Pathogen risk forecasting models, soil health diagnostics, and climatic data can guide selection of targeted seed treatments based on anticipated disease pressure. This site-specific approach optimizes fungicide use and supports resistance management strategies.

In conclusion, recent advances in seed treatment technologies emphasize integrated, sustainable and precision-based disease management. By targeting pathogens at the earliest stage of crop development, modern seed treatments reduce primary inoculum, improve seedling survival, and contribute significantly to yield stability. Continued interdisciplinary research will be essential to refine these technologies and ensure environmentally responsible disease control in future agricultural systems.



Recommendations to Improve Productivity of Groundnut in Rabi



Dr. B. Santhosh and Dr. Ch. Bhargava Rami Reddy

Scientist, ANGRAU

Abstract

Rabi groundnut cultivation is predominantly dependent on residual soil moisture, making crop performance highly sensitive to variety selection, nutrient availability and moisture management. Yield limitations commonly arise from terminal drought, calcium deficiency during pod development, nutrient imbalance and foliar disease incidence. This article provides regionally relevant, research-based recommendations for enhancing productivity of Rabi groundnut, emphasizing suitable varieties, fertilizer management, moisture conservation, plant population optimization, and integrated pest and disease management. Adoption of these practices can significantly improve pod yield, kernel quality, and economic returns. This article mainly emphasises on understanding effect of heat and moisture stress on groundnut in Rabi under rainfed conditions.

Introduction

Groundnut (*Arachis hypogaea* L.) is a vital oilseed crop widely cultivated under Rabi conditions in peninsular India. Unlike Kharif crops, Rabi groundnut frequently relies on residual soil moisture with limited irrigation support. India stands as the world's second-largest groundnut producer (101 lakh tonnes) with productivity of 1,863 kg/ha and acreage of 54.2 lakh hectares. Primarily a kharif crop (90% of acreage), productivity has risen from roughly 741 kg/ha (1950s) to over 1,500–1,800 kg/ha in recent years. Gujarat leads production, followed by Rajasthan and Tamil Nadu. Further, the productivity depends on careful synchronization of crop phenology with moisture availability, along with balanced nutrition and stress mitigation.

Adequate soil moisture at critical stages of crop (*viz.*, flowering and pegging), calcium availability at pod filling and management of foliar diseases are most prominent determinants of yield in Groundnut. Adoption of suitable varieties and addressing location specific problems may bridge this gap.

Varieties Suitable for Rabi Cultivation

The varieties with short to medium duration (110-115 days), drought resilience, tolerance to foliar diseases and high shelling percentage are preferable.

Commonly Recommended Varieties (Andhra Pradesh & Similar Regions)

Bunch Types (Preferred for Rabi Systems):

- TAG 24 – Short duration, early maturity, suitable under limited moisture
- Dharani (TCGS 1043) – High yield potential, good kernel quality
- Narayani (TCGS 320) – Stable performer with moderate disease tolerance
- Kadiri 6 (K-6) – Widely adapted, good pod filling
- Kadiri 9 (K-9) – Improved yield and tolerance traits

Conditions	Suitable varieties
For sowing in Nov-December	Dheeraj, dharani, Kadiri Lepakshi
Rice fallows	K-6, Dheeraj, dharani
Tolerant to foliar diseases leaf spot, rust	Kadiri Lepakshi

Sowing Window and Crop Establishment

Ideal Sowing at late October to November is ideal for Rabi. This prevents synchrony of terminal moisture stress during pod filling stage of crop. Seed rate of 120–140 kg pods/ha is adopted with spacing of 22.5 X 10 cm is adopted in Rabi.

Seed Treatment with Fungicide (e.g., thiram 3g/Kg seed or carbendazim 1g/ Kg seed) to reduce seedling diseases and with Rhizobium inoculation where groundnut is newly introduced.

Nutrient Management for Rabi Groundnut

Groundnut requires balanced fertilization, despite being a legume, especially under nutrient-poor Rabi soils. Nitrogen, Phosphorus and Potassium (at 20, 40-60 and 40-50 Kg/Ha) is recommended in Rabi. For calcium Gypsum at 400-500 Kg/ha is applied at flowering of pegging phase. For micronutrients ZnSO₄ (0.5%), Fe SO₄ (1%) is recommended.



Fig 1: Groundnut crop showing heat & moisture stress at 50 DAS.

For irrigation, micro irrigation systems like sprinkler or drip may be adopted. The flowering and pegging stages are critical for moisture stress. Excess irrigation may promote foliar diseases and excessive vegetative growth. The early 30-40 days are crucial for weed damage. Pre-emergence herbicide Pendimethalin 30% EC should be applied at 8-10 ml/Litre water. Early leaf spot, late leaf spot and rust are major diseases and thrips, leaf miner and spodoptera are major pests of Groundnut.

Harmonizing crop growth, with adequate nutrition, moisture and proper stress management can enhance groundnut productivity. Developing varieties that suit to local conditions and solve location specific problems is important.

POLLINATORS IN PERIL: WHY FARMERS MUST PROTECT BEES TO PROTECT THEIR YIELD



Vignesuwar T

Undergraduate Student, School of Agricultural Sciences, Karunya Institute of Technology and Sciences, Coimbatore - 641114

INTRODUCTION:

The continuously rising human population has brought about several threats, which, in turn, have created an urgent demand for food security. Bees are one of the key players in the pollination of food crops alongside other animal pollinators such as bats, birds, beetles, moths, hoverflies, wasps, thrips, and butterflies, besides natural elements like wind and water. Bees contribute to the world food supply by pollinating a wide range of plants including fruits, vegetables, oilseeds, and legumes. The annual economic benefit of bees for food production also extends to cash crops like coffee, cocoa, almonds, and soybeans, which get a greater advantage from bee pollination than self-pollination.

Bee pollination results in better and more fruits, nuts, and oils. However, bee colonies are subjected to several challenges that influence their development, reproduction, and continuity. These challenges include climate change, pesticides, land use, and management practices. The resolution of these issues is crucial for the continuation of effective pollination. For farmers, this invisible labour directly translates into income and food security. Recognizing bees as essential farm partners is the first step toward safeguarding both harvests and livelihoods.

MECHANISM OF POLLEN TRANSFER IN FLOWERING PLANTS:

Pollination is a biological process involving flowering plants, as a means of reproducing sexually, producing fruits/seeds. Pollination occurs with the release of pollen grains from male reproductive structures (the anthers) of flowers to the pollen receptor on the flower of the female reproductive organ (stigma). Transfer of pollen can occur either by abiotic agents (air and water) and/or by biotic agents (flowers and/or insects, birds and bats with bees being the best pollen transfer carrier).

When a bee collects nectar and pollen from flowers, it gathers pollen from the pollen-bearing flowers it has visited and carries it back to its hive as a food source for its colony. The fuzzy body of the bee traps pollen grains as it goes about its dance collecting nectar and storing it away for future use. When it goes to visit an adjacent flower, all or some of these pollen grains are dropped onto the pollen receptor of the flower it is visiting of the same type of flower.

When the perfect match is found, the pollen receptacle accepts the deposited pollen grain, the pollen grain will germinate; it creates a pollen tube and continues downward to the ovary through the style; through this tube, the male gametes are carried to the ovule for fertilization, and the result will be the growth of the seed and then the formation of a fruit. Failure of pollen transfer results in failure of reproduction of flowering plants; successful transfer will provide for an increased yield, quality and genetic diversity of agricultural products of human food supply on a global basis.

CHALLENGES FACED IN BEE POLLINATION:

1. **Pathogens and pests** weaken the health of bee colonies, including bacterial infections, viral infections and parasitic infections that have a negative impact on health and longevity of Bees. Bees that are infected with viruses may not be able to develop their immune system; this creates a situation where whole hives can become infected. One of the major examples of this is Colony Collapse Disorder (CCD), an event where there are several missing workers from the hive. In addition, parasites like *Nosema apis* and *Nosema ceranae* have resulted in the death of many honey Bees; as a result, they are severely at risk for the Pollination service. Insects that are parasitic in nature cause significant damage to Bee keeping through the feeding on the Brood, Honey and Adult Bees, thus making them weak by reducing their power and productivity and decreasing the length of time that they will survive in a hive and their ability to provide pollination services for crops.

2. **Shortages of nutritional food and physical resources** such as a shortage of pollen, nectar and sugar prevents bees from receiving adequate nutritional food. These Nutritional Shortages cause bees more difficulty in Foraging, and thus they have Less Efficiency in the Process of Pollination.

3. **Toxicities** associated with synthetic Pesticides & Agrochemicals include toxic residues left in the pollen and nectar after pesticide application, which eventually accumulated to the level of causing various forms of neurotoxicity, immune dysfunctions, abnormal behaviours, and chronic ill health within bee populations. Synthetic neonicotinoid insecticides are considered one of the most significant factors in global bee population decline. According to several field studies outlined in the referenced article, when a farmer applied pesticides, it led to a decline in the number of bees visiting their crops and thus a reduced yield for their crops.

4. **Environmental Changes** caused by Climate Change & Environmental Extremes will alter the normal growth/ reproductive success of bee colonies & influence the long-term aggregate Population Variability among All Bee Species. Bee colonies' environmental stressors can lead to a decrease in the population size in any ecosystem, thus affecting how much food is produced due to fewer bees being present to forage and now have other competing factors for their resources.

5. The destruction and degradation caused by **Habitat loss/deforestations** will ultimately cause bees to lose their Foraging areas, nesting places, and food sources.

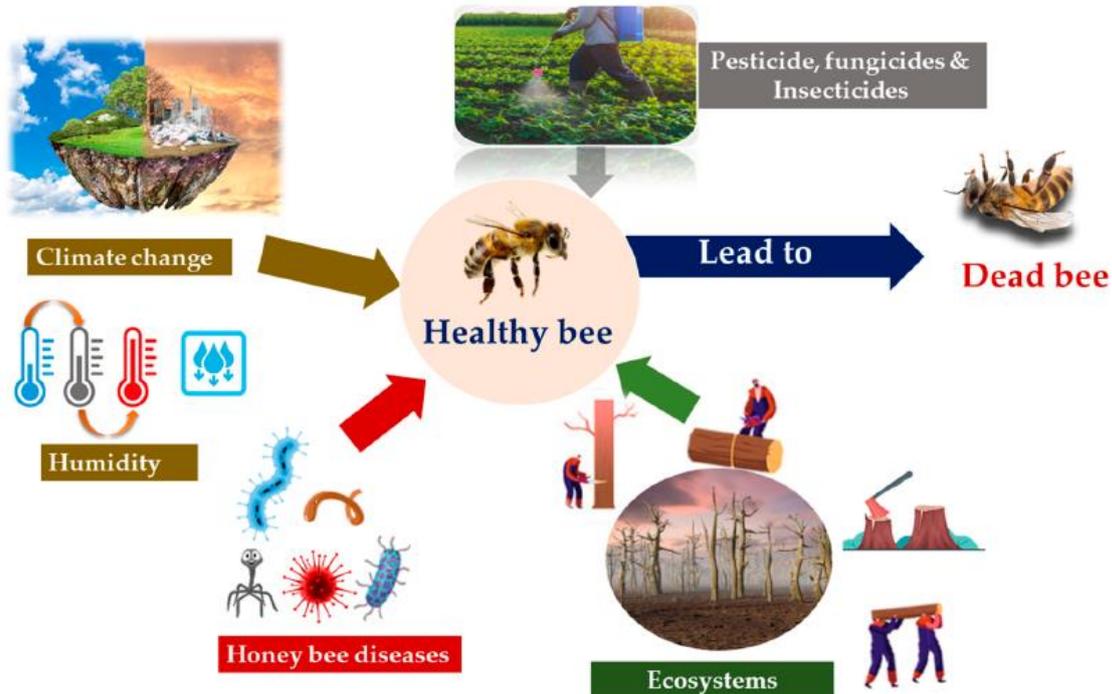
DIFFERENT BEES, DIFFERENT STRENGTHS IN CROP POLLINATION:

Bee Species	Crop(s) Pollinated	Observed Advantages on Crops	Reported Yield / Quality Gain
Honey bee (<i>Apis mellifera</i>)	Apple, Almond, Mustard, Sunflower, Cucumber, Watermelon, Guava, Citrus, Coffee	Increased fruit set, seed number, fruit size, improved taste and market quality	Yield increases 10–60%; fruit set up to 60% higher
Asian honey bee (<i>Apis cerana</i>)	Mango, Mustard, Coriander	Higher fruit set, increased siliqua and seed number	Seed yield increase ~17–20%
Giant honey bee (<i>Apis dorsata</i>)	Coffee	Fruit production significantly higher than wind pollination	~50% higher fruit production
Bumble bees (<i>Bombus spp.</i>)	Tomato, Sweet pepper, Apple, Pear	Enhanced fruit weight, size, seed set, uniformity	Fruit set increased up to 49%; superior quality
Stingless bees (<i>Melipona, Scaptotrigona, Heterotrigona</i>)	Cucumber, Tomato, Acai palm, Apple	Larger and heavier fruits, increased fruit number per bunch	Yield increases up to 2.5 times in some crops
Solitary bees (<i>Osmia spp.</i>)	Strawberry, Apple, Almond, Cherry	Higher fruit weight, better seed fertilization, improved shelf life	Commercial value increased 38–54%
Carpenter bees (<i>Xylocopa spp.</i>)	Passion fruit, Honeydew melon	Increased fruit set, seed number, faster pollination	Fruit set increased up to threefold
Wild bees (mixed species)	Sunflower, Sesame, Mustard, Watermelon	Improved pollination efficiency and genetic diversity	Yield improvement up to fivefold over single-species pollination

WHAT HAPPENS WHEN BEE VANISHES?

Agricultural production is impacted first as bees begin to disappear from the landscape. High-value crops such as fruit, vegetable, oilseeds and nut production rely heavily on bee pollination for optimal fruit and seed set development. Without bees pollinating, flowers produce poor or no fruit. Thus, farmers experience poor crops, odd shaped items and lower amounts of crops at harvest time. Farmers' productivity is thus affected negatively. As yield becomes lower some farmers will have no choice but to use expensive options for pollination including mechanical and/ or manual pollination methods. Both methods are much more labour intensive, consume more

time and reduce the efficiency of producing a crop when compared to using natural bee pollination methods. As farmers incur additional costs for these other methods of pollinating crops their profit margin becomes smaller and lessened economically sustainable for farmers, especially small and marginal farmers.



Challenges faced in Bee pollination

Image source: Khalifa, S.A.M.; Elshafiey, E.H.; Shetaia, A.A.; El-Wahed, A.A.A.; Algethami, A.F.; Musharraf, S.G.; AlAjmi, M.F.; Zhao, C.; Masry, S.H.D.; Abdel-Daim, M.M.; et al. Overview of Bee Pollination and Its Economic Value for Crop Production. *Insects* **2021**, *12*, 688. <https://doi.org/10.3390/insects12080688>

On a larger scale, if there is a reduction in the production of crops that are pollinator-dependent it will create an environment for shortages of these crops available in their respective markets. The imbalance of supply versus demand will create price pressures for these products (fruits, vegetables, cooking oils and nuts), which will make it increasingly difficult for consumers to purchase enough nutritious food in their diets and contribute to malnutrition or dietary imbalances, and have a significant impact on low-income consumers.

The ultimate impact of the decline in bee populations will be felt through a domino effect starting with lower crop yield from farms, increasing cost to produce food products and creating shortages on the market, followed by escalating food prices, and greater pressure on national food security systems. Thus, protecting our pollinators is more than just an environmental concern; it is also an agricultural and economic imperative.

FROM FIELD TO FLOWER: FARMERS' ROLE IN POLLINATOR CONSERVATION:

1. **Protect and Preserve Habitat:** Farmers can conserve hedgerows, flower strips, and a few wildflower patches at the farm edges. These offer bees and other pollinators a bit of paradise, feeding them and keeping them safe all seasons. Even very tiny gardens can do wonders for the pollinator population.
2. **Reduce or Optimize Pesticide Use:** Using chemicals sparingly or converting to green alternatives greatly lessens the danger to pollinators. Also, if pesticides are applied at nighttime or during other less active hours for pollinators, it is possible to decrease their death toll, while at the same time crops will still be safe.
3. **Promote Crop Diversity:** Cultivating several crop types or crop rotation will lead to the continuous presence of flowers. Hence, pollinators will find nectar and pollen all the time, their numbers will increase, and so will crop yields.

4. **Adopt Integrated Pest Management (IPM):** IPM methods involve the use of biological control, cultural practices, and a minimum change in chemicals. By depending on natural enemies and resistant varieties, farmers can lessen the use of harmful chemicals that can wipe out pollinator populations.
5. **Partner with local environmental NGOs** or become a pollinator, friendly program volunteer to raise awareness and create a more extensive network of protected habitats. Joint efforts bring about more significant changes beyond just the work of single farms.



Agriculture students undergoing the Experiential Learning Programme (ELP) learn about commercial beekeeping as a part of their curriculum at Karunya University.

SUCCESS STORIES OF BEEKEEPING FROM RURAL INDIA:

CASE 1: Beekeeping in Nongthymmai village of Meghalaya is an ancient tradition passed down through generations, thought to enhance household well-being. Previously considered frivolous, this activity is currently an indispensable financial resource for many households. Mr. Stevenson Shadap started beekeeping as an endeavour driven by enthusiasm but transformed it into a lucrative venture upon completing training at the EFC in Umnsing. Through increasing production of exotic species and refining both products and their presentation, this individual currently generates an annual income ranging from ₹ 100, 000 to ₹ 200, 000 through sales of honey sourced items in markets like Nong Pho and Shilong areas, experiencing strong customer interest surpassing expectations. Inspired by his achievements, the neighbourhood has initiated an apiary association aimed at boosting collaboration in producing honeys, crafting their packages more efficiently, promoting them effectively through marketing strategies, and creating additional



valuable items for sale. The revered Shadap is confident that the state of Meghalaya's apiculture initiative will facilitate more substantial demands and ensure continuity in their family-based economy.

CASE 2: Beekeeping is now an important way for people in the Kupwara region of Jammu and Kashmir to earn money due to government assistance and local entrepreneurs taking charge. With financial support including

subsidies on colony purchases amounting to forty percent and construction funding for an industrial facility in Gulgam capable of processing up to two tons per day into branded "Kupwara Honey," governmental initiatives aim to boost apiculture among novice beekeepers through this initiative. Zakir Hussain Bhat, an enthusiastic local youngster, started out managing only five hives but has since grown into overseeing more than two hundred colonies, yielding approximately twenty thousand kilograms of honey each year while also providing employment for many individuals. With backing from governmental training



programs and well-developed infrastructures, currently around 500 farmers cultivate an annual output of nearly 480 quintals of pure honey, which brings in approximately ₹3 crores in revenue each year. Efforts are currently in progress regarding the implementation of genetic identification on "Kupwara Organic Honey" products to improve their accessibility in markets and increase pricing opportunities.

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Hajipur Golden Crop: The Cultural Significance of Banana Cultivation in Vaishali, Bihar



Neeraj Raj

Ph.D. Research Scholar

Department of Agricultural Extension Education

School of Agricultural Science (SAS), Nagaland University Medziphema Campus, Nagaland, India

Abstract

Hajipur, located in the fertile Gangetic plains of Vaishali, Bihar, serves as a vital epicenter for banana (*Musa species*) cultivation, where the fruit is revered as the "Golden Crop." This article explores the profound intersection of the region's agricultural heritage and its emerging agro-industrial future, noting that bananas are not merely a livelihood but a cornerstone of cultural identity, most notably during the Chhath Puja festival. While traditional varieties like Chinia and Malbhog anchor the local economy, the region is currently undergoing a transformative shift toward value-added entrepreneurship. By processing surplus yields into high-demand products such as banana chips, prebiotic green banana powder, and eco-friendly pseudo-stem fiber paper, Hajipur is tackling systemic challenges like post-harvest losses and market volatility. Despite infrastructural bottlenecks in cold storage and technology, robust government support through schemes like PMFME and NHM is empowering rural youth and Self-Help Groups. Ultimately, the integration of organic certification, mechanized processing clusters, and agri-tourism is positioning Vaishali to evolve from a traditional farming belt into India's premier hub for sustainable, zero-waste agri-innovation.

Keywords: Hajipur, Vaishali, Banana Cultivation, Agro-entrepreneurship, Value Addition, Chhath Puja, Sustainable Agriculture, Rural Development.

Introduction

Hajipur, located in the culturally rich district of Vaishali in Bihar, stands as one of India's most prominent banana (*Musa species*) producing regions. The area's fertile Gangetic plains, ideal climatic conditions, and centuries-old agricultural traditions have made banana cultivation an integral part of local heritage and livelihood. Popularly known as the "Golden Crop," bananas are more than just a source of income in Hajipur—they represent cultural identity, community pride, and a rapidly evolving hub for banana-based entrepreneurship.

As India witnesses a boom in sustainable agriculture and rural startups, Hajipur's banana industry is undergoing significant transformation. Modern agri-business models, value-added processing units, and youth-led enterprises are driving economic growth. Products such as banana chips, banana powder, and banana fiber paper sheets are generating new opportunities, strengthening rural employment, and placing Hajipur on the map as a rising center for agri-innovation. The commercial importance which this fruit has gained can be judged from the fact that its consumption in the U.S.A. and the European continents is enormous. The composition of banana is presenting in table no. 1.1

Table No. 1.1 Composition of banana

	Percentage	
Water		70.0%
Carbohydrates	-do-	27.0%
Crude fiber	-do-	0.5%
Protein p	-do-	1.2%
Fat	-do-	0.3%
Ash	-do-	0.9%
Calcium	PPM	80 PPM
Phosphorus	-do-	290 PPM
Iron	-do-	6 PPM
Beta carotene	-do-	2.4 PPM
Thiamin	-do-	0.5 PPM
Riboflavin	-do-	0.5 PPM
Niacin	-do-	7 PPM
Ascorbic acid	-do-	120 PPM

Energy Cals/100gms: 104 cal.

Historical Evolution of Banana Cultivation in Vaishali

Vaishali, celebrated as one of the world's oldest republics, has a deep agricultural foundation. Over centuries, the region has relied heavily on crops suited to its fertile alluvial soil. Banana cultivation became popular due to its adaptability, nutrient-rich composition, and consistent demand in both local and regional markets.

Traditional farming families in Hajipur have maintained indigenous growing methods, focusing on organic fertilizers, intercropping, and natural pest management. With its strategic location near urban centers such as Patna and Muzaffarpur, Hajipur developed strong supply chains, enabling farmers to supply bananas throughout eastern India. Today, Hajipur is renowned as one of the largest banana cultivation belts in Bihar contributing significantly to the state's fruit economy.

Cultural Significance of Banana in Hajipur and Vaishali

In the Vaishali district of Bihar, and most notably in the city of Hajipur, the banana is far more than an agricultural commodity; it is a foundational pillar of the region's cultural, spiritual, and agrarian identity. Historically renowned for the sweet, small-sized *Chinia* variety, the landscape of Hajipur is defined by its sprawling banana orchards. The cultural significance of this fruit is most vibrantly displayed during Chhath Puja, Bihar's most revered festival. During this time, entire, unblemished bunches of bananas, locally known as *ghawad*, are considered a mandatory and sacred offering to the Sun God and Chhathi Maiya. Because the fruit grows high off the ground and is protected by a thick skin, it is viewed as inherently pure and untouched, making it the ultimate symbol of devotion and sanctity.

Beyond the fruit itself, the entire banana plant is treated as an auspicious symbol of fertility, prosperity, and continuous growth. The trunks and broad leaves are indispensable in local rituals, frequently used to construct the sacred canopy (*mandap*) for marriages, thread ceremonies, and household pujas. It is a common and welcoming sight during festivals to see banana leaves tied to the entrances of homes and temples to invite good fortune and ward off negative energy. Culinary traditions in Vaishali are equally intertwined with the crop. Mashed ripe bananas are a primary ingredient in traditional *prasada* distributed after religious ceremonies, while raw bananas are a staple in daily meals, transformed into traditional savory curries and koftas.

Because the cultural and religious demand for bananas is so deeply ingrained in the local way of life, the prosperity of Vaishali's agrarian communities is inextricably tied to the success of this crop. The rhythm of life here revolves around the planting and harvesting cycles of these orchards. The heavy reliance on bananas during peak festival seasons creates a unique socio-economic dynamic where local growers carry the weight of both economic survival and cultural preservation. Recognizing this profound cultural dependency sheds light on exactly why documenting and addressing the everyday constraints faced by local banana cultivators is essential to securing not just their livelihoods, but the living heritage of the entire region.

Economic Importance: Banana as the Golden Crop

In the fertile plains of Vaishali district, particularly in the agricultural hub of Hajipur, the banana has rightfully earned its moniker as the "golden crop." For local farmers, it represents a profound economic engine that transforms rural livelihoods through its high yield potential and exceptional profitability. Unlike traditional seasonal staples such as wheat or paddy that offer a single, annual payout, banana cultivation in Hajipur provides a staggered, almost continuous cycle of income. Once a plantation is established, the frequent harvesting periods ensure a reliable cash flow throughout the year. This steady revenue stream acts as a financial lifeline for rural households, enabling better debt management, higher living standards, and the capital necessary to reinvest in future agricultural cycles. Furthermore, the sheer volume of fruit produced per hectare in this region maximizes the economic return even for smallholder farmers, making it a highly efficient use of the fertile Gangetic soil.

The economic footprint of Hajipur's banana industry extends far beyond the direct sale of the famed *Chinia* or *Malbhog* varieties; it sustains a vast, dynamic supply chain that generates widespread local employment. Every phase of the crop's lifecycle—from meticulous orchard preparation and planting to harvesting, transportation, and

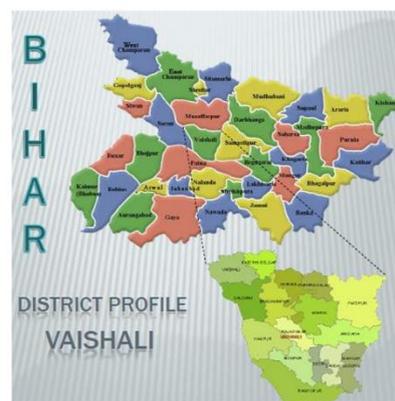


Figure 1. District Profile of Vaishali

retail—demands significant labor, thereby anchoring the micro-economy of the entire district. Moreover, the banana plant is a zero-waste agricultural asset where virtually every component can be monetized. Farmers frequently supplement their income by selling the broad leaves for traditional dining and ceremonial uses, while the pseudo-stems are increasingly being processed to extract natural fibers for textiles and handicrafts. This localized, secondary cottage industry provides crucial supplementary income and empowers allied agricultural workers across Vaishali.

The true economic weight of the banana in Hajipur is most visible during major regional festivals like Chhath Puja, where surging cultural demand dictates the financial health of the region for the entire year. By acting as a highly lucrative cash crop with diverse market applications, the banana elevates farming from subsistence to a



thriving commercial enterprise. However, this heavy economic reliance also means that the region's overall prosperity is deeply vulnerable to localized agricultural challenges. Consequently, rigorously documenting and analyzing the everyday constraints perceived by these local growers—whether they stem from post-harvest losses, disease management, or volatile market access—is an absolute necessity. Understanding these specific, on-the-ground hurdles is the critical first step in safeguarding the economic backbone of Hajipur and ensuring the long-term sustainability of its most vital crop.

Entrepreneurship in Banana-Based Products

The transition from traditional banana cultivation to value-added entrepreneurship represents the most promising frontier for agricultural growth in Hajipur. While the region is celebrated for its massive raw *Chinia* and *Malbhog* yields, the untapped economic potential lies in processing the fruit and its by-products into high-demand commodities such as banana chips, nutrient-rich banana powder, bakery items like cookies, and eco-friendly paper sheets. Establishing micro-processing units locally serves as a direct, highly effective solution to some of the most severe constraints local growers face on the ground, particularly high post-harvest losses and the extremely short shelf life of the fruit. By converting perishable surplus into long-lasting consumer goods like vacuum-sealed chips or baby-food-grade banana powder, cultivators can bypass the volatility of local raw markets and significantly reduce their reliance on traditional middlemen. Furthermore, the entrepreneurial extraction of banana fiber from discarded pseudo-stems to produce biodegradable paper sheets, textiles, and handicrafts successfully transforms agricultural waste into a lucrative secondary industry. Initiatives supporting this shift toward agro-processing are already beginning to empower rural youth and women's self-help groups across Vaishali through localized job creation and skill development. Ultimately, for an agrarian community so deeply invested in a single crop, fostering entrepreneurship in value-addition is not just an alternative business venture; it is the definitive strategy for building long-term economic resilience against the systemic, everyday challenges of traditional farming.

Popular value-added products include:

Banana Chips – High consumer demand, ideal for small manufacturing units



Banana Powder – Growing popularity in health foods, smoothies, and bakery items



Banana Fiber Paper Sheets – Eco-friendly alternative to wood-based paper, supporting sustainability.

These industries not only create rural employment but also position Hajipur as a leading center for Agri-based startups in Bihar.

Banana Chips Manufacturing: A Fast-Growing Rural Business

In the agricultural landscape of Hajipur, the transition from harvesting raw fruit to manufacturing banana chips has emerged as one of the most successful and highly scalable business models. As urban consumers increasingly prioritize clean-label and natural alternatives to heavily processed junk food, the national demand for healthy, plant-based snacks has surged. Consequently, crispy, naturally flavored banana chips have rapidly evolved from a regional specialty into a top-selling retail product across India, presenting a lucrative commercial opportunity for local agrarian communities.

Strategic Advantages of Local Manufacturing For aspiring rural entrepreneurs in Vaishali, establishing a banana chips unit offers a strategic blend of manageable financial risk and high economic reward.

- **Abundant Raw Material:** Located in the heart of Bihar's banana belt, manufacturers have direct, year-round access to ideal processing varieties, virtually eliminating exorbitant transportation and sourcing costs.
- **Low Initial Investment:** Transitioning into agro-processing does not require a massive industrial footprint. Micro-units can be established with relatively modest capital, which is frequently supported by state and central government subsidies.
- **High Profit Margins:** By converting a highly perishable raw crop—which is often subjected to volatile local market prices—into a shelf-stable, packaged consumer good, businesses can unlock exceptional profit margins, often ranging between 50% to 60%.
- **E-Commerce and Branding:** The extended shelf life of processed chips perfectly positions the product for direct-to-consumer online sales, allowing rural producers to bypass traditional middlemen and build a brand presence on national e-commerce platforms.

Scaling Through Mechanization and Quality Control :- Automated machinery, such as mechanical slicers and temperature-controlled batch fryers, is essential for scaling banana chip production and ensuring consistent volume and quality. When paired with strict hygiene and premium packaging, this mechanized process allows the product to meet rigorous retail and international export standards. Ultimately, adopting this modern technology empowers local enterprises in Hajipur to expand their reach and build a nationally recognized agro-brand.



Banana Powder: A Rising Superfood

As global dietary trends shift toward clean-label and plant-based nutrition, banana powder—particularly the variety milled from raw, green bananas—is rapidly ascending as a global superfood. Unlike its sweet, ripe counterpart, green banana powder is celebrated for its exceptionally high concentration of resistant starch. This complex carbohydrate acts as a powerful prebiotic, nourishing beneficial gut bacteria to improve digestive health while maintaining a low glycemic index that provides sustained energy and helps regulate blood sugar. Beyond gut health, it is a nutritional powerhouse packed with potassium, magnesium, and essential vitamins like B6 and

C. Because it is naturally gluten-free, mild in flavor, and easily digestible, it has become a highly sought-after functional ingredient in everything from commercial baby foods and sports nutrition to gluten-free baking. From an agricultural standpoint, the surging demand for this superfood represents a transformative opportunity. By converting raw, highly perishable bananas into a shelf-stable, premium health product, cultivators can drastically reduce crushing post-harvest losses and bypass local market volatility. This value-addition process effectively bridges the gap between traditional farming and the modern wellness industry, turning a local staple into a highly lucrative, globally recognized commodity.

Banana Fiber Paper Sheets: A Sustainable Innovation

The extraction of banana fiber from the pseudo-stem—a plant part historically discarded as agricultural waste after the fruit harvest—is catalyzing a green manufacturing revolution across Bihar. Through a meticulous process of mechanical extraction and pulping, this fibrous byproduct is transformed into a highly durable, flexible, and completely biodegradable alternative to conventional wood-pulp paper. Because this process relies on abundant crop residue rather than deforestation, it is an inherently sustainable practice that yields premium, eco-friendly goods, ranging from robust craft paper and handmade notebooks to luxury packaging sheets, file folders, and intricate decorative items.

Beyond its remarkable environmental benefits, the true power of this emerging industry lies in its profound socio-economic impact. In agricultural hubs like Hajipur and Vaishali, fiber extraction and crafting have become vital engines for rural employment, particularly through localized self-help groups and Farmer Producer Organizations (FPOs). By training women artisans and local youth in the end-to-end production process—from operating mechanical fiber extractors to paper-crafting and weaving—this sector is actively converting agricultural waste into a reliable source of income. It not only provides these communities with financial independence and valuable skill development but also establishes a sustainable, circular micro-economy that champions both ecological conservation and local empowerment.

Challenges in Banana Entrepreneurship

Despite the transformative potential of value-added products, the journey from traditional banana cultivation to successful agro-entrepreneurship in Hajipur is currently hindered by several systemic bottlenecks. Foremost among these is the glaring lack of modern processing technology coupled with insufficient cold storage and transportation infrastructure. Without adequate facilities to safely store highly perishable yields or the advanced machinery required to efficiently process them at scale, local entrepreneurs face an uphill battle against post-harvest losses and compromised product quality.

Furthermore, those who do manage to establish micro-processing units often hit a commercial glass ceiling due to limited exposure to broader national markets. This geographic and economic isolation is compounded by a widespread low awareness of modern branding, packaging, and digital marketing strategies, which keeps innovative local products from competing on a larger, more lucrative stage. Amplifying these operational hurdles is a severe financial barrier; rural innovators frequently struggle to navigate complex bureaucratic channels to access the essential government loans, grants, and agricultural subsidies required for initial capital and business expansion.

To truly unlock the region's entrepreneurial potential, these hurdles must be systematically dismantled. Empowering local communities through targeted skill-development training, fostering robust cooperative models like Farmer Producer Organizations (FPOs), and ensuring streamlined, transparent government support are critical steps. By actively addressing these infrastructural, educational, and financial gaps, Hajipur can accelerate



its economic progress, ensuring that the wealth generated by its "golden crop" securely anchors the community's future.

Government Support and Agricultural Policies

Transforming the banana sector from traditional farming into a resilient, agro-industrial powerhouse requires robust institutional backing. Recognizing the profound economic potential of this crop, both the Government of Bihar and the Government of India have deployed a strategic framework of subsidies, credit-linked schemes, and training programs aimed at dismantling financial barriers for local cultivators and aspiring entrepreneurs.

Subsidies for Cultivation and Area Expansion: At the foundational level, the **National Horticulture Mission (NHM)**, operating under the broader Mission for Integrated Development of Horticulture (MIDH), provides targeted incentives to encourage high-quality, commercial farming. In Bihar, cultivators can avail themselves of substantial financial assistance—often covering up to 75% of the unit cost (up to ₹45,000 per hectare) for banana plantation. This critical financial cushion allows smallholder farmers to invest in disease-free, tissue-cultured plant varieties and modern micro-irrigation systems, drastically improving yield quality while mitigating initial agricultural risks.

Financing for Agro-Processing and Infrastructure: To combat the severe constraints of post-harvest losses and short shelf life, government policies are heavily pivoting toward value addition and localized infrastructure.

- **Machinery Subsidies:** The PM Formalisation of Micro Food Processing Enterprises (PMFME) scheme provides a 35% credit-linked capital subsidy (up to ₹10 lakhs) explicitly for upgrading or setting up micro food processing units. Paired with the Bihar State Food Processing Policy, entrepreneurs are empowered to purchase the modern machinery necessary for scaling the production of banana chips, powder, and fiber products.
- **PMEGP:** For local youth and Self-Help Groups (SHGs) looking to establish new manufacturing ventures, the Prime Minister's Employment Generation Programme (PMEGP) offers highly accessible margin money subsidies (ranging from 15% to 35%) to finance non-farm, agro-based enterprises.
- **NABARD:** To address the glaring lack of preservation facilities, NABARD provides affordable, low-interest term loans and refinancing options aimed at developing rural Godowns, cold storage, and primary processing infrastructure. This ensures that seasonal harvest gluts do not lead to economic ruin for the growers.

Capacity Building and Skill Development: Capital injection is most effective when paired with the technical know-how to sustain a business. Financial initiatives are increasingly intertwined with skill development programs facilitated by institutions like Krishi Vigyan Kendra (KVKs) and the State Rural Livelihoods Mission (JEEViKA). These programs train rural farmers, youth, and women-led cooperatives in modern agronomic practices, machinery operation, standard packaging, and basic business management.

By weaving together direct cultivation subsidies, infrastructural loans, and targeted education, these cohesive policies provide a comprehensive safety net. They empower local visionaries to scale their operations confidently, bridging the gap between traditional agricultural practices and modern, profitable production methods.

The Future of Banana Cultivation in Hajipur

The future of banana cultivation in Hajipur is exceptionally promising, standing on the brink of a major agricultural renaissance. Driven by a surging global and domestic demand for organic produce, eco-friendly natural fibers, and healthy, plant-based snacks, the Vaishali district is uniquely positioned to transition from a traditional farming region into a leading agricultural innovation hub.

Organic Certification and Premium Markets The first major leap toward this future lies in **organic banana certification**. As health-conscious consumers increasingly seek clean-label foods, securing organic credentials for local varieties like the famed *Chinia* and *Malbhog* can exponentially increase their market value. Because many traditional farmers in the Ganga basin already utilize natural bio-fertilizers and lower-chemical interventions, the transition to officially certified organic farming is highly achievable. This certification will not only command premium pricing in domestic metropolitan markets but also open the doors to lucrative international trade.

Mega Processing Clusters and Global Export To truly capitalize on its massive yield potential, the future landscape of Hajipur must include the development of **large-scale, banana-based processing clusters**. By consolidating fragmented micro-processing units into centralized agro-industrial parks equipped with state-of-the-art cold storage, automated slicing, milling, and fiber-extraction technology, the region can achieve massive economies of scale. This infrastructure is the critical missing link that will enable the **export of value-added products**. Instead of merely supplying raw, perishable fruit, Hajipur can dominate the global export market with vacuum-sealed premium banana chips, baby-grade green banana powder, and biodegradable banana-fiber textiles. **The Rise of Agri-Tourism** Beyond physical products, the lush, sprawling orchards of Hajipur offer a massive, untapped opportunity for **agri-tourism centered around banana farms**. By opening their estates to tourists, students, and agricultural researchers, farmers can create a highly profitable secondary revenue stream. Visitors could experience the entire lifecycle of the crop—from tissue culture planting to harvesting—participate in hands-on workshops making handmade paper from banana fiber, and enjoy farm-to-table culinary experiences. This holistic approach not only generates immediate income but also elevates the cultural heritage of the region onto a national stage.

A Hub for Entrepreneurship Ultimately, the transformation of Hajipur relies on bridging the gap between traditional agrarian practices and modern commercial enterprise. With targeted investments in improved technology, robust infrastructural support, and streamlined market access, the district is rapidly moving past mere cultivation. It is poised to become India's undisputed leading center for banana-based entrepreneurship, setting a benchmark for sustainable, profitable, and zero-waste agriculture.

Conclusion

Banana cultivation in Hajipur represents a profound and powerful blend of deeply rooted cultural tradition and emerging modern enterprise. As the region transitions from simply harvesting a raw commodity to establishing dynamic, value-added industries—ranging from premium banana chips and nutrient-dense powders to eco-friendly fiber products—it is actively reshaping the economic landscape of Vaishali. This evolution ensures that banana farming not only preserves its sacred cultural significance but also acts as the primary catalyst for rural entrepreneurship and women's empowerment.

However, realizing the full magnitude of this economic potential requires a grounded understanding of the cultivators themselves. Systematically addressing the everyday, on-the-ground constraints perceived by these growers—whether they are battling post-harvest losses, navigating market volatility, or seeking modern processing technology—is the critical bridge between traditional agrarian struggles and a thriving, resilient startup ecosystem.

By championing sustainable, zero-waste practices, modernizing local infrastructure, and fully leveraging targeted institutional support, the district can safeguard the livelihoods of its farming communities. In doing so, Hajipur will not only secure its rich agricultural heritage but will confidently step into the future as India's premier hub of agro innovation, truly cementing its legacy as the land of the Golden Crop.

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