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TRANSCRIPTION FACTORS: KEY REGULATORS OF GENE EXPRESSION IN PLANTS

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Introduction

Plants constantly face a wide range of environmental challenges such as drought, heat, pathogens, and nutrient limitations. To survive and adapt, plants rely on sophisticated molecular mechanisms that regulate when and how genes are expressed. One of the most important groups of proteins involved in this regulation are transcription factors (TFs). Transcription factors are specialized proteins that control the process of gene expression by binding to specific DNA sequences located in the regulatory regions of genes. By interacting with DNA and other proteins, transcription factors can either activate or repress the transcription of target genes. Through this process, it plays a central role in controlling plant growth, development, and responses to environmental signals. Plants possess several families of transcription factors, many of which are unique to the plant kingdom. These families are distinguished by their characteristic DNA-binding domains, which allow them to recognize specific DNA sequences and regulate particular groups of genes. Important plant-specific transcription factor families include AP2/ERF, B3, WRKY, NAC, and SBP. Many of these transcription factors have been extensively studied in the model plant *Arabidopsis thaliana*, which has provided valuable insights into their structure and function.

AP2/ERF family

The AP2/ERF family is one of the largest and most diverse groups of plant transcription factors. Members of this family share a conserved DNA-binding region that enables them to regulate genes involved in plant growth and stress responses. Based on their structural features, AP2/ERF transcription factors are divided into four major subfamilies: AP2, ERF, DREB, and RAV. Each subgroup recognizes specific DNA sequences and regulates different biological processes.

Functions

Proteins belonging to the AP2/ERF family are known to play important roles in plant responses to environmental stresses such as drought, cold, heat, and mechanical damage. They also participate in hormone-mediated signaling pathways, particularly those involving ethylene. In addition to stress responses, AP2/ERF transcription factors contribute to various developmental processes including flower formation, root development, embryo growth, and seed development.

B3 family

The B3 family is another group of plant-specific transcription factors characterized by a conserved DNA-binding domain. These proteins regulate genes that are important for plant development and hormone responses. B3 transcription factors are involved in signaling pathways associated with plant hormones such as auxin and abscisic acid. Through these pathways, they help control processes like seed maturation, embryonic development, and stress adaptation. Two important subgroups within the B3 family include the LAV group and the REM group, both of which contribute to plant developmental regulation.

WRKY family

The WRKY transcription factor family is widely known for its role in plant defense and stress responses. These proteins contain a conserved sequence motif that allows them to bind to specific regions of DNA known as W-box elements. WRKY transcription factors regulate genes involved in both biotic stresses, such as pathogen infection, and abiotic stresses, including drought and temperature extremes. By activating or repressing defense-related genes, WRKY proteins help plants respond rapidly to environmental threats.

NAC family

The NAC family represents another large group of plant transcription factors. These proteins function as dimers, meaning that two protein molecules associate together to perform their regulatory role. NAC transcription factors are involved in many important biological processes, including plant development, aging of leaves, and responses to environmental stress. They also participate in regulating genes associated with cell division, tissue differentiation, and stress tolerance.

SBP (SPL) family

The SBP (SQUAMOSA Promoter Binding Protein) family is a smaller group of transcription factors that play important roles in plant growth and development. These proteins are known to regulate flowering time, plant architecture, and nutrient uptake. Members of this family are particularly important in controlling flower development and copper uptake, which are essential processes for plant reproduction and metabolism.

Other Important Functional Domains of Transcription Factors

In addition to DNA-binding domains, transcription factors often contain several other functional regions that help them perform their regulatory roles. Activation domains help initiate gene transcription by interacting with RNA polymerase and other components of the transcriptional machinery. In contrast, repression domains suppress gene expression by recruiting proteins that inhibit transcription. Transcription factors also contain nuclear localization signals (NLS), which direct them to the cell nucleus where gene regulation occurs. Without these signals, transcription factors would not reach the correct cellular location to function properly. Another important feature is the presence of post-translational modification sites. Chemical modifications such as phosphorylation, acetylation, or ubiquitination can influence the activity, stability, and interactions of transcription factors. Finally, many transcription factors possess dimerization domains, which allow them to interact with other transcription factors. This interaction enables cooperative regulation of gene expression and increases the diversity of regulatory networks within plant cells.

Mechanism of TF action

Transcription factors control gene expression through a meticulously orchestrated process. Initially, they identify and attach to specific DNA sequences found in the promoter or enhancer regions of their target genes. This attachment is facilitated by specialized DNA-binding domains, enabling the transcription factor to detect distinct nucleotide patterns within the DNA. After binding to the DNA, transcription factors engage with various regulatory proteins and components of the transcriptional machinery. These interactions can either enhance or suppress the function of RNA polymerase, the enzyme tasked with synthesizing messenger RNA from DNA templates. Through these interactions, transcription factors serve as molecular switches that dictate whether a gene is activated or deactivated. In numerous instances, transcription factors do not operate in isolation. Rather, they

collaborate with other transcription factors and regulatory proteins to form complexes. This cooperative interaction enables plants to assimilate multiple signals from their environment and respond in a harmonized manner.

Role of Transcription Factors in Plant Stress Tolerance

Plants often face environmental challenges such as drought, salinity, extreme temperatures, and attacks by pathogens. In contrast to animals, plants are unable to relocate from unfavorable circumstances. As a result, they depend significantly on molecular regulatory systems, including transcription factors, to adapt and endure. Numerous transcription factors activate stress-responsive genes that assist plants in managing adverse situations. For instance, specific transcription factors oversee the production of protective proteins, osmolytes, and antioxidants that mitigate cellular damage during stressful periods. Others regulate the expression of genes that are crucial for water conservation, ion transportation, and metabolic adjustments. Through these mechanisms, transcription factors are essential in strengthening plant resilience to environmental stresses. Investigating these regulatory pathways has emerged as a key focus of research aimed at developing crops capable of better enduring shifting climate conditions.

Transcription Factors in Plant Development

In addition to their role in stress responses, transcription factors serve as crucial regulators of plant development. They oversee a diverse array of developmental processes, such as seed formation, germination, leaf development, flowering, and fruit production. Throughout plant growth, transcription factors manage the expression of genes responsible for cell division, cell differentiation, and tissue formation. For instance, specific transcription factors dictate the identity of floral organs, whereas others control the timing of flowering. Additionally, certain transcription factors contribute to root development, allowing plants to effectively absorb water and nutrients from the soil. Given that plant development entails intricate interactions among various genes and signaling pathways, transcription factors act as essential coordinators that guarantee proper growth and timing of development.

Interaction of Transcription Factors with Plant Hormones

Plant hormones, also known as phytohormones, are chemical messengers that regulate growth, development, and stress responses. Transcription factors play a central role in mediating the effects of these hormones. When a plant hormone signal is received, specific transcription factors become activated and bind to the promoters of hormone-responsive genes. This process leads to changes in gene expression that ultimately produce physiological responses. For example, transcription factors regulate genes involved in the responses to hormones such as auxin, abscisic acid, gibberellins, ethylene, and jasmonic acid. These hormone-regulated pathways influence processes such as seed germination, stem elongation, stress responses, and defense mechanisms. The interaction between transcription factors and plant hormones forms complex regulatory networks that allow plants to respond efficiently to internal and external signals.

Importance of Transcription Factors in Crop Improvement

The exploration of transcription factors has become increasingly vital in contemporary agricultural biotechnology. Since transcription factors govern extensive arrays of genes, altering a single transcription factor can affect numerous biological pathways at once. Scientists are investigating methods to modify transcription factors to enhance crop characteristics such as drought resistance, disease immunity, nutrient utilization, and overall yield. For instance, incorporating stress-

responsive transcription factors into agricultural plants can boost their capability to endure severe environmental challenges. Progress in molecular biology and genome editing techniques has enabled more in-depth examination of transcription factor networks. These advancements are creating fresh possibilities for the development of climate-resilient crops and promoting global food security.

Conclusion

Transcription factors play a vital role in regulating gene expression and enabling plants to adapt to changing environmental conditions. Plant-specific transcription factor families such as AP2/ERF, B3, WRKY, NAC, and SBP control a wide range of biological processes, including development, stress tolerance, and hormone signaling. Understanding how these transcription factors function provides valuable insights into plant biology and opens new opportunities for improving crop productivity and stress resistance. As research continues to uncover the complex networks controlled by transcription factors, scientists may be able to develop crops that are better equipped to withstand environmental challenges and meet future agricultural demands.

Referance

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SMALL FARMERS VS BIG MARKETS: WHO REALLY BENEFITS FROM AGRICULTURAL GROWTH?

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Introduction

Agricultural growth stands as a cornerstone of rural development and poverty alleviation in the developing world. However, a paradox persists: despite global expansion in agricultural output, why do small-scale farmers—who produce a substantial share of the world's food—remain trapped in poverty? The distribution of agricultural growth benefits reveals a deeply unequal landscape, with structural market disadvantages, asymmetric power dynamics, and policy biases systematically disadvantaging smallholders while concentrating gains among large-scale producers and agribusinesses. This article examines empirical evidence on who benefits from agricultural growth, the mechanisms driving inequality, and potential policy interventions to create more equitable outcomes.

The Productivity Paradox: Understanding Farm Size and Performance

The relationship between farm size and agricultural performance presents a deceptive picture when viewed through different lenses. A comprehensive meta-analysis of over 1,000 research cases published between 1997 and 2018 reveals that the answer depends fundamentally on how productivity is measured (González-Quintero *et al.*, 2021). When productivity is assessed using gross output indicators—yields or total production—an inverse relationship predominates: approximately 58% of cases show smaller farms producing more per hectare than larger farms. This finding has long supported international development strategies favouring smallholder agriculture.

However, this narrative shifts dramatically when examining indicators that are more economically informative. When profitability (net value) is measured, differences between small and large farms largely disappear; when technical efficiency is assessed, the relationship inverts entirely, and larger farms prove significantly more efficient, showing higher output per unit of input (González-Quintero *et al.*, 2021). This methodological distinction is critical: small farms achieve high yields through intensive deployment of family labour, but this labour intensity masks poor returns on labour, capital, and other inputs. In other words, small farms generate substantial physical output at the cost of low profitability and worker productivity.

The productivity paradox extends to labour economics. Larger farms consistently demonstrate superior labour productivity—output per worker—which directly translates into higher incomes per capita despite potentially lower yields per hectare (FAO, 2023; Hazell *et al.*, 2025). The fundamental trade-off is evident: small farms can maximize land productivity through intensive family labour. Still, this strategy fails to maximize income per person, a far more relevant metric for household welfare.

Market Access as a Structural Barrier

While technical characteristics partly explain differences in smallholder benefits from agricultural growth, market access emerges as the primary structural barrier to smallholder participation in

value chains and to price realization. Transaction costs—encompassing transportation, storage, market information, and intermediation fees—constitute invisible taxes on smallholder incomes, often exceeding 30-40% of the final consumer price (Okoye *et al.*, 2016). These costs disproportionately burden smallholders due to their distance from markets, poor infrastructure, and their inability to aggregate production for efficient transport.

Remote location compounds these challenges. In Sub-Saharan Africa and South Asia, poor road infrastructure substantially increases transportation costs, while limited market information creates information asymmetries that favour traders and intermediaries. Research from Madagascar shows that improved rural road access significantly increases farmers' propensity to market, with road quality to the nearest town emerging as a key determinant of commercialization (Okoye *et al.*, 2016). The poorest smallholders, paradoxically, often sell at farm gates to traders offering the lowest prices because they are unable to bear transportation and storage costs.

The intermediation problem proves particularly acute. Multiple layers of traders and intermediaries extract rents by exploiting smallholders' lack of market information and bargaining power. In Ghana, where farmers face a binary choice between farm-gate sales at depressed prices or expensive transportation to market centres, mediators operating in local markets extract substantial margins through information monopolies and collusion (Aworosuyi & Yirenkyi, 2020). Evidence from Uganda demonstrates that when smallholders lack direct market access, traders capture approximately 80% of value gains from cost reductions through collusion, passing through only 20% to consumers while offering negligible price improvements to farmers (Bergquist & Dinerstein, 2020).

The Green Revolution's Unequal Legacy

The historical case of the Green Revolution (1960s-1980s) provides cautionary evidence on how agricultural growth can exacerbate inequality when mechanisms for inclusive access fail. The Green Revolution's technology—high-yielding varieties paired with chemical fertilizers, irrigation, and mechanization—dramatically increased production but concentrated gains among larger, wealthier farmers who had capital, land access, and information.

Several factors produced this inequitable distribution. First, high capital requirements for modern inputs created a barrier for resource-constrained smallholders (Pingali, 2012). Government credit and subsidies for mechanization and inputs disproportionately flowed to larger farms due to collateral requirements and bureaucratic processes that favoured documented landholders (Feder *et al.*, 1985). Third, smaller farms exhibited rational risk aversion toward unproven technologies, particularly in uncertain institutional environments lacking extension services (Feder & O'Mara, 1982). The result: wealthier farmers adopted technologies and reaped productivity gains while poor smallholders fell further behind.

Contemporary India's experience echoes this pattern. Between 1960 and 1990, tenant-operated farms declined as owner-operated large farms increased, reflecting smallholders' inability to afford Green Revolution inputs and subsequent land abandonment or consolidation. Regional disparities widened as irrigation-blessed areas benefited while rainfed regions with low irrigation coverage—accounting for over a quarter of India's farm suicides—remained trapped in subsistence farming (Feder & O'Mara, 1982).

Corporate Consolidation and Market Power

Modern agricultural growth increasingly concentrates among large-scale producers and agribusinesses, amplifying historical inequalities. India's experience illustrates this trend starkly:

post-1991 liberalization policies systematically favoured capital-intensive corporations by reducing public investment in support for smallholders, while agribusiness conglomerates expanded control over seeds, inputs, logistics, and markets. By 2024, India's top 10 agribusinesses received loans totalling ₹1.3 lakh crore—approximately five times the amount available to all small and marginal farmers combined —demonstrating an institutional bias toward corporate agriculture (Insights on India, 2025).

This corporate penetration extends across value chains. Multinational agribusinesses control seed markets through intellectual property and cross-licensing agreements, effectively displacing local seed varieties and independent producers. In input markets, concentration ratios exceeding 40%—the threshold at which economists identify a risk of monopolistic abuse—have been documented in fertilizers, pesticides, and machinery across developing countries. When buyers and suppliers are similarly concentrated, small farmers face simultaneous squeezes: inflated input costs and depressed output prices.

The Minimum Support Price (MSP) system in India, despite theoretical benefits, fails smallholders when procurement mechanisms remain distant and insufficiently coordinated. Farmers selling at farm gates frequently receive prices 250-400 below the MSP due to poor procurement infrastructure and asymmetric information, negating policy protections intended to ensure remunerative prices (Government of India, 2024). While buffer stock operations in Ghana demonstrated 12-17% income increases for participating farmers (Aworosuyi & Yirenkyi, 2020), such programs require sustained investment and transparent implementation that many developing countries lack.

Agricultural Growth Distribution: Recent Evidence

Recent agricultural growth has not uniformly benefited smallholders. India's agricultural gross value added (GVA) at current prices doubled from ₹25 lakh crore in 2015-16 to ₹51 lakh crore in 2023-24, yet the benefits were distributed unevenly. While the small and marginal farmer segment's share of aggregate output increased from 41% to 57%, this reflects farming intensification rather than income gains proportional to the growth rate (Government of India, 2024). In real terms, agricultural growth in India has averaged only 3% annually, insufficient for meaningful income expansion given population pressures.

In Latin America, farm size exhibits a consistent positive relationship with agricultural income and wage levels (Hazell *et al.*, 2025). Regions with higher average farm sizes exhibit higher average agricultural household incomes and wages, even after controlling for land suitability and climate, indicating that structural consolidation—not just productivity—drives regional income variations.

Export commodity chains demonstrate particular disparities. While smallholders produce 73% of global coffee, 90% of cocoa, and the majority shares of tea and bananas, they capture minimal value—typically 5-15% of final consumer prices. Larger farms and processors dominating export channels retain 85-95% of the value, with smallholders receiving commodity prices vulnerable to global market fluctuations, absent long-term contracts or value-added processing (FAO, 2023).

Market Access Interventions: Evidence on Effectiveness

However, rigorous evidence demonstrates that targeted interventions can substantially improve smallholder benefits from agricultural growth. A comprehensive review of 29 randomized controlled trials and quasi-experimental studies identifies several high-impact market-access interventions (Abdul Latif Jameel Poverty Action Lab & Centre for Effective Global Action, 2024).

Contract farming emerges as particularly effective. In Benin, rice farmers who offered fixed-price contracts increased cultivated area by 23%, yields by 29%, sales volumes by 140%, and incomes by 52% (approximately US\$140) compared to control groups (Arouna *et al.*, 2021). The mechanism operates through uncertainty reduction: guaranteed prices enable optimal investment in inputs and resource allocation. Similar patterns appear in coffee quality-upgrading programs in Colombia, where contracting increased the prices paid to quality-focused smallholders by a significant amount.

Digital market linkage platforms have increased income by 20-25% for farmer-producer organizations (FPOs) in India by reducing intermediation layers and connecting them directly to bulk buyers. However, adoption remains limited among the poorest farmers lacking digital literacy or access (StarAgri, 2025). Agrifood value chain finance, where financial institutions lend through anchor firms purchasing farmer output, overcomes collateral constraints while ensuring market access—successfully deployed in dairy value chains across East Africa, Punjab, and Central Europe (IFAD, 2014).

Infrastructure investment yields consistent 2-3% income gains: rural road development enabling market access, combined with proximate banking services, increased farmer incomes by 2.8% as farmers diversified into higher-risk, higher-return crops made feasible by reduced transaction costs (Abdul Latif Jameel Poverty Action Lab & Centre for Effective Global Action, 2024). Storage technologies paired with credit improve farmer incomes by enabling harvest sales timing optimization—in Burkina Faso, access to warehouse-backed credit increased grain sales revenues by 15% (approximately US\$235) as farmers stored during peak supply seasons and sold during higher-price periods (Delavallade & Godlonton, 2023).

Mechanisms of Unequal Benefit Distribution

The fundamental mechanisms concentrating agricultural growth benefits among larger producers and agribusinesses operate across multiple domains. First, scale economies in input access persist: large farms negotiate favourable terms for bulk inputs, while smallholders pay premium rates through fragmented purchases via local traders. Second, information asymmetries enable trader exploitation; smallholders lack timely price information and knowledge of market standards, while traders profit from information arbitrage. Third, credit access disparities force smallholders into informal lending at 36-60% annual rates, consuming margins that larger farms retain through institutional credit access at 8-12%.

Fourth, policy bias toward commercial agriculture reflects political economy considerations: large farmers and agribusinesses exercise disproportionate political influence, securing subsidies for mechanization, irrigation, and inputs. Simultaneously, extension services degraded in many countries, reducing smallholder access to productivity-enhancing technical knowledge. Fifth, value chain positioning disadvantages smallholders: as primary producers occupying the lowest value-added position in supply chains, smallholders capture minimal margins regardless of output growth, with processors, retailers, and exporters capturing the majority of consumer-paid value.

Smallholder Contributions Often Overlooked

Despite unequal benefit distribution, smallholders' efficiency and contribution merit recognition. Farms smaller than two hectares produce approximately one-third of global food on one-quarter of agricultural land; those between two and five hectares produce 46% of global food on one-third of land (FAO, 2023). Small farms dedicate 70% of their production to direct human consumption,

compared to 55% globally, suggesting a stronger nutritional orientation. In specific crops—rice, peanut, cassava, millet—smallholders produce 60-80% of global supplies, rendering them essential for food security.

Small-farm resilience through crop diversification and ecological practices contrasts favourably with large-farm monocultures. Research across Sub-Saharan Africa documents higher non-crop biodiversity on small farms due to field-edge preservation, limited chemical use, and diverse land-cover types, thereby sustaining both ecosystem functions and farmers' risk management (FAO, 2023).

Policy Imperatives and Recommendations

Evidence suggests several policy directions for achieving a more equitable distribution of agricultural growth. First, value chain integration through FPO support, cooperative strengthening, and contract farming promotion can reduce transaction costs and intermediation layers, as documented in India's 10,000 FPO Formation Program, with evidence of 20-25% income improvements where successfully implemented. Second, targeted infrastructure investment in rural roads, electricity, and market facilities reduces transaction costs, particularly benefiting smallholders in remote areas.

Third, reformed credit systems that emphasize agricultural value chain finance and group lending overcome collateral constraints that block smallholder investment, as demonstrated across dairy value chains and export commodity systems. Fourth, technology and information provision through extension services and digital platforms, though requiring investments in digital literacy, can reduce information asymmetries, enabling better price realization and input decisions. Fifth, institutional reforms to ensure MSP implementation through proximate procurement centres and transparent mechanisms reach marginal and small farmers rather than merely large commercial operations.

Sixth, anti-monopoly enforcement that limits corporate concentration in seed, input, and output markets preserves competitive conditions that benefit smallholders. This extends to regulating contract farming terms to prevent farmer exploitation and ensuring equitable benefit sharing.

Conclusion

Agricultural growth fails to equally benefit small farmers primarily because of structural market disadvantages, corporate consolidation, information asymmetries, and policy biases, rather than inherent technical inefficiency. While small farms achieve impressive land productivity through intensive family labour, this masks poor profitability and worker productivity, rendering them vulnerable to income poverty despite adequate physical output. Market access barriers—high transaction costs, trader exploitation, limited credit access, and distance from organized markets—consume potential gains, concentrating benefits among large-scale producers who are positioned to navigate complex value chains.

Contemporary evidence demonstrates that targeted interventions—contract farming, digital market linkage, value chain finance, infrastructure investment, and storage technologies—can substantially improve smallholder benefit realization from agricultural growth. However, scaling these interventions requires political commitment to smallholder support, institutional reforms to limit corporate market power, and investment in public goods that benefit remote, poor farmers whom markets alone will not serve. The choice between inclusive agricultural development and deepening rural inequality is fundamentally a policy choice reflecting political priorities and

institutional capacity. Achieving shared agricultural growth requires deliberate intervention in markets where private incentives alone perpetuate inequality.

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GENETIC ENGINEERING: A NEW HOPE FOR PROTECTING CROPS FROM PLANT DISEASES

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Introduction

Plant diseases caused by bacteria, fungi, and other pathogens have always posed a major challenge to global agriculture. Studies estimate that 11–30% of global crop production is lost each year due to pests and diseases, and these losses are often greatest in regions already suffering from food shortages. Plant pathogens such as fungi, bacteria, and viruses attack crops in fields across the world, reducing yields and affecting the livelihoods of millions of farmers. Traditional disease control methods such as chemical pesticides, crop rotation, and breeding for resistant varieties have helped manage these problems, but they are often insufficient to keep up with rapidly evolving pathogens. In recent decades, advances in biotechnology have opened new possibilities for protecting crops. Genetic engineering and genome editing technologies allow scientists to directly modify plant genes or introduce new ones that enhance resistance to diseases. These approaches expand the genetic toolbox available to plant breeders and provide powerful new strategies for sustainable crop protection. Understanding how plants defend themselves against pathogens has been the foundation for developing these technologies. Research over the past few decades has revealed that plants possess a sophisticated immune system capable of recognizing invading microbes and activating defense responses.

The plant Immune system: How plants detect pathogens

Although plants lack specialized immune cells like those found in animals, they have evolved highly effective defense mechanisms to detect and respond to pathogens. The plant immune system operates through a multi-layered surveillance system that distinguishes between “self” and “non-self” molecules. The first layer of plant immunity involves proteins located on the surface of plant cells known as pattern recognition receptors (PRRs). These receptors detect molecules that are commonly found in pathogens, known as pathogen-associated molecular patterns (PAMPs). When PRRs detect these molecules, they trigger a defense response known as pattern-triggered immunity (PTI). However, pathogens have evolved ways to bypass this defense mechanism. Many microbes produce specialized proteins called effectors, which interfere with the plant’s immune responses and help the pathogen invade plant tissues. To counter this strategy, plants have developed a second layer of defense involving intracellular receptors known as NLR (nucleotide-binding leucine-rich repeat) proteins. These receptors detect the presence or activity of pathogen effectors and activate a stronger immune response called effector-triggered immunity (ETI). Together, PTI and ETI form a powerful defense network that allows plants to detect and respond to microbial invasion. Understanding this system has enabled scientists to develop new strategies for engineering disease-resistant crops.

Enhancing pathogen recognition through genetic engineering

One of the most promising strategies for improving plant disease resistance involves enhancing the plant's ability to recognize pathogens. Scientists can introduce immune receptors from one plant species into another, enabling crops to detect pathogens they previously could not recognize. For example, researchers have successfully transferred immune receptors between plant species to improve resistance to bacterial diseases. A well-known example involves introducing the EF-Tu receptor gene from *Arabidopsis thaliana* into crops such as tomato and rice. This receptor allows plants to detect bacterial proteins and activate defense responses more effectively. Another strategy involves transferring NLR resistance genes from wild plant relatives into cultivated crops. These genes enable plants to detect pathogen effectors and trigger strong immune responses. A successful case involves genetically engineered potatoes that contain resistance genes against late blight caused by *Phytophthora infestans*, the pathogen responsible for the historic Irish potato famine. These potatoes demonstrate how genetic engineering can provide effective protection against devastating plant diseases. Researchers have also developed innovative approaches known as "protease traps" or decoy systems. In this method, plants are engineered so that pathogen enzymes trigger immune responses by interacting with specially designed host proteins. This approach expands the range of pathogens that plants can detect and resist.

Strengthening plant defense signaling pathways

After a pathogen is detected, plants must activate complex signaling pathways to mount an effective defense response. Several plant hormones play critical roles in this process, including salicylic acid, jasmonic acid, and ethylene. Salicylic acid is primarily associated with resistance against pathogens that feed on living plant tissues, while jasmonic acid and ethylene are involved in defense against pathogens that kill plant cells. These hormones coordinate the expression of defense-related genes and activate protective mechanisms. Genetic engineering can enhance these signaling pathways by increasing the expression of key regulatory genes. For instance, scientists have modified genes involved in salicylic acid signaling to strengthen plant defense responses. However, continuously activating defense responses can negatively affect plant growth and productivity. To avoid this problem, researchers are developing systems that activate defense genes only when pathogens attack, ensuring that plants remain productive while still being protected.

Targeting susceptibility genes using genome editing

In some cases, plant genes actually make plants more vulnerable to pathogens. These genes are known as susceptibility genes because pathogens exploit them during infection. Modern genome editing technologies allow scientists to modify or remove these genes, thereby making plants resistant to disease. One well-known example involves the MLO gene, which is associated with susceptibility to powdery mildew. When this gene is disrupted, plants become resistant because the fungus can no longer invade plant cells effectively. Genome-edited tomatoes with modified MLO genes have shown strong resistance to powdery mildew disease, demonstrating the potential of this strategy for crop improvement.

Transferring resistance genes between Plant Species

Some plants naturally possess genes that provide strong resistance to pathogens. These genes can sometimes be transferred into other crop species to improve their disease resistance. For example, proteins such as plant ferredoxin-like protein (PFLP) and hypersensitive response-assisting protein (HRAP) were originally discovered in sweet pepper plants. When these genes were introduced into crops such as rice and bananas, the plants showed enhanced resistance to bacterial diseases. Field

trials in Uganda demonstrated that bananas expressing these genes were highly resistant to bacterial wilt caused by *Xanthomonas campestris*, without affecting plant growth or yield. This approach demonstrates how genes from one plant species can be used to strengthen disease resistance in another.

Using antimicrobial proteins to protect crops

Many organisms produce antimicrobial compounds that protect them from pathogens. Scientists have explored the possibility of introducing these natural defense molecules into crops. These antimicrobial proteins can attack pathogens in various ways, including destroying fungal cell walls, disrupting cell membranes, or interfering with essential metabolic processes. For example, a defensive protein derived from radish has been expressed in wheat plants, providing increased resistance to fungal pathogens. Similarly, synthetic antimicrobial peptides have been introduced into crop plants to improve resistance to disease. Although promising, this approach must be carefully evaluated because antimicrobial proteins can sometimes affect plant growth or interact with other organisms in the environment.

RNA Interference: A new strategy for disease control

Another powerful tool for disease control is RNA interference (RNAi), a natural biological process that regulates gene expression. In this approach, plants are engineered to produce small RNA molecules that silence essential genes in invading pathogens. When the pathogen infects the plant, these RNA molecules interfere with the pathogen's gene expression, preventing it from growing or reproducing. This technique, known as host-induced gene silencing, has been successfully used to control several fungal pathogens. For example, RNAi strategies targeting important fungal genes have significantly reduced infections in various crop species. RNA interference represents a highly targeted method for disease control because it affects only the pathogen without altering the plant's own genes.

Transgenic approaches for bacterial disease resistance

Bacterial diseases are another major threat to crop production. Genetic engineering has provided several strategies to improve resistance against bacterial pathogens. Researchers have introduced antibacterial proteins from different organisms into plants. These proteins can kill or inhibit bacteria, reducing disease symptoms. For example, genes encoding antimicrobial peptides from insects have been expressed in crops such as potato and tobacco. These plants showed improved resistance to bacterial pathogens that cause wilt diseases. In addition, transferring immune receptors between plant species has allowed crops to recognize bacterial pathogens more effectively and activate their defense responses.

Challenges and Future Prospects

Despite the promising potential of genetic engineering, several challenges remain before these technologies can be widely adopted. Transgenic plants must perform well under field conditions while maintaining high yield and quality. Regulatory approval processes also require extensive testing to ensure that genetically engineered crops are safe for human consumption and the environment. Future advances in genome editing, gene stacking, and molecular breeding are expected to accelerate the development of disease-resistant crops. Modern tools such as Resistance gene enrichment sequencing (RenSeq) help scientists identify new resistance genes more quickly, while advanced gene assembly techniques allow multiple beneficial genes to be combined into a single crop variety. These innovations are paving the way for the next generation of disease-resistant crops that can thrive in challenging environments.

Conclusion

Plant diseases remain a major obstacle to global food security, but advances in biotechnology offer promising solutions. By understanding how plants detect and respond to pathogens, scientists have developed innovative strategies to enhance disease resistance through genetic engineering and genome editing. Approaches such as improving pathogen recognition, strengthening defense signaling pathways, modifying susceptibility genes, and using RNA interference are transforming modern crop protection strategies. With continued research and responsible application, these technologies have the potential to produce crops that are more resilient to disease, reduce reliance on chemical pesticides, and help ensure sustainable food production for the growing global population.

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WHEN RIVERS STOP FLOWING: WHY WATER VELOCITY MATTERS MORE THAN WE THINK

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The overlooked heartbeat of a river

Ask most people what keeps a river healthy, and they will mention clean water, good rainfall, or the absence of pollution. Few will say water velocity. Yet, the speed at which water moves is the river's hidden heartbeat (Kumar et al. 2022). It governs how oxygen dissolves, where sediments settle, how nutrients travel, where algae grow, and which fish can survive.

A river is not defined only by how much water it carries, but by how fast that water moves.

Velocity creates habitats you can't see at a glance

Natural rivers form a repeating pattern called riffle–run–pool:

- Riffles: shallow, fast, turbulent stretches over stones; rich in oxygen
- Runs: moderate depth and speed; ideal feeding corridors for fish
- Pools: deeper, slower pockets; refuges during heat or low flow

This mosaic exists because of velocity differences. Many aquatic organisms are specialized for one of these micro-habitats. When velocity declines uniformly, this diversity of habitats collapses into a single, slow, featureless stretch.

Oxygen: mixed by motion, not by magic

Oxygen does not simply “exist” in water. It is mixed in by turbulence. Fast water breaks the surface, traps air, and keeps dissolved oxygen high. Slow water becomes stratified, warm, and oxygen-poor—especially at night when plants and algae respire.

This is why fish that thrive in swift currents struggle in still reaches, even if the water looks clear.

What happens upstream of a barrage

When a barrage or dam slows a river:

- Current velocity drops sharply
- Water residence time increases
- Suspended particles settle
- Sunlight penetrates deeper
- Nutrients accumulate instead of flushing downstream

The river begins to behave like a pond. Algae multiply, water turns green, and oxygen fluctuates widely between day and night. These changes are driven less by pollution inputs and more by loss of flow energy (Vannote *et al.*, 1980).

Sediment: the architect controlled by speed

Sediment transport depends entirely on velocity. Fast water carries sand and silt; slow water drops them.

Upstream of barriers, sediment settles and buries rocky beds that many fish use for spawning. Downstream, the water—now starved of sediment—erodes banks and scours the channel. The same structure creates siltation on one side and erosion on the other, purely through altering velocity (Kumar *et al.*, 2026).

From flow to food webs

When velocity declines:

1. Algae and phytoplankton increase due to longer retention time
2. Cyanobacteria often dominate in stagnant, nutrient-rich water
3. Zooplankton food quality declines
4. Oxygen dips during night respiration
5. Sensitive, current-loving (rheophilic) fishes disappear
6. Tolerant species replace them

What looks like a simple slowing of water becomes a complete restructuring of the food web.

Why fish ladders don't solve this problem

Fish passages are designed to help migration across barriers. But they do not restore the velocity regime across kilometres of upstream river. Even if fish can cross, the habitat they return to may no longer suit their ecological needs.

Fish require not just passage, but flowing habitat.

Clues visible to the naked eye

You can often tell velocity loss without instruments:

- Greenish, still water upstream of gates
- Fine silt covering stones
- Absence of riffles and bubbling sounds
- Foul smell during low flow
- Increase in aquatic weeds and algal mats

These are not merely aesthetic changes; they signal a river losing its functional dynamics.

Measuring the invisible driver

Hydrologists measure velocity with simple current meters. Ecologists interpret it as a master variable controlling habitat quality. Yet, river monitoring programs often record only discharge (volume), not how that volume is distributed across the channel in terms of speed and turbulence.

Two rivers with the same discharge can be ecologically very different if their velocities differ.

Why this matters for people

For fisher communities, reduced velocity means:

- Lower fish catch
- Loss of native species
- Nets clogged with algae
- Poor water quality during lean seasons

For cities, it means a greater risk of eutrophication and foul water. For biodiversity, it means habitat simplification (Pal *et al.*, 2024).

Restoring a river's heartbeat

Improving river health is not only about reducing pollution. It is about restoring flow characteristics:

- Environmental flow releases that mimic natural velocity
- Avoiding prolonged water stagnation upstream of barrages
- Designing operations that create periodic flushing flows
- Recognizing velocity as an ecological parameter in river management

A river must move to remain a river.

The simple truth

Clear water is not always healthy water. A slow river is often a stressed river. The life of a river depends not just on how much water it holds, but on how energetically that water travels.

When rivers stop flowing, ecology begins to fade—quietly, gradually, and invisibly.

Water velocity is not a minor detail of hydrology. It is the defining force of river life.

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GENETIC ENGINEERING FOR RESISTANCE AGAINST SUBMERGENCE AND HIGH-TEMPERATURE STRESS

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Introduction

Agriculture around the world is facing serious challenges due to climate change and unpredictable environmental conditions. Among the many factors that affect crop productivity, abiotic stresses such as drought, flooding, salinity, and high temperature are the most common and damaging. It is estimated that only about 10% of the world's agricultural land is free from environmental stress. The remaining land is affected by one or more stress conditions that reduce crop growth and yield. Abiotic stresses are non-living environmental factors that negatively affect plant growth. These include drought, salinity, flooding, extreme temperatures, nutrient deficiency, heavy metal toxicity, and ultraviolet radiation. Such stresses disturb plant metabolism, damage plant tissues, and ultimately reduce crop productivity. With the increasing effects of global climate change, these stresses are becoming more severe and frequent. Plants have naturally evolved different mechanisms to cope with environmental stress. However, natural tolerance is often not sufficient to protect crops under severe conditions. Therefore, scientists are exploring modern techniques such as genetic engineering to develop crop varieties that can tolerate harsh environmental conditions. Genetic engineering allows scientists to introduce specific genes into plants that help them survive under stressful conditions. By manipulating genes that control stress responses, researchers can improve plant tolerance to flooding, heat, drought, and other environmental challenges. This technology provides new opportunities to improve crop productivity and food security in a changing climate. Two major environmental stresses that significantly affect crop production are submergence/ flooding and high-temperature stress. Understanding how plants respond to these stresses and how genetic engineering can help improve tolerance is essential for developing climate-resilient crops.

Plant responses to abiotic stress

Plants cannot move away from unfavorable environmental conditions. Instead, they adapt by activating various physiological, biochemical, and molecular responses. When plants experience stress, they trigger a series of protective mechanisms that help them survive.

These responses include:

- Activation of stress-responsive genes
- Production of protective proteins
- Stabilization of cell membranes
- Removal of toxic molecules
- Adjustment of plant metabolism

One of the most important groups of proteins involved in stress tolerance are heat shock proteins (HSPs). These proteins help protect other proteins from damage during stressful conditions such as

heat or oxidative stress. Plants also produce antioxidants that help neutralize harmful molecules known as reactive oxygen species (ROS), which accumulate during stress. In addition, plants regulate hormones and signaling pathways to coordinate stress responses. However, these natural responses are often not strong enough to protect crops under extreme environmental conditions. Therefore, scientists are using genetic engineering to enhance these natural mechanisms.

Submergence or flooding stress

Flooding is one of the major environmental stresses affecting agriculture worldwide. It occurs when agricultural land is covered with water for a prolonged period. Flooding reduces oxygen availability in the soil, which is essential for root respiration. As a result, plant growth slows down and crops may die if the stress continues for a long time. Rice is one of the few crops that can tolerate waterlogged conditions. However, even rice plants can be severely damaged when completely submerged under water for several days. In recent decades, the risk of flooding has increased due to climate change, heavy rainfall, and rising water levels. Flooding can destroy crops within a short period, leading to major losses in agricultural production and threatening food security. Plants respond to flooding by activating anaerobic metabolism because oxygen becomes limited in submerged conditions. Under such conditions, plants shift from aerobic respiration to fermentation in order to generate energy. Scientists have identified several genes that help plants survive under submerged conditions. By transferring or manipulating these genes, it is possible to develop crop varieties that can tolerate flooding more effectively.

Genetic approaches for flooding tolerance in rice

Rice is one of the most important staple crops in the world, feeding billions of people. Researchers have identified several genetic mechanisms that help rice plants survive under flooding conditions.

Three important types of flooding tolerance in rice include:

- Anaerobic germination tolerance
- Flash flooding tolerance
- Stagnant flooding tolerance

1. Anaerobic Germination

During flooding, seeds may germinate in oxygen-deficient conditions. Some rice varieties can germinate successfully under such anaerobic conditions. Researchers found that genes involved in energy metabolism play an important role in this process. One such gene controls the production of Trehalose-6-phosphate, which helps improve energy supply during low oxygen conditions. When this gene is overexpressed, rice seedlings grow faster and establish better under submerged conditions.

2. Flash Flooding Tolerance

Flash flooding occurs when crops are suddenly submerged due to heavy rainfall or river overflow. In such conditions, plants must conserve energy until the floodwater recedes. One of the most important genes associated with submergence tolerance in rice is Sub1A. This gene belongs to a family of ethylene-responsive transcription factors. Research led by Pamela Ronald and David Mackill discovered that the Sub1A gene helps rice plants survive under submerged conditions for up to two weeks. Rice varieties containing the Sub1A gene slow down their growth during flooding and conserve energy. This strategy helps them survive until the water level decreases. When normal conditions return, the plants resume growth and produce normal yields. The flood-tolerant rice variety FR13A became famous for its remarkable ability to survive prolonged submergence. This

discovery led to the development of improved flood-tolerant rice varieties that are now cultivated in many flood-prone regions.

3. Stagnant Flooding Tolerance

In some areas, floodwater remains in the field for a long time, but the plants are not completely submerged. Under such conditions, rice plants need to grow taller in order to keep their leaves above the water surface. Scientists discovered special genes known as SNORKEL genes that help rice plants adapt to deep-water conditions. SNORKEL1 and SNORKEL2 genes trigger rapid stem elongation in rice plants, allowing them to keep their leaves above the water level. This elongation is regulated by the plant hormone gibberellin, which promotes internode growth. As a result, deep-water rice varieties can survive in flooded environments by growing taller.

High temperature stress in plants

Another major environmental stress affecting agriculture is high temperature. Global warming has increased the frequency of heat waves and extreme temperature conditions in many parts of the world. According to the Intergovernmental Panel on Climate Change (IPCC), the global average temperature is expected to rise significantly in the coming decades. Even a small increase in temperature can have serious effects on crop productivity.

High temperatures affect plants in many ways:

- Reduced photosynthesis
- Damage to proteins and enzymes
- Increased water loss
- Poor seed germination
- Reduced grain formation
- Lower crop yields

Heat stress also causes the accumulation of damaged or misfolded proteins inside plant cells. These damaged proteins can disrupt normal cellular functions and eventually lead to cell death. To protect themselves, plants produce special proteins called heat shock proteins (HSPs).

Role of Heat Shock Proteins in Heat Tolerance

Heat shock proteins act as molecular chaperones, which means they help other proteins maintain their proper structure and function during stressful conditions. These proteins prevent the aggregation of damaged proteins and assist in their proper folding. As a result, they help maintain cellular stability under high temperatures. Several types of heat shock proteins have been identified in plants, including:

- HSP100
- HSP70
- Small heat shock proteins (sHSPs)

Scientists have successfully introduced genes encoding these proteins into plants using genetic engineering techniques. This approach helps plants tolerate higher temperatures than normal.

Transgenic approaches for heat tolerance

Many genes have been studied for improving heat tolerance in plants. Some important examples include:

- Heat shock transcription factors (HSF) that regulate the expression of heat-responsive genes
- HSP101 which helps plants recover from heat damage

- Small heat shock proteins that stabilize cellular structures
- Antioxidant enzymes that reduce oxidative stress

One of the most notable studies involved introducing the HSP17.7 gene from carrot into potato plants. Transgenic potato plants expressing this gene exhibited improved membrane stability under high temperatures. These genetically modified plants were able to maintain better growth and produce larger tubers even under elevated temperature conditions. Another study demonstrated that overexpression of HSP101 from *Arabidopsis* improved heat tolerance in basmati rice. In this research, transgenic rice plants were exposed to temperatures as high as 45°C. The genetically engineered plants showed better survival and recovery compared to normal plants. These results demonstrate the potential of genetic engineering to improve crop tolerance to extreme temperatures.

Other genetic strategies for heat stress tolerance

In addition to heat shock proteins, scientists have explored several other genes that help protect plants from heat stress. For example:

- Overexpression of ascorbate peroxidase genes improves antioxidant defense systems in plants.
- Glutathione peroxidase genes help remove harmful reactive oxygen species.
- Superoxide dismutase enzymes protect cells from oxidative damage caused by heat stress. These genes strengthen the plant's natural defense mechanisms and improve survival under stressful conditions.

Importance of genetic engineering in modern agriculture

Genetic engineering has become an important tool for developing stress-tolerant crops. Traditional plant breeding methods can take many years to develop improved varieties, whereas genetic engineering allows scientists to introduce specific genes more precisely and efficiently. The development of stress-tolerant crops offers several benefits:

- Increased crop productivity under adverse conditions
- Reduced crop losses due to environmental stress
- Improved food security for a growing population
- Better adaptation to climate change

Flood-tolerant rice varieties developed using the Sub1A gene are already helping farmers in flood-prone regions of Asia. Similarly, research on heat-tolerant crops is becoming increasingly important as global temperatures continue to rise.

Future Prospects

With advances in biotechnology, new techniques such as gene editing and genome sequencing are making it easier to identify and manipulate stress-related genes. Modern tools such as CRISPR gene editing allow scientists to modify plant genes with high precision. This technology has the potential to accelerate the development of climate-resilient crops. Future research will focus on combining multiple stress-tolerance genes in a single crop variety. This will help plants withstand several environmental stresses simultaneously, such as drought, heat, and flooding. Such innovations will play a key role in ensuring sustainable agriculture and global food security in the coming decades.

Conclusion

Abiotic stresses such as flooding and high temperature pose serious threats to agricultural productivity worldwide. Climate change is expected to intensify these stresses, making it increasingly difficult to maintain stable crop yields. Genetic engineering provides a powerful

approach to improve plant tolerance to environmental stresses. Genes such as Sub1A, SNORKEL, and various heat shock proteins have shown significant potential in enhancing plant survival under submergence and high-temperature conditions. The development of genetically engineered crops that can withstand extreme environmental conditions will be essential for meeting the food demands of a growing global population. Continued research in plant biotechnology will help create resilient crop varieties capable of sustaining agriculture in a changing climate.

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UNLOCKING SEED VITALITY AND SOIL HEALTH WITH *BEEJAMRIT*

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Introduction

Seed is the foundation of agriculture. The health, vigour and productivity of a crop largely depend on the quality and condition of the seed used for planting. Farmers across the world adopt various seed treatment practices to protect seeds from diseases, improve germination and ensure healthy seedling establishment. In recent years, natural farming approaches have revived traditional seed treatment practices, among which *Beejamrit* has emerged as a key component. Considered one of the pillars of natural farming, *Beejamrit* is widely promoted for its ability to protect seeds from soil-borne pathogens while enhancing microbial activity and early seedling vigour. Natural farming systems and similar agroecological approaches emphasise reducing dependence on synthetic chemicals and restoring the natural biological processes of the soil. Within this framework, *Beejamrit* acts as a biological seed treatment formulation prepared from locally available natural ingredients, primarily derived from indigenous cow products and soil microbes (Table 1). The use of *Beejamrit* represents a transition from chemical-intensive seed protection methods towards ecologically balanced crop establishment practices.

What is *Beejamrit*?

Beejamrit is a traditional fermented microbial concoction containing loads of beneficial microbes and used to protect seeds from pathogens, improve seed germination and promote early seedling growth. The term *Beejamrit* refers to *Beej* (meaning seed) dipped in *Amrit* (meaning magical liquid), reflecting its role in enhancing seed vitality and resilience.

Table 1. Ingredients used in the preparation of *Beejamrit*

Ingredient	Quantity (for one acre land or 100 kg seed)
Cow dung (fresh)	5 kg
Cow urine (aged)	5 L
Lime	50 g
Topsoil from a native 'virgin' soil	Handful
Water	20 L

These ingredients are thoroughly mixed and fermented for 24 hours to allow beneficial microbes to multiply (Fig. 1). The seeds are then coated with the *Beejamrit* solution and shade-dried before sowing, or the seedling roots may be dipped in the solution for five minutes prior to transplanting. The rhizomes/tubers/grafts/cuttings may be dipped in *Beejamrit* for 10-20 minutes before planting.

The microbial diversity present in cow dung, cow urine and native virgin soil contributes to the biological effectiveness of *Beejamrit*. These components contain various beneficial bacteria, fungi and actinomycetes that help suppress harmful pathogens in the seed environment. Lime helps maintain a suitable pH and contributes to the overall stability of the formulation.

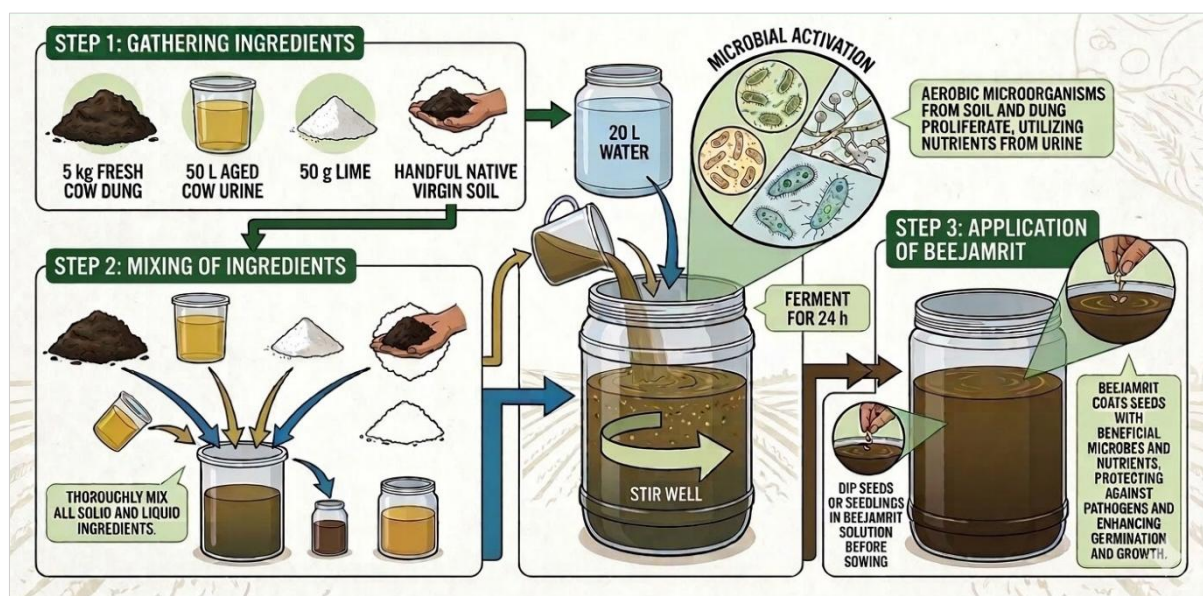


Fig. 1. A scientific flow diagram of the preparation of *Beejamrit*

Role of *Beejamrit* in natural farming

In natural farming systems, *Beejamrit* performs several important functions related to seed protection and crop establishment:

1. *Beejamrit* acts as a biological shield against seed-borne and soil-borne diseases. Seeds often carry fungal pathogens such as *Fusarium*, *Rhizoctonia* and *Pythium*, which can cause seed rot, damping-off and poor germination. The beneficial microorganisms present in *Beejamrit* compete with these pathogens for space and nutrients, thereby reducing their ability to infect the seed or young seedlings.
2. It promotes healthy microbial colonisation around the seed surface. The beneficial microbes form a protective layer that enhances nutrient availability and supports early root development.
3. It contributes to improved germination and seedling vigour. The nutrients and microbial metabolites present in the preparation can stimulate enzymatic activities within the seed, encouraging faster germination and stronger root growth.
4. *Beejamrit* supports soil microbial diversity. When treated seeds are sown in the field, the microbes associated with *Beejamrit* multiply in the rhizosphere, interact with native soil microorganisms and contribute to a biologically active soil environment.
5. It is cost-effective and accessible to small farmers, as it relies on locally available materials such as cow dung, cow urine and farm soil. This reduces the dependency on purchased agrochemicals and lowers production costs.

Comparison between *Beejamrit* and chemical seed treatment practices

Beejamrit and chemical seed treatments represent two different philosophies of crop protection, as illustrated in Table 2.

Table 2. Fundamental differences between *Beejamrit* and chemical seed treatment

Parameter	<i>Beejamrit</i>	Chemical seed treatment
Nature of treatment	Biological formulation prepared from natural ingredients	Synthetic chemical formulation containing fungicides/insecticides
Principle of action	Promotes beneficial microbes that suppress pathogens through competition and antagonism	Directly kills or inhibits pathogens using toxic chemical compounds
Source of inputs	Locally available farm resources	Commercial agrochemical products purchased from markets
Cost	Very low cost; easily prepared on farm	Relatively higher cost due to purchase of chemicals
Soil health	Enhances microbial diversity and soil biological activity	May reduce beneficial microbial populations if used repeatedly
Speed of action	Works gradually through biological processes	Rapid due to chemical toxicity
Standardisation	Limited; preparation may vary among farmers	Well-researched, standardised and widely validated
Consistency of results	Effectiveness may vary depending on microbial activity and preparation quality	Generally consistent due to standardised formulations
Environmental impact	Environmentally safe and biodegradable	Potential environmental contamination if misused
Performance under high disease pressure	May be less effective when pathogen populations are very high	Effective even under severe disease pressure
Risk of resistance	Very low risk of pathogen resistance	Repeated use may lead to development of resistant pathogen strains
Compatibility with natural farming	Core component of natural farming systems	Generally avoided in natural farming

Scientific basis of *Beejamrit*

Although *Beejamrit* originates from traditional farming knowledge, its effectiveness can be explained through well-known microbiological and plant physiological processes. When seeds are treated with *Beejamrit*, they become coated with a diverse population of beneficial microbes derived from cow dung, cow urine and native soil from forest/bund/under a peepal tree. These microbes colonise the seed surface and later, the rhizosphere. Once established, they help protect germinating seeds from harmful pathogens. Another important mechanism is the production of antimicrobial substances, such as antibiotics and siderophores, and enzymes by beneficial microbes. These compounds inhibit the growth of pathogenic fungi and bacteria in the soil, creating a protective microbial barrier around the seed. Certain microbes associated with cow dung and soil are capable of producing plant growth-promoting substances, such as indole-3-acetic acid (IAA), and other growth regulators. These compounds stimulate root development and enhance nutrient uptake during the early stages of plant growth. Additionally, some microbes help in nutrient

mobilisation, making nutrients like phosphorus and micronutrients more available to young plants. The lime used in *Beejamrit* preparation also contributes to its effectiveness. It helps maintain a slightly alkaline pH that discourages certain pathogenic fungi while supporting microbial activity. Moreover, the small amount of calcium supplied through lime contributes to stronger cell wall development in young seedlings. Through these combined mechanisms, *Beejamrit* supports healthy germination and strong seedling establishment while contributing to a biologically active soil ecosystem.

Integrating natural and chemical approaches

The debate between natural and chemical seed treatments should not necessarily be viewed as an either-or choice. In many agricultural systems, a balanced and integrated approach may offer the best results. For instance, *Beejamrit* can be combined with improved agronomic practices, disease-resistant varieties and healthy soil management to reduce disease pressure naturally. In situations where severe disease outbreaks occur, carefully regulated chemical interventions may still play a role. Such integrated approaches can help farmers achieve both crop productivity and environmental sustainability, ensuring that agricultural systems remain resilient in the face of changing climatic and ecological conditions.

Conclusion

Beejamrit represents an important pillar of natural farming, reflecting a broader movement towards ecological and sustainable agricultural practices. By harnessing beneficial microorganisms and farm-derived inputs, *Beejamrit* offers a low-cost and environmentally friendly method for protecting seeds and promoting healthy crop establishment. While chemical seed treatments have played a significant role in modern agriculture due to their efficiency and reliability, concerns about environmental impacts and long-term sustainability have encouraged the exploration of biological alternatives such as *Beejamrit*. Both approaches have their own strengths and limitations. Understanding these differences allows farmers and agricultural professionals to make informed decisions based on local conditions, crop requirements and sustainability goals. As agriculture moves towards more resilient and environmentally responsible systems, traditional practices like *Beejamrit*, supported by scientific research and innovation, may play an increasingly important role in ensuring sustainable crop production and healthy agroecosystems.

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NANOFERTILIZERS FOR SOIL HEALTH AND ENVIRONMENTAL SUSTAINABILITY

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Abstract

Nanofertilizers engineered nutrient carriers operating at the nanoscale—represent a transformative advancement in sustainable agriculture. Their nano-dimensions enhance nutrient uptake, reduce nutrient losses, and minimize the environmental burdens associated with chemical fertilizers. Under changing climatic conditions marked by erratic rainfall, drought, and heat stress, nanofertilizers improve nutrient-use efficiency, strengthen plant tolerance to abiotic stress, and protect soil structure and microbial ecology. Evidence shows that nano-enabled nitrogen, phosphorus, and micronutrient formulations can reduce leaching, greenhouse gas emissions, and eutrophication. Additionally, nanofertilizers hold potential human health benefits by reducing chemical residues and enhancing micronutrient density in food crops. This paper synthesizes nanofertilizers mechanisms, environmental impacts, soil ecological responses, and human health considerations, while highlighting remaining challenges and the need for science-based regulatory frameworks.

Introduction

Agriculture underpins food, economic stability, and rural livelihoods worldwide. In developing countries such as India, the sector sustains nearly half the population and remains central to national food security. Yet agriculture now stands at a critical juncture as climate change, soil degradation, and declining nutrient-use efficiency threaten productivity. Over the past five decades, chemical fertilizers have contributed enormously to global food production, but this progress has come with environmental costs—nutrient leaching, eutrophication, greenhouse gas emissions, soil acidification, and degradation of water quality. With climate change amplifying extreme events and disrupting agroecosystem functions, reliance on conventional fertilizers is increasingly unsustainable. Studies indicate significant inefficiency in conventional fertilizer use. Chen et al. (2021) report that only 30–50% of applied nitrogen, 15–20% of phosphorus, and 40–50% of potassium are effectively absorbed by crops. The remaining nutrients are lost to leaching, runoff, or volatilization, contributing to groundwater contamination and increased nitrous oxide emissions—one of the most potent greenhouse gases. These inefficiencies elevate production costs, burden ecosystems, and reduce long-term soil fertility.

Climate change further destabilizes nutrient dynamics. Rising temperatures accelerate nutrient mineralization and volatilization, while irregular rainfall increases nutrient runoff. Drought reduces nutrient mobility in soil solution, weakening crop uptake. Such instability underscores the necessity of nutrient-management strategies that can operate effectively under fluctuating climatic conditions. Nanotechnology has emerged as a promising innovation to address these challenges. Nanofertilizers formulations engineered at the nanoscale (1–100 nm) provide higher surface area, enhanced reactivity, better solubility, and controlled-release characteristics. Liu and Lal (2015)

suggest that nano-enabled fertilizers can increase nutrient-use efficiency by 20–40%, thereby reducing environmental loss pathways. Their ability to deliver nutrients in synchrony with crop demand is particularly valuable in climate-stressed environments, where nutrient availability and plant uptake fluctuate sharply.

The ability of nanofertilizers to penetrate plant tissues through stomatal openings, root epidermal cells, or seed coats facilitates rapid nutrient assimilation. Zhang et al. (2019) highlight how nano-enhanced formulations improve photosynthesis, metabolic activity, and root functionality, even under stress conditions induced by heat or drought. As climate change intensifies abiotic stresses, such attributes become increasingly crucial for maintaining yield stability. Nutrient use efficiency also benefits from nano-approaches. In India, LNG and phosphate rock reserves are finite, potash reserve is nil, improving nitrogen, phosphorus and potassium use efficiency is a global priority. Nano-hydroxyapatite and coated phosphorus nanofertilizers enhance solubility and reduce fixation in soils, decreasing dependency on raw phosphate resources. This is aligned with the sustainability principles required in modern agronomy.

However, nanoparticle behaviour differs fundamentally from bulk materials. Their mobility in soil, potential accumulation in plant tissues, and interactions with microbial communities raise important safety considerations. Chen et al. (2021) points out that engineered nanoparticles may exhibit unique ecotoxicological properties, necessitating rigorous long-term risk assessment. Despite these concerns, the emerging body of peer-reviewed literature supports nanofertilizers as a promising tool for climate-resilient agriculture. They represent a shift from blanket application to precision nutrient management delivering nutrients more efficiently, reducing environmental impacts, and supporting soil and plant health. With appropriate regulation and research, nanofertilizers can contribute to more sustainable and resilient agricultural systems.

Mechanisms and Characteristics of Nanofertilizers

Nanofertilizers differ fundamentally from conventional fertilizers in nanoscale properties, behaviour, and interactions within plants and soils. Their high surface-area-to-volume ratio and enhanced solubility improve nutrient mobility and biological activity, making them more effective at lower dosages. The mechanisms of action documented in literature demonstrate how nanoscale structure gives rise to superior nutrient-use efficiency (Fig,1).

Nanoparticles possess unique physicochemical properties such as higher surface energy, greater reactivity, and improved dispersibility. This facilitates stronger interactions with plant tissues and soil components. For example, nano-hydroxyapatite dissolves more efficiently in the soil compared to bulk phosphorus, enhancing P availability even in high-fixation soils (Liu & Lal, 2015). Their small size enables penetration through stomatal pores and cellular membranes, allowing direct entry into plant metabolic pathways (Zhang et al., 2019).

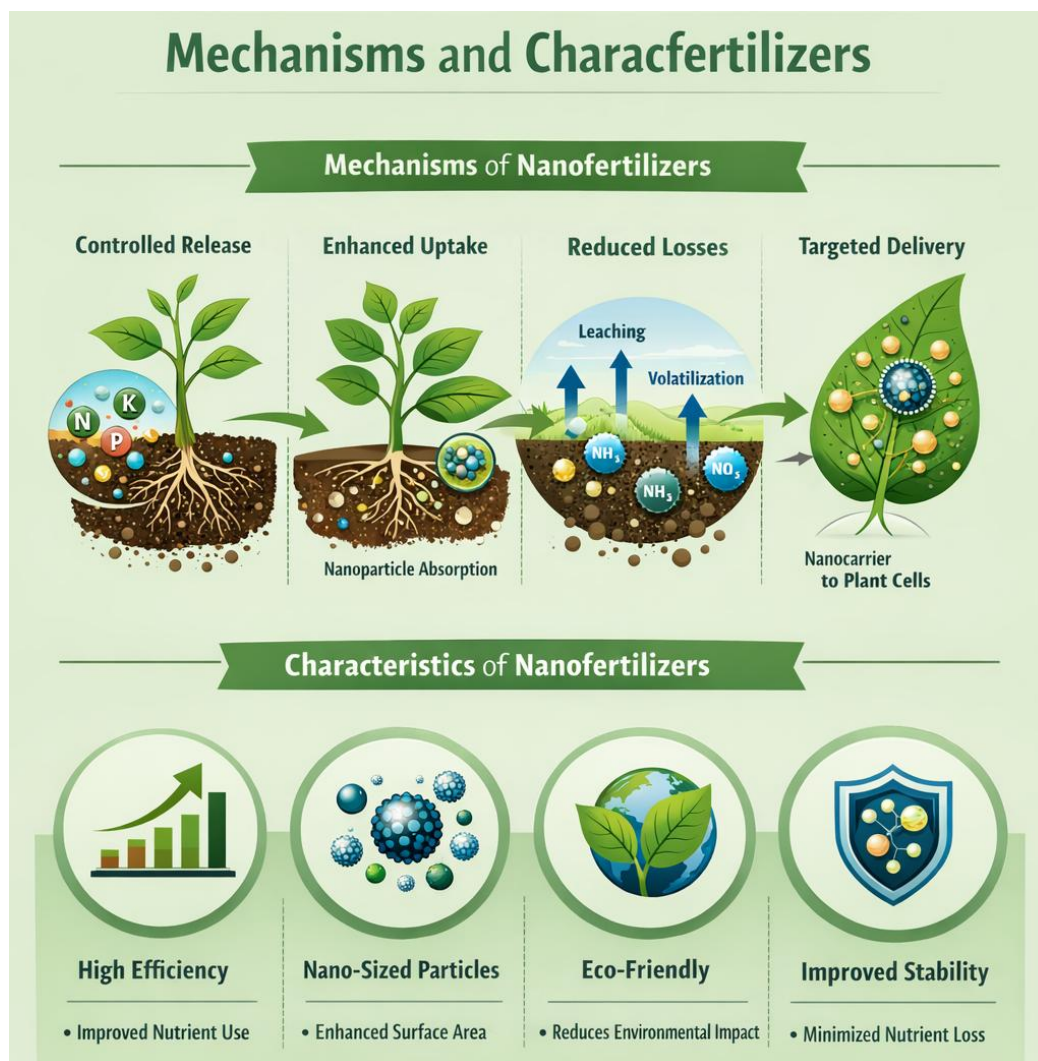


Fig. 1. Mechanisms and Characteristics of Nanofertilizers

Nutrient Delivery Mechanisms

Nanofertilizers function through highly efficient nutrient delivery pathways that differentiate them from conventional bulk fertilizers. Their small particle size, higher surface area, and enhanced reactivity enable faster absorption, targeted transport, and improved assimilation within plant tissues.

Foliar Uptake: Foliar-applied nanofertilizers penetrate leaves primarily through *stomatal openings*, cuticular cracks, and nano-scale pores present on the leaf surface. Due to their nano-size and favourable surface charge, these particles adhere easily to leaf cuticles, increasing retention time and reducing losses caused by rainfall or volatilization. Once they enter the mesophyll, nanoparticles dissolve or disintegrate to release nutrient ions that move through the *phloem*, reaching actively growing tissues. As demonstrated by Liu and Lal (2015), foliar nano-urea significantly enhances nitrogen assimilation while reducing volatilization losses. This is because the nano-formulation ensures that a higher proportion of nitrogen is absorbed directly into systemic circulation rather than being lost to the atmosphere as ammonia. Consequently, plants exhibit improved chlorophyll content, greener canopy formation, and enhanced amino acid synthesis following nano-urea foliar application.

Root Uptake: When applied to soil, nanofertilizers interact with root surfaces through both the *apoplastic (cell wall continuum)* and *symplastic (cytoplasmic) pathways*, enabling rapid and efficient nutrient movement. Nanoparticles can pass through root epidermal cell gaps, enter the cortex, and eventually reach the vascular bundle. For example, **nano-silicon** improves root elongation and branching, strengthens the root endodermis, and enhances water absorption capacity. As reported by Zhang et al. (2019), nano-silicon also increases structural resilience during drought stress by enhancing osmotic adjustment and strengthening cell walls, thereby helping plants cope with water scarcity. The improved root structure facilitates better uptake of nutrients, water, and signalling compounds essential for growth.

Controlled Release: Controlled-release nanofertilizers utilize polymeric, lipid, or biodegradable organic coatings that protect nutrient cores and regulate their release kinetics. These coatings respond to environmental triggers such as moisture, pH, or microbial enzymes. According to Yadav et al. (2023) nano-encapsulated nutrients maintain a steady supply for 20–30 days longer than conventional fertilizers, reducing the need for frequent applications. This sustained release minimizes nutrient spikes, prevents leaching and runoff, and synchronizes nutrient availability with plant demand an essential factor in achieving higher nutrient-use efficiency.

Types of Nanofertilizers

Nanofertilizers can be classified into three major categories based on composition and nutrient-release characteristics. The first includes nano-scale nutrients, such as nano-urea, Nano DAP, nano-Zn, Nano Cu and nano-Fe, where nutrients are engineered at the nanoscale. Their high surface-area-to-volume ratio improves solubility, reactivity, and plant uptake efficiency, thereby reducing nutrient losses through different pathways (Liu & Lal, 2015). The second category comprises *nanosstructured fertilizers*, including nano-zeolites and nano-biochar, which enhance nutrient retention, soil structure, and microbial activity. The third group involves *controlled-release nanocomposites*, such as nano-encapsulated NPK fertilizers that gradually release nutrients, synchronizing supply with crop demand and improving nutrient-use efficiency and plant productivity.

IFFCO Nanofertilizers

Nanofertilizers developed by the *Indian Farmers Fertiliser Cooperative Limited (IFFCO)* represent a significant technological innovation in plant nutrition aimed at improving nutrient-use efficiency and reducing the environmental footprint of conventional fertilizers. These fertilizers utilize nanotechnology to deliver nutrients in nano-sized particles (typically 20–100 nm), enabling faster absorption and more efficient utilization by plants.

IFFCO launched *Nano Urea (Liquid)* in 2021 (4% N), soon after *Nano Urea Plus (Liquid)* as the world's first commercially available nano-nitrogen fertilizer which contains 20% nitrogen in nano form and is applied as a foliar spray (Fig. 2). Due to the extremely small particle size (20–50 nm) and very high surface area, nano urea can be readily absorbed through leaf stomata and transported within plant tissues, resulting in improved nitrogen use efficiency and reduced nutrient losses through leaching or volatilization.

Building on the success of Nano Urea, IFFCO introduced Nano DAP (Liquid), which supplies both nitrogen and phosphorus (Fig. 2). This formulation typically contains about 8% nitrogen and 16% phosphorus (P_2O_5) and helps correct nutrient deficiencies in standing crops. The nano-scale formulation enhances nutrient availability, promotes chlorophyll formation, and improves photosynthetic efficiency and crop productivity.



Fig 2. IFFCO Nano Urea Plus and Nano DAP

IFFCO has also developed *Nano Zinc* and *Nano Copper* to address micronutrient deficiencies and improve crop productivity through nanotechnology-based nutrient delivery (**Fig.3**). *IFFCO Nano Zinc* enhances enzyme activation, chlorophyll synthesis, and plant growth, helping correct widespread zinc deficiency in soils. *IFFCO Nano Copper* supports plant metabolism, strengthens disease resistance, and improves grain quality. Applied as foliar sprays in small doses, these nanofertilizers improve micronutrient-use efficiency while reducing environmental losses and input requirements in sustainable crop production systems.



Fig.3 IFFCO Nano Zinc and Nano Copper

One of the major advantages of IFFCO nanofertilizers is their potential to partially substitute conventional fertilizers. Overall, IFFCO nanofertilizers represent a promising approach toward *precision nutrient management*, *improved crop productivity*, and *environmentally sustainable agriculture*, although long-term field validation and large-scale adoption remain important areas for continued research and policy support.

Environmental Impacts of Nanofertilizers

Nanofertilizers are increasingly recognized for their potential to address some of the most persistent environmental challenges associated with chemical fertilizer use. Traditional fertilizer practices often result in excessive nutrient losses, soil degradation, greenhouse gas emissions, and water contamination. In contrast, nanofertilizers employ controlled-release mechanisms, enhanced surface reactivity, and efficient plant uptake pathways that can significantly reduce these impacts. Their nanoscale properties allow them to interact more precisely with plant and soil systems, resulting in both improved nutrient-use efficiency and reduced ecological stress. The following subsections elaborate on the major environmental benefits and emerging concerns related to nanofertilizer application.

Reduced Nutrient Losses: Conventional nitrogen fertilizers typically exhibit low nutrient-use efficiency, with nearly half of the applied nitrogen lost through leaching, volatilization, or surface runoff. Nanofertilizers, due to their high surface area and controlled-release characteristics, minimize these losses by synchronizing nutrient release with plant demand. Yadav et al. (2023) reported that certain nano-coated nutrient formulations can reduce nitrogen leaching losses by more than 50%, contributing to improved efficiency and reduced environmental contamination. By decreasing nutrient escape pathways, nanofertilizers prevent the accumulation of excess nitrogen in groundwater, eutrophication, fixation etc. and reduce the burden on surrounding ecosystems.

Lower Greenhouse Gas Emissions: One of the critical environmental benefits of nanofertilizers lies in their ability to reduce emissions of nitrous oxide (N_2O), a potent greenhouse gas produced during soil nitrogen transformations. Traditional fertilizers often release nitrogen in large pulses, overwhelming soil microbial systems and stimulating rapid nitrification and denitrification. Nano-enabled slow-release fertilizers provide a steady supply of nitrogen, moderating these microbial processes. Liu and Lal (2015) documented a 15–40% decline in N_2O emissions when nanofertilizers were used in place of conventional fertilizers, demonstrating their potential to support climate-smart agricultural practices.

Water Quality Protection: Water pollution from agricultural runoff remains a widespread concern, particularly the eutrophication of lakes and rivers caused by excessive phosphate and nitrate inputs. Nanophosphate formulations dissolve gradually, thereby reducing the sudden phosphorus surges that often lead to runoff. Zhang et al. (2019) observed a 20–30% reduction in phosphorus runoff under nano-phosphate treatments. Similarly, nano-controlled-release nitrogen formulations decrease nitrate leaching. These reductions directly improve water quality, supporting healthier aquatic ecosystems and reducing downstream treatment costs.

Soil Structural Benefits: Beyond nutrient management, nanofertilizers improve soil physical properties, contributing to long-term soil health. Nano-silicon and nano-biochar, for example, enhance soil porosity, aggregation, and water retention traits essential for soils facing climatic stressors such as drought or erratic rainfall. Yadav et al. (2023) highlighted how these materials strengthen soil structure, improve aeration, and enhance moisture-holding capacity, creating more resilient agricultural environments and reducing the need for frequent irrigation.

Controlled-Release Behaviour: A defining advantage of nanofertilizers is their controlled-release capability, which allows nutrients to be delivered gradually in synchrony with plant demand. This slow and sustained release prevents the sudden nutrient surges that commonly occur with conventional fertilizers, especially after heavy rainfall or excessive irrigation. By avoiding these

spikes, nanofertilizers significantly reduce nutrient runoff, volatilization, and leaching. Controlled-release behaviour also enhances nutrient-use efficiency, ensuring plants receive a steady supply over extended periods, which supports healthier growth and reduces the need for repeated fertilizer applications. This characteristic is particularly valuable under unpredictable climate conditions that intensify nutrient losses.

Effects on Soil Microbial Health and Soil Ecology

Nanofertilizers influence soil ecosystems in complex ways, with outcomes that range from enhanced microbial functioning to potential ecological disturbances. Their interactions with soil microbes depend on the type of nanomaterial, particle size, surface chemistry, and application concentration. As soil microbiota play a central role in nutrient cycling, organic matter decomposition, and overall soil fertility, understanding these interactions is essential for assessing the sustainability of nanofertilizer use in agricultural systems. The subsections below expand on both the beneficial and adverse effects that have been documented using the references you provided.

Positive Effects of Nanofertilizers on Soil Microbial Activity: Carbon-based nanofertilizers, particularly *nano-biochar*, are widely recognized for enhancing soil microbial activity and biological functioning. Their highly porous nanoscale structure creates favourable microhabitats for beneficial bacteria and fungi by providing stable moisture, protection, and attachment surfaces. Studies indicate that soils amended with nano-biochar exhibit higher microbial biomass, improved soil respiration, and increased activity of enzymes involved in nutrient cycling (Yadav et al., 2023).

In addition to physical benefits, nano-biochar improves nutrient retention by adsorbing nutrients and organic compounds, reducing leaching losses and increasing nutrient availability. It also enhances soil moisture retention, creating a stable environment for microbial communities. These combined effects strengthen soil resilience, productivity, and ecosystem stability under environmental stress conditions.

Enhanced Nutrient Cycling: Nanofertilizers also promote more efficient nutrient cycling by aligning nutrient release more closely with microbial activity. Nano-nitrogen (Nano-N) formulations, (for example, IFFCO Nano Urea Plus) are designed to release nitrogen gradually rather than in sudden pulses. This slow and steady release supports balanced microbial processes such as nitrification and ammonification. According to Liu and Lal (2015), the controlled nitrogen supply ensures that nitrifying and ammonifying bacteria continuously receive an optimal substrate supply. This stability prevents the ammonia toxicity spikes often associated with conventional fertilizers, which can temporarily suppress microbial communities or disrupt soil metabolic pathways. As a result, nitrogen transformation processes proceed more efficiently, improving nitrogen-use efficiency (NUE) and reducing gaseous and leaching losses. More importantly, steady nutrient cycling contributes to long-term soil biological stability, sustaining microbial communities that are essential for organic matter breakdown and soil fertility regeneration.

Toxicity Risks: While nanofertilizers offer several advantages, their potential risks must be carefully studied. Prolonged exposure to ROS-generating nanoparticles can reduce microbial diversity, limit soil functional redundancy, and destabilize ecological interactions among microbial groups. Sensitive species may decline disproportionately, leading to imbalances that affect nutrient cycling, decomposition, and soil structure formation. Thus, while nanofertilizers hold promise, their application must be guided by careful concentration thresholds.

Mycorrhizal Associations: Mycorrhizal fungi especially *arbuscular mycorrhizal fungi (AMF)* play a central role in phosphorus uptake and soil aggregation. Zhang et al. (2019) report that moderate applications of nanofertilizers can enhance AMF colonization by improving root morphology, stimulating root exudation, and increasing localized nutrient availability in the rhizosphere. Greater AMF colonization improves plant nutrient acquisition, water absorption, and resistance to abiotic stress. However, excessive nanoparticle inputs can have the opposite effect. High concentrations may inhibit fungal hyphae growth, disrupt spore germination, and suppress sensitive fungal taxa. The dual nature of these effects highlights the importance of precision in application and monitoring.

Soil Enzymes: Soil enzyme activities reflect microbial metabolic health and are vital for biochemical transformations. Nanofertilizers used at recommended doses enhance crucial enzymes such as *dehydrogenase*, *phosphatase*, and *urease* - key drivers of organic matter decomposition, phosphorus mobilization, and nitrogen transformation. Enhanced enzyme activity suggests improved microbial functioning and increased soil fertility. However, mirroring other biological responses, overly high nanoparticle concentrations may inhibit enzyme function or interfere with enzyme–substrate interactions, emphasizing the need for balanced application strategies.

Impacts on Human Health

The introduction of nanofertilizers into modern agriculture has generated considerable interest regarding their potential to enhance crop nutrition while simultaneously reducing environmental burdens. However, understanding their implications for human health is equally important, given that food is the primary exposure pathway for most consumers. The following subsections examine both the potential benefits and the emerging concerns associated with nanofertilizer use.

Reduced Nitrogen Residues: One of the most promising human health benefits associated with nano-urea application is the reduced accumulation of harmful nitrate residues in vegetables. Conventional nitrogen fertilizers often supply nutrients in excess, leading to nitrate buildup in plant tissues, which can pose health risks when consumed in large quantities. According to Liu and Lal (2015), nano-urea improves nitrogen assimilation efficiency due to its controlled-release behaviour and enhanced uptake pathways. By delivering nitrogen in smaller, more bioavailable forms, nano-urea enables crops to convert nitrogen into amino acids and proteins more efficiently, thereby lowering the tendency for nitrate accumulation. This reduction in nitrate residues not only enhances the nutritional quality of vegetables but also minimizes exposure to compounds associated with methemoglobinemia and other nitrate-related disorders.

Enhanced Micronutrient Content: Beyond reducing harmful residues, nanofertilizers also contribute positively to the micronutrient profile of food crops. Iron deficiency remains a widespread public health challenge, particularly in developing regions where cereal-based diets dominate. By improving Fe bioavailability and uptake at the root level, nano-iron can help fortify crops naturally, offering a sustainable approach to combating micronutrient malnutrition. Increased micronutrient density in staple foods has downstream health benefits, particularly for women, children, and marginalized populations that are more susceptible to deficiencies.

Concerns on Nanoparticle Accumulation: Despite clear benefits, concerns remain about the potential accumulation of nanoparticles within edible plant tissues. Chen et al. (2021) caution that metal-based nanoparticles smaller than 20 nanometres possess the capacity to penetrate biological barriers and translocate to edible parts of the plant. Because these particles exhibit distinct

physicochemical properties, their behaviour within biological systems is not yet fully understood. While some nanoparticles may dissolve or transform into ionic forms, others could persist and accumulate. Understanding these pathways is critical, as nanoparticle residues in food could introduce novel exposure risks to consumers, particularly if particles accumulate over time.

Toxicological Considerations: High levels of exposure to certain engineered nanoparticles have been associated with potential toxicological effects in biological systems. Although agricultural use typically involves low-dose applications, concerns include oxidative stress, inflammation, and potential DNA damage when exposure exceeds biological thresholds. These outcomes are influenced by particle size, concentration, solubility, surface coatings, and plant metabolism. While current evidence is limited and largely based on laboratory studies, the possibility of nanoparticle-induced toxicity underscores the need for thorough risk assessments before large-scale deployment.

Regulatory Frameworks: Given the dual nature of Nanofertilizers - beneficial yet potentially risky, the development of clear and comprehensive regulatory frameworks is essential. Standards defining permissible nanoparticle size, concentration, dosage, and exposure limits are necessary to ensure consumer safety and maintain public trust. Regulations must also address product labelling, residue monitoring, and acceptable daily intake levels. Without such guidelines, it remains difficult to guarantee that nanofertilizer-derived food products are safe for human consumption, especially in the long term.

Challenges and Policy Gaps in Nanofertilizer Adoption

Nanofertilizers are increasingly recognized for their potential to enhance nutrient-use efficiency, reduce fertilizer losses, and improve environmental sustainability. However, their large-scale adoption remains constrained by several scientific, institutional, and policy-related challenges. Major barriers include limited long-term safety data, low farmer awareness, regulatory uncertainties, high production costs, and fragmented research efforts. Addressing these issues through coordinated policies, strong extension systems, and interdisciplinary research is essential for ensuring the safe and effective integration of nanofertilizers into modern agricultural systems.

Low Farmer Awareness and Technical Knowledge Gaps: Limited farmer awareness and technical knowledge significantly hinder the adoption of nanofertilizers, especially among small and marginal farmers. Many producers are unfamiliar with nanotechnology and its role in improving nutrient delivery and plant uptake. The lack of training programs, field demonstrations, and effective extension services restricts knowledge dissemination, leading to skepticism and perceptions that nanofertilizers are complex inputs suited mainly for large commercial farms.

Limited Long-Term Environmental and Health Safety Data: Although short-term studies show improved nutrient uptake and reduced losses, the broader ecological impacts remain unclear. Uncertainties exist regarding nanoparticle interactions with soil microbes, nutrient cycles, and aquatic systems, as well as their potential accumulation in soil and entry into the food chain. The scarcity of long-term studies on persistence, bioaccumulation, and toxicity often makes policymakers cautious about large-scale deployment.

Regulatory and Standardization Gaps: Regulatory uncertainty is a major barrier to nanofertilizer adoption. Existing fertilizer regulations are primarily designed for conventional inputs and do not adequately address the unique properties of nanomaterials. The absence of harmonized standards

for product quality, labelling, nanoparticle concentrations, and safety thresholds complicates commercialization, reduces farmer confidence, and increases the risk of substandard or counterfeit nano-enabled products entering the market.

Need for Integrated Multidisciplinary Research: The development and deployment of nanofertilizers require integrated research combining agricultural sciences, nanotechnology, soil microbiology, toxicology, plant physiology, and environmental monitoring. Currently, research efforts remain fragmented across institutions and disciplines. Comprehensive studies assessing agronomic performance, environmental safety, long-term soil health impacts, and socioeconomic feasibility are essential. Stronger collaboration among research institutions, policymakers, industry, and extension systems can help translate laboratory innovations into scalable field applications. Overall, although nanofertilizers offer significant potential for sustainable nutrient management, their responsible adoption will depend on coordinated policy frameworks, stronger regulations, farmer capacity-building, and robust interdisciplinary research (Chen et al., 2021).

Summary and Conclusion

Nanofertilizers represent a promising innovation for advancing climate-smart and environmentally sustainable agriculture. Their nano-scale formulations enhance nutrient-use efficiency, reduce nutrient losses, and improve soil biological activity, thereby addressing many limitations associated with conventional fertilizers. By lowering fertilizer requirements, minimizing environmental pollution, and supporting healthier plant growth, nanofertilizers contribute to both environmental sustainability and agricultural productivity. However, their large-scale adoption requires responsible governance. Strong regulatory frameworks, standardized safety protocols, and long-term ecological monitoring are essential to ensure environmental and human safety. With appropriate policies, scientific validation, and careful implementation, nanofertilizers can play a significant role in building resilient, resource-efficient, and sustainable agricultural systems.

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SUSTAINABLE FINANCE AND INVESTMENT STRATEGIES FOR STRENGTHENING PLANT HEALTH IN INDIA

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Introduction

Indian agriculture contributing significantly to food security, employment generation, and rural livelihoods. Though the country's economic landscape paradigm shift happened from Agriculture to Service sector for its valuation from pre independence to the present conditions; still, Agricultural sectors remains the backbone of the country, with a population of over 1.40 billion, ensuring inclusive livelihood and sustainable food production is both a national priority and a global responsibility. In agriculture, among all areas of crop production and supply chain systems; the Plant health management forms the foundation of agricultural sustainability. Healthy crops ensure higher productivity, better quality produce, and stable farm incomes. In the context of increasing global trade, climate change, and emerging pest and disease outbreaks, strengthening plant health systems has become most important factor. However, plant health initiatives require sustained financial investment, technological innovation, and institutional coordination. Mobilizing sustainable finance for plant health management at country level. Therefore, Plant health initiatives not merely an agricultural issue, but a developmental and environmental importance and necessary.

Importance of Plant Health in Indian Agriculture

Plant health comprehends prevention, detection, monitoring, and management of pests, diseases. Also, effective plant health systems contribute to:

- Enhanced crop productivity and farm income
- Reduction in crop losses due to pests and diseases
- Safe and residue-free food production
- Environmental sustainability
- Strengthened export competitiveness in global market
- Support to Macro Economic stability

India's agricultural operations—including crop improvement, intercultural operations, plant protection, harvesting, post-harvest management, and agricultural marketing—are all interconnected with plant health management system. So, sustainable plant health management directly supports food security and international agricultural trade, most particularly in India with developing nations and Global South countries.

Emerging Challenges in Plant Protection

Despite progress in agricultural research and extension, India faces a dual challenge in plant health management:

1. Excessive and Indiscriminate Use of Agrochemicals

Majorly the double and triple cropping intensively cultivated regions, overuse and misuse of pesticides have resulted in:

- Environmental degradation
- Soil and water contamination
- Pesticide residues in food
- Health risks to farmers and consumers

This disparity usually give attention to give the importance of eco-friendly sustainable and residue-free food production.

2. Lower-adoption of plant health management practices in Rainfed and Resource-Constrained Areas

In the rainfed and marginal farming regions of the country; due to low access of quality plant protection inputs, inadequate financial resources, less Institutional and extension support and less awareness of integrated plant health practices. Most importantly the majority of the Small and marginal farmers often lack the technical, financial, and organizational capacity to prevent and manage pest and diseases effectively.

3. Climate Change and Emerging Biotic Threats

The changing climatic conditions in agriculture in India have also altered pest dynamics, leading to:

- New pest invasions
- Increased frequency of outbreaks
- Greater unpredictability in disease patterns

Hence, at national level; strengthening plant health management systems is essential to build resilience against these emerging threats. It also requires sustainable financial investment at farm level and country level based on the agro-ecosystem diversity and commercial importance of agriculture and allied sectors.

Need for Sustainable Finance in Plant Health

In the present globalized agricultural marketing and supply chain systems, the Traditional public funding mechanisms alone are insufficient to address the growing investment needs of plant health systems of the country. Hence, finance mobilization from various sectors such as private sector, institutional investors and other stakeholder responsibilities are very important. It also supports long-term financial flow, environmental, social, and economic sustainability.

The importance of mobilizing sustainable finance for plant health management get importance to expand access to modern plant protection technologies, encourage responsible pesticide use, promote integrated pest management (IPM), support climate-resilient agricultural practices and to enhance digital and precision agriculture services. Also the investment in plant health should be viewed as a preventive investment to reduce the future economic losses and ecological damages.

Major Opportunities for Mobilizing Sustainable Finance

1. Digital Technology–Based Smart Application Services

The advancements in digital agriculture provide new opportunities for efficient plant health management; particularly in the drone-based pesticide application, Satellite-based Geographical Information System based pest surveillance, Artificial Intelligence-driven decision support systems and mobile based advisory services for farmers.

However, these technologies require substantial capital investment. Innovative financing models such as custom hiring services, and agri-tech startups models and contract and cooperative financial models can help reduce to entry barriers for smallholders. Also, the Farmer Producer Organizations (FPOs) and cooperatives can aggregate demand and access credit to invest in community-based drone services and digital plant health tools.

2. Community-Based Financing Mechanisms

The community-based models can strengthen plant health management systems at the grassroots level through providing revolving funds for plant protection inputs, cluster-based pest surveillance systems, custom hiring machinery arrangement and establishment of village-level plant health clinics. These such mechanisms reduce individual risk and improve collective pest management outcomes. Community-based financing ensures inclusiveness and enhances local accountability.

3. Strengthening Farmer–Society–Industry Linkages

Stronger collaboration between farmers, research institutions, private industry, and financial institutions can get to the bottom of new investment avenues. There are certain potential strategies include:

- Contract farming arrangements with quality compliance standards
- Input companies offering credit-linked technology packages
- Agri-startups providing digital plant health advisory services
- Industry participation in farmer training and capacity building practices

Further, the Public research institutions and universities can play a catalytic role in validating technologies and ensuring responsible adoption.

4. Blended Finance and Public–Private Partnerships

Blended finance combines public funding with private investment to reduce risk and attract larger capital flows. In plant health initiatives, blended finance can support:

- Pest surveillance infrastructure
- Digital monitoring platforms
- Biocontrol production units
- Integrated plant health laboratories

The Public–Private Partnerships (PPPs) model can also facilitate innovation while ensuring public accountability and environmental safeguards.

5. The Climate Finance and Green Investment

The developing and global south countries requires climate resilience adaptation related financial requirements. Hence, the Plant health interventions aligned with climate resilience and ecological sustainability; it can attract green finance and climate funds. Most importantly in the areas of Promotion of bio pesticides and biological control agents at farmers' level, Integrated pest management practices, Conservation agriculture practices adoption perspectives and other eco-friendly plant health management initiatives and Precision input application technologies.

Institutional and Policy Support

Effective mobilization of sustainable finance requires enabling policy frameworks:

- Incentives for adoption of eco-friendly plant protection practices
- Subsidies for digital plant health technologies
- Credit guarantees for agri-tech investments

- Strengthened extension systems
- Regulatory frameworks to promote safe pesticide use

At national level, the financial Institutions such as National Bank for Agriculture and Rural Development and cooperative financial institutions, Regional Rural Banks, priority sector lending of commercial banks can play a crucial role in designing innovative financial instruments tailored to plant health initiatives. Also, Integration of plant health strategies into national agricultural and climate policies is essential for long-term sustainability.

Awareness and Capacity Building initiatives

Awareness and Capacity Building initiatives are much important along with the financial investment in the plant health management initiatives. The Key areas include:

- Farmer training in integrated pest management
- Awareness on safe and balanced pesticide use
- Strengthening plant health diagnostic services
- Digitally supportive precision farming initiatives

And so, establishment of human capital enhances the effectiveness and sustainability of financial investments.

Development of Resilient Plant Health Systems

A resilient plant health system establishment also very important effort in early detection and rapid response mechanisms in plant Health management systems. The strong research–extension–farmer linkages and digital surveillance and advisory systems, sustainable and diversified financing mechanisms and climate-adaptive pest management strategies in connection with multi-stakeholder collaboration such as Governments, financial institutions, private sector actors, research bodies, and farmer organizations must work in in a convergence basis to achieve the Resilient Plant Health Systems.

Conclusion

The present study identifies key opportunities for mobilizing sustainable finance and investment opportunities to strengthen plant health initiatives, including digital technology–based smart application services, community-based financing and implementation mechanisms, and stronger farmer society–industry linkages. Additionally, the study also highlights the potential of blended finance models such as public–private partnerships and digital innovation–driven multi-stakeholder collaborations to build resilient plant health systems capable of addressing emerging biotic threats under changing climatic conditions.

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NON-ALCOHOLIC BEVERAGES: EMERGING ALTERNATIVES FOR HEALTH-CONSCIOUS CONSUMERS

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Abstract

The increasing demand for healthier lifestyle choices has driven the growth of non-alcoholic beers and spirits as alternatives to traditional alcoholic beverages. These products appeal to health-conscious consumers seeking flavorful drinks without the negative effects of alcohol. Non-alcoholic beverages can retain certain beneficial bioactive compounds while eliminating alcohol-related risks, making them particularly attractive to younger and wellness-focused demographics. Various production techniques are used to develop these beverages, including controlled fermentation, the use of specialized yeast strains and physical methods such as heat treatment and membrane-based dealcoholization. Emerging approaches like precision fermentation are also being explored to improve flavor and aroma profiles. Despite technological progress, challenges remain in replicating the sensory characteristics of alcoholic beverages and achieving broader consumer acceptance. Pricing concerns and regulatory frameworks further influence market growth. Nevertheless, rising awareness of responsible drinking and public health initiatives encouraging reduced alcohol consumption continue to support the expansion of this rapidly evolving beverage segment.

Keywords: Non-alcoholic beverages, Alcohol-free beer, Non-alcoholic spirits, Dealcoholization techniques, Precision fermentation, Consumer perception, Health-conscious consumption.

Introduction

The rise of non-alcoholic spirits and beers is driven by health-conscious consumers seeking alternatives that offer complex flavors without the adverse effects of alcohol. These alternatives are gaining traction due to their potential health benefits, innovative production techniques and evolving consumer perceptions. However, they also face challenges related to flavor quality, market acceptance and regulatory considerations.

Health Benefits and Consumer Demand

- Non-alcoholic beers and spirits are increasingly popular among consumers who are aware of the health risks associated with alcohol consumption. These beverages offer a healthier alternative by eliminating alcohol-related harms while still providing some of the beneficial bioactive compounds found in traditional beers (Mellor *et al.*, 2020) (Gliszczyńska-Świątło *et al.*, 2025).
- The demand for these products is particularly strong among younger, wealthier and health-conscious demographics who are turning away from alcohol in favor of safer alternatives (Nutt *et al.*, 2022).

- Despite the growing interest, consumer demand is tempered by the perception that non-alcoholic options do not facilitate social interactions in the same way as alcoholic beverages (Nutt *et al.*, 2022).

Flavor and Production Techniques

- The production of non-alcoholic beers involves both biological and physical methods. Biological methods include altering fermentation conditions and using special yeast strains, while physical methods involve removing alcohol through heat or membrane processes (Muller *et al.*, 2020).
- Precision fermentation and the use of non-conventional yeasts are emerging as promising techniques to enhance the flavor profile of non-alcoholic beers, addressing common complaints about their lack of aroma and presence of off-flavors (Dusséaux *et al.*, 2023) (Piornos *et al.*, 2022).
- Membrane-based dealcoholization methods, such as pervaporation, are particularly effective in preserving the natural constituents of beer aroma, resulting in a product that more closely resembles its alcoholic counterpart (Muller *et al.*, 2020).

Consumer Perception and Market Challenges

- Consumer perception of non-alcoholic beers is mixed, with many finding them less satisfactory in terms of sensory quality compared to regular beers. However, prior experience with non-alcoholic options can lead to more favorable perceptions and increased willingness to try and pay for these products (Dupuis *et al.*, 2024).
- The market faces challenges in producing non-alcoholic beers that match the sensory characteristics of traditional beers, particularly in terms of flavor and body (Sohrabvandi *et al.*, 2010) (Gliszczyńska-Świgło *et al.*, 2025).
- Pricing remains a significant barrier, as non-alcoholic beverages are often priced higher than consumer expectations, which can deter potential buyers (Dupuis *et al.*, 2024).

Regulatory and Social Considerations

- Regulatory frameworks play a crucial role in the development and marketing of non-alcoholic beverages. These products must navigate complex regulations that vary by region, particularly in countries where alcohol consumption is restricted or prohibited (Sohrabvandi *et al.*, 2010).
- The World Health Organization encourages the substitution of high-alcohol products with non-alcoholic alternatives to reduce overall alcohol consumption, but this must be done without circumventing existing regulations or targeting new consumer groups with alcohol marketing (Purei, 2023).
- Socially, non-alcoholic beverages are gaining acceptance as part of a broader trend towards responsible drinking, although they do not yet fully replicate the social facilitation effects of alcohol (Nutt *et al.*, 2022).



Fig. 1: Alcohol alternatives: health benefits, production innovations, flavor challenges, regulatory and social issues.

Conclusion

Non-alcoholic spirits and beers offer a promising alternative for health-conscious consumers, they must overcome significant challenges related to flavor quality, consumer perception and regulatory compliance. Continued innovation in production techniques and strategic marketing efforts are essential to enhance their appeal and market penetration. As the industry evolves, it will be important to balance consumer demand with regulatory and social considerations to ensure these products contribute positively to public health goals.

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AMARANTH: THE ANCIENT SUPERGRAIN FOR MODERN NUTRITION

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Introduction

Amaranth has emerged as a remarkable crop with both ancient roots and modern relevance. Often referred to as a “supergrain,” amaranth is not a true cereal like wheat or rice but a pseudocereal valued for its exceptional nutritional profile, adaptability, and versatility. Once a staple food of ancient civilizations, it is now regaining global recognition as a solution to contemporary challenges such as malnutrition, climate change, and food insecurity. Amaranth has been cultivated for more than 6,000 years. It was a major food crop of the Aztec, Mayan, and Incan civilizations in Central and South America. In these cultures, amaranth was not only consumed as a daily staple but also held cultural and religious importance. After colonization, its cultivation declined significantly. However, traditional farming communities preserved the crop, allowing it to survive and eventually re-emerge as an important agricultural commodity. Today, amaranth is grown in many parts of the world, including Asia, Africa, and the Americas. In India, it is commonly known as “rajgira” and is widely consumed during fasting periods, highlighting its long-standing cultural integration. These plants have indeed been known to offer beneficial health-promoting characteristics for millennia. Guidelines for nutritional supplements, functional foods, and pharmaceutical items are based on their formulations.

Amaranth (*Amaranthus*) is not technically a grain but a pseudocereal – a plant that produces fruits or seeds consumed as grains, though botanically they are neither grasses nor true cereal grains. This ancient crop has been cultivated for thousands of years, originating in Mesoamerica, where it was a staple food for the Aztecs and Incas. The plant itself is impressive, growing up to 6-8 feet tall with vibrant flowers ranging from deep red to gold. There are over 60 species of amaranth, but only three are commonly cultivated for their edible seeds: *Amaranthus caudatus*, *Amaranthus cruentus*, and *Amaranthus hypochondriacus*.



Amaranthus caudatus



Amaranthus cruentus



A. hypochondriacus

Amaranth as a Supergrain for Modern Nutrition

In 2025, Amaranth has become increasingly popular in Western eating patterns as consumers look for foods that are both highly nutritious and environmentally sustainable. Despite their tiny size—similar to poppy seeds—amaranth grains are remarkably nutrient-rich. They provide abundant protein, essential amino acids, fiber, and important minerals, often matching or even exceeding the nutritional value of many traditional cereal grains.

- Amaranth grains contain 65 to 75% starch, 4 to 5% dietary fibers, a 2 to 3 times higher content of sucrose in comparison to wheat grain, and nonstarch polysaccharide components (Malik *et al.*, 2023).
- Sucrose is the major sugar, followed by raffinose, whereas inositol, stachyose, and maltose are in small amounts in the amaranth grains (Venskutonis *et al.*, 2013).
- Amaranth grains contain 15.4-16% protein with a balanced composition of amino acids as compared to wheat (13.5-14.5%), maize (10.6-13.8%), barley (10-14.9%), and oats (12.4-12.9%) and total essential amino acids of about 47.6 g/100g protein (Malik *et al.*, 2023).
- Amaranth grains contain 6.98-7.22% lipids, with 71.58-72.44% of it being unsaturated fatty acids (Alemayehu *et al.*, 2015).
- Amaranth has about twice the saturated fatty acids (C16:0 and C18:0) than quinoa. Amaranth grains are found to be rich in palmitic but deficient in oleic and linolenic acids in comparison with major grains and oilseeds (Jahaniaval *et al.*, 2000).
- Amaranth grains contain a high amount of macro- and microelements. Macromineral components are usually less those or comparable to that of wheat grains except for magnesium, as amaranth has twice as much Mg as that of wheat (Tomoskozi *et al.*, 2009).
- Amaranth grains have higher antioxidant activity and phytochemical content than oat, barley, wheat, corn, millet, and rice, revealing it to be a good substitute for traditional cereals and a potential source of health-promoting bioactive compounds (Akin-Idowu *et al.*, 2017).

Beyond standard nutrients, amaranth contains several bioactive compounds that contribute to its health benefits:

- **Squalene:** A compound typically found in olive oil and shark liver oil, with potential antioxidant and cancer-fighting properties
- **Phytosterols:** Plant compounds that can help lower cholesterol levels
- **Amaranthine:** A pigment with potent antioxidant properties
- **Phenolic acids:** Including gallic acid, p-coumaric acid, and vanillic acid, which have anti-inflammatory and antioxidant effects

Conclusion

Amaranth is an ancient crop that has regained importance in modern nutrition due to its exceptional nutritional value and adaptability to diverse environmental conditions. As a pseudocereal, it offers a rich source of high-quality protein, essential amino acids, dietary fiber, healthy lipids, minerals, and various bioactive compounds with antioxidant and health-promoting properties. Its nutrient profile often surpasses that of many conventional cereal grains, making it a valuable alternative for improving dietary quality and addressing malnutrition. In addition to its nutritional benefits, amaranth is a resilient crop capable of growing under challenging climatic conditions, which makes it an important component of sustainable agriculture and food security

strategies. With increasing global interest in functional foods and sustainable diets, amaranth has the potential to play a significant role in modern food systems. Promoting its cultivation, processing, and consumption can contribute to improved human health, agricultural diversity, and long-term nutritional sustainability.

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CLIMATE CHANGE AND ITS IMPACT ON LAND DEGRADATION PROCESSES

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Abstract

Anthropogenic climate change has emerged as a dominant driver of environmental transformation in the 21st century, significantly intensifying global land degradation processes. With only approximately 11% of the Earth's surface classified as highly productive arable land, increasing population pressures and unsustainable land-use practices pose severe risks to food security and environmental stability. This article examines the complex interactions between climate change and major land degradation mechanisms, including accelerated soil erosion, desertification, drought intensification, soil salinization, and glacial melt-induced mountain instability. Rising temperatures, altered precipitation regimes, and the growing frequency of extreme climatic events are disrupting soil structure, hydrological cycles, and biogeochemical processes, thereby reducing land productivity and ecological resilience. Particular emphasis is placed on soil erosion as a leading cause of terrestrial degradation and biodiversity loss, alongside the expansion of drylands and destabilization of mountain ecosystems due to cryospheric changes. The findings highlight that nearly 40% of global land is already degraded, with profound implications for food systems, water resources, ecosystem services, and socio-economic stability. Addressing climate-driven land degradation requires integrated, adaptive land management strategies and urgent global climate action to safeguard environmental sustainability and future human well-being.

Keywords: Climate Change, Land Degradation, Desertification, Soil Erosion, Sustainable Land Management etc.

Introduction In the 21st century, anthropogenic climate change has emerged as one of the most powerful drivers of environmental transformation. The issue of land degradation carries profound implications for world food security and overall environmental quality [Blaikie P, Brookfield H (1987) Barrow CJ (1992)]. Its significance becomes even more striking when one considers that only about 11% of the global land surface qualifies as prime or Class I land—the most fertile and productive category of soil. This limited resource must sustain a rapidly growing population, estimated at 6.3 billion at the time and projected to reach 8.2 billion by 2020 (Reich *et al.*, 2001). With such immense pressure placed on a shrinking base of productive land, the challenge of safeguarding soil resources becomes increasingly urgent. For this reason, land degradation is not merely an environmental concern but a global development issue, ensuring that it remains high on the international agenda throughout the 21st century. Change has emerged as one of the most powerful drivers of environmental transformation. Among its most alarming consequences is land degradation, a growing global concern that silently threatens ecosystems and human livelihoods alike. Land degradation refers to the reduction in the potential of land to produce benefits under a particular land use and specific management practices.

Among the various processes driving land degradation, soil erosion stands out as one of the most significant (Koch *et al.*, 2013). It primarily strips away the fertile topsoil layer — the very foundation of agricultural productivity and ecosystem stability. This thin yet vital layer supports the functioning

of (agro)ecosystems and plays a fundamental role in ensuring food security worldwide (Amundson *et al.*, 2015). Beyond the visible loss of soil, erosion also disrupts critical biogeochemical cycles, altering the natural movement of nutrients and carbon within ecosystems. In doing so, it does not merely result from climate change, but actively interacts with and influences it, creating a complex feedback system (e.g., Regnier *et al.*, 2013; Tan *et al.*, 2020; Zhang *et al.*, 2020).

Impacts of Soil Erosion

Anthropogenic climate change has become a dominant force reshaping terrestrial ecosystems, with far-reaching consequences for land stability and productivity. One of its most critical yet often under-recognized outcomes is the intensification of land degradation processes. Shifts in temperature regimes, variability in precipitation patterns, increased frequency of extreme climatic events, and prolonged drought conditions are accelerating geomorphological and biophysical processes such as soil erosion, desertification, salinization, nutrient depletion, and vegetation decline. These climate-induced stressors disrupt soil structure, alter hydrological cycles, and impair essential biogeochemical functions, thereby reducing the land's carrying capacity and ecological resilience. As climate dynamics continue to evolve, understanding their synergistic interaction with land degradation mechanisms becomes imperative for designing adaptive and sustainable land management frameworks.

1. Accelerated Soil Erosion

Soil erosion is the silent sculptor of the Earth's surface—shaping landscapes through the relentless forces of wind, water, waves, and glaciers. Yet when this natural process intensifies into accelerated erosion, the balance tips dangerously, with soil being stripped away faster than it can regenerate. Fine, fertile particles are detached and carried off—sometimes across vast distances as dust, as seen during the Dust Bowl of the 1930s in the United States—leaving behind impoverished land. The consequences ripple far beyond the soil itself: declining fertility, reduced crop productivity, degraded air and water quality, and increased risks of flooding, mudslides, and sedimentation. As the leading cause of global soil degradation, erosion transforms once-productive landscapes into barren grounds, forcing abandonment and threatening both terrestrial and aquatic ecosystems.

2. Desertification Expansion

Desertification represents one of the most severe manifestations of climate change—induced land degradation, particularly in arid, semi-arid, and dry sub-humid regions. Defined by the United Nations Convention to Combat Desertification (UNCCD, 1994) as land degradation resulting from climatic variations and human activities, desertification is not simply the outward spread of existing deserts but a progressive decline in land quality and ecosystem productivity. Recent assessments by the Intergovernmental Panel on Climate Change indicate that degradation rates in drylands are now 30–35 times higher than historical norms. Rising global temperatures, erratic rainfall patterns, and prolonged droughts—hallmarks of climate change—accelerate the breakdown of soil structure, reduce vegetation cover, and intensify erosion processes. As productive landscapes are transformed into barren terrain, desertification threatens food security, water availability, biodiversity, and the livelihoods of millions, underscoring its critical role in the expansion of land degradation under a changing climate.

3. Increased Frequency of Droughts

Climate change has significantly increased the frequency and intensity of droughts, making them a critical driver of land degradation processes worldwide. A drought, defined as a prolonged

deficiency of precipitation resulting in water shortages, is now being intensified by rising global temperatures. Warmer conditions enhance evaporation and evapotranspiration, reducing surface water availability and drying out soils and vegetation more rapidly than under cooler climatic conditions. Even when precipitation deficits are only moderate, higher temperatures exacerbate soil moisture loss, leading to severe agricultural droughts that directly affect crop productivity and soil health. Climate change is also altering the timing of water availability by reducing snowpack in many regions, thereby limiting gradual water release during warmer months. Recent events, such as the January 2025 wildfires in the Los Angeles region, highlight how increased aridity and heat contribute to extreme land degradation through vegetation loss and soil exposure. Scientific assessments indicate that out of 103 drought events studied globally, 71 were made more severe or more likely due to global warming. Although meteorological droughts show relatively smaller direct changes, agricultural and ecological droughts are increasing worldwide, accelerating soil erosion, desertification, and long-term declines in land productivity.

4. Salinization of Soils

Climate is a major factor influencing soil formation, development, and management, with temperature, precipitation, and wind playing key roles. Soils in warm and humid regions are generally more developed than those in cold or dry climates. There is a close feedback relationship between soil and climate, as soil processes affect greenhouse gas levels, which in turn regulate climate. Over the past 150–200 years, rising temperatures have altered precipitation patterns, vegetation, and soil properties. Climate change also impacts soil temperature, organic matter, biological activity, and salt content. Increasing aridity due to global warming is accelerating soil salinization and desertification, particularly in arid regions, reducing land productivity and increasing irrigation demand.

5. Glacial Melt and Mountain Land Instability

Climate change is accelerating global glacier melt and intensifying mountain land degradation processes worldwide. According to the 2025 United Nations World Water Development Report published by UNESCO on behalf of UN-Water, climate disruption, biodiversity loss, and unsustainable human activities are rapidly transforming mountain ecosystems, threatening critical freshwater resources that sustain billions of people. The Himalayan glaciers, a key component of the Earth's cryosphere, are retreating at an unprecedented rate due to anthropogenic climate change (Nie *et al.*, 2021; Molden *et al.*, 2022). This accelerated glacial melt destabilizes mountain slopes by weakening permafrost, increasing soil saturation, and altering hydrological regimes, thereby triggering more frequent and intense landslides, debris flows, and glacial lake outburst floods. These processes significantly contribute to land degradation by stripping vegetation cover, eroding fertile soil layers, and reshaping fragile mountain landscapes, ultimately undermining ecosystem stability and human livelihoods.

Conclusion

Climate change is no longer a distant environmental concern — it is a driving force accelerating land degradation across the globe. As rising temperatures intensify droughts, desertification, and extreme weather events, already-stressed ecosystems are losing their ability to function as carbon sinks, food sources, and biodiversity reservoirs. With nearly 40% of the world's land degraded and drylands expanding each year, the pressure on croplands, freshwater systems, and forests is becoming unsustainable. This degradation not only threatens global food and water security but also undermines economic stability and ecosystem services worth trillions of dollars annually. If

current patterns of land misuse and climate inaction continue, vast regions could become unproductive, displacing millions of people by mid-century. Addressing climate change and restoring degraded lands must therefore be central to achieving environmental sustainability and safeguarding future generations.

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AQUATIC ANIMAL QUARANTINE UNIT (AAQU): STRUCTURE, BIOSECURITY, AND OPERATIONAL GUIDELINES

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Abstract

The movement of live shrimp broodstock across regions poses a significant risk of introducing infectious diseases into aquaculture systems. The use of Specific Pathogen-Free (SPF) shrimp has improved biosecurity; however, potential contamination during transport and handling cannot be completely ruled out. An Aquatic Quarantine Facility (AQF) serves as a critical safeguard by isolating newly imported SPF broodstock under controlled and bio secure conditions before their introduction into hatchery operations. During the quarantine period, broodstock are observed for clinical signs of disease, subjected to health screening and diagnostic testing, and allowed to recover from transport stress while acclimatizing to local environmental conditions. Strict measures such as controlled access, disinfection protocols, water treatment systems, and secure waste disposal prevent the entry or escape of pathogens. Only individuals that meet health standards are released for breeding purposes. Thus, quarantine facilities play a vital role in preventing disease outbreaks, protecting native aquatic fauna, ensuring sustainable shrimp production, and supporting responsible aquaculture development.

Keywords : Aquatic quarantine, SPF shrimp broodstock, Disease prevention, Quarantine facility, Standard Operating Procedures (SOPs), Transboundary Aquatic Animal Diseases (TAADs).

Introduction

Quarantine is the controlled isolation of a group of aquatic animals from all other populations, preventing any direct or indirect contact, for a specified period to allow systematic observation, health assessment, diagnostic testing, treatment when necessary, and the safe management of discharged (effluent) water. Quarantine is a concept that has been described in both broad and narrow terms. In a wide sense, it includes all actions taken to prevent the introduction and spread of serious animal diseases across international and domestic borders an approach now commonly associated with overall biosecurity programs (FAO/NACA, 2000). In a more specific sense, quarantine refers to the controlled isolation and maintenance of animals in secure conditions that prevent their escape, as well as the escape of any pathogens, parasites, or disease-causing organisms associated with them into the surrounding natural environment (Arthur, 1996). This controlled holding period allows authorities to monitor the health status of animals before they are moved, traded, or released. Biosecurity is a broader concept that includes quarantine measures and encompasses policies, procedures, and practices designed to prevent disease introduction and spread. These measures aim to protect wild fisheries, aquaculture industries, biodiversity, and the livelihoods of communities that depend on aquatic resources. The primary objective is to prevent the entry, establishment, and spread of serious Transboundary Aquatic Animal Diseases (TAADs),

which can cause significant ecological damage and economic loss. Effective biosecurity involves surveillance, risk assessment, movement controls, sanitation practices, and emergency response planning to reduce the likelihood of disease outbreaks and their impacts.

Key Principles of Quarantine Practice

According to FAO (2007), quarantine is an essential biosecurity measure used to manage the risks associated with the movement or importation of live aquatic animals. When the health risk posed by a consignment is considered unacceptable, quarantine either alone or combined with other control measures can be applied to reduce the risk to a level consistent with the country's Appropriate Level of Protection (ALOP). The strictness of quarantine procedures should match the assessed level of risk, which depends on factors such as the origin and destination of the animals. Because aquatic diseases are extremely difficult, and often impossible, to eliminate once established in natural environments, special caution is required for species intended for release into open waters. Quarantine activities, including observation for clinical signs, diagnostic testing, and treatment, may be conducted in the exporting country, during transit, or in the importing country. Effective quarantine facilities must meet minimum standards related to location, design, infrastructure, security, water treatment systems, trained personnel, and operational protocols to prevent the escape of animals or pathogens into the environment. Movements that involve high or uncertain disease risks, particularly from regions where exotic pathogens are present should occur only when fully contained facilities and adequate support services, such as diagnostic capabilities, inspection, and security, are available. Quarantine facilities handling aquatic animals must operate under strict regulatory compliance to prevent the introduction and spread of infectious diseases. The selection and application of disinfectants, antibiotics, and other chemicals should follow national laws and safety guidelines, ensuring protection for facility personnel, the animals under care, and the surrounding environment. Only approved substances should be used, and their application must minimize any harmful side effects. Effective sanitation of quarantine units requires the use of appropriate cleaning agents and disinfection procedures. Regulatory or competent authorities should assess these products under local environmental conditions to confirm their effectiveness against relevant pathogens. Clearly documented Standard Operating Procedures (SOPs) should guide staff on the correct preparation, use, contact time, and disposal of disinfectants to maintain consistent biosecurity standards. All wastewater, effluents, and solid wastes produced within the facility must undergo proper treatment before discharge to ensure complete destruction of potential pathogens. This prevents contamination of natural water bodies and protects wild aquatic populations. To reduce the risk of introducing diseases, countries are encouraged to import early life stages such as eggs, embryos, or juveniles rather than adult animals. These stages typically carry fewer hidden infections and are easier to manage under controlled quarantine conditions. Animals selected for introduction or transfer should be handled in clearly defined batches. Each batch should consist of individuals of the same age from the same source population and maintained separately on an independent water system. Mixing between batches whether of animals, water, equipment, or personnel must be strictly avoided to prevent cross-contamination. Although many diseases, particularly those caused by external parasites, can be treated, chemical treatments must be used judiciously. Improper or excessive use can lead to complications such as toxicity, stress, or the emergence of antibiotic-resistant microorganisms. Therefore, treatments should only be administered under expert supervision and with careful monitoring. If a severe and untreatable disease is detected within a quarantined population, immediate action is required. This

may involve humane destruction of the entire affected stock followed by thorough cleaning and disinfection of the facility to eliminate the pathogen and prevent further spread. Stocks originating from facilities that have successfully completed approved quarantine procedures may be granted special clearance, provided that conditions at the source remain unchanged. Such approval can reduce the duration or intensity of subsequent quarantine requirements.

WOAH Listed Pathogens OIE is now called WOA – (World Organization for Animal Health)

- ✓ White Spot Syndrome Virus (WSSV)
- ✓ Yellow Head Virus (YHV)
- ✓ Taura Syndrome Virus (TSV)
- ✓ Infectious Myonecrosis Virus (IMNV)
- ✓ Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV)

Non-WOAH Listed / Other Pathogens

- ✓ Baculovirus Penaei (BP)
- ✓ Necrotizing Hepatopancreatitis (NHP)
- ✓ Enterocytozoon hepatopenaei (EHP) is currently not included in the WOA listed diseases.

Essential Elements of an Aquatic Quarantine Facility

An Aquatic Quarantine Facility (AQF) must incorporate a comprehensive set of infrastructure and operational systems, established in accordance with prescribed Standard Operating Procedures (SOPs), to ensure effective containment, health surveillance, and biosecurity of aquatic organisms.

The principal components include:

- ✓ Water Intake, Treatment, and Distribution System
- ✓ In-house PCR-based Diagnostic Laboratory
- ✓ Freshwater Supply and High-Pressure Freshwater (HPFW) System
- ✓ Consignment Reception and Handling Unit
- ✓ Controlled Quarantine Units
- ✓ Packing, Storage, and Dispatch Section
- ✓ Environmental Control Systems (Air Blowers, Oxygenators, Ozone, Air Conditioning, and Lighting)
- ✓ Effluent Treatment System (ETS) for safe waste management
- ✓ Integrated Biosecurity and Disinfection System
- ✓ Data Recording, Monitoring, and Management System
- ✓ Reliable Energy Supply and Backup Power System
- ✓ Aquatic Quarantine Management System (AQMS)

Guidelines for Accessing an Aquatic Quarantine Facility

The utilization of an Aquatic Quarantine Facility (AQF) is governed by strict regulatory protocols to safeguard aquaculture biosecurity and prevent the introduction of transboundary aquatic diseases. In India, only shrimp hatcheries duly authorized by the Coastal Aquaculture Authority (CAA) are permitted to import broodstock and use AQF services. These hatcheries must source Specific Pathogen Free (SPF) broodstock of *Litopenaeus vannamei* exclusively from approved international suppliers. Prior to importation, the prospective importer must obtain a formal Letter of Permission from the CAA specifying the sanctioned quantity of broodstock. In addition, a valid Sanitary Import Permit issued by the Ministry of Agriculture & Farmers Welfare, Government of India, is mandatory. These documents certify that the proposed import complies with national biosecurity

regulations and aquatic animal health standards. Upon securing the required approvals, the importer is required to notify the AQF authorities at least 30 days before the expected arrival of the consignment to reserve quarantine space. Allocation of space is typically conducted on a first-come, first-served basis due to the limited holding capacity of quarantine installations. To finalize the reservation, confirmation must be provided no later than 10 days prior to shipment arrival. This confirmation should be accompanied by the prescribed quarantine fee and a formal undertaking stating that the importer agrees to abide by all operational rules, biosecurity measures, and terms of the facility. Failure to import the broodstock within the allotted schedule, or any delay attributable to the importer, may result in forfeiture of the reservation fee, as the reserved quarantine units could otherwise have been assigned to other applicants. This policy ensures efficient utilization of the facility and prevents logistical disruptions. After arrival, the imported broodstock obtained from authorized SPF suppliers are transferred under controlled conditions to the AQF quarantine units. The stock is maintained in strict isolation for a minimum period of five days. During this time, comprehensive health monitoring, diagnostic screening, and observation are conducted to verify the SPF status and overall health of the animals. Only broodstock confirmed to be free from specified pathogens and in sound physiological condition are subsequently cleared for transfer to hatchery facilities. Thus, the AQF serves as a critical biosecurity barrier, ensuring that only healthy, disease-free broodstock enter the domestic aquaculture system, thereby protecting both farm productivity and the surrounding aquatic environment.

Conclusion

The Aquatic Quarantine Facility (AQF) plays a vital role in ensuring the safe importation of disease-free broodstock and maintaining biosecurity in aquaculture. Strict procedures and regulatory approvals by the Coastal Aquaculture Authority and the Ministry of Agriculture & Farmers Welfare help prevent the introduction of harmful pathogens. By allowing only Specific Pathogen Free stocks of *Litopenaeus vannamei*, AQFs protect farm productivity, aquatic ecosystems, and the sustainability of the shrimp industry.

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DETERMINANTS OF CONSUMER PERCEPTION AND PURCHASE INTENTIONS TOWARDS ORGANIC FOOD

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Abstract

India has become a global leader in organic agriculture, with a 78% increase in organic farmland and a global market exceeding USD 350 billion. This study examines the determinants of organic food consumption. It finds that adoption is highest among educated, urban young adults (ages 18 to 33) and is strongly influenced by income levels ($p < 0.05$). Consumers primarily choose organic products for perceived health benefits, which are associated with higher levels of polyphenols and omega-3 fatty acids, as well as reduced exposure to synthetic pesticides. Using models such as the Health Belief Model (HBM) and the Theory of Planned Behaviour (TPB), the research demonstrates that environmental awareness and health consciousness lead to "green" purchasing intentions. Despite strong interest, market growth is constrained by high prices and trust issues regarding certifications. To close the gap between intention and action, stakeholders should focus on clear labelling, targeted pricing, and government-led awareness campaigns to increase the prevalence of sustainable consumption.

Keywords: Organic agriculture, Consumer behaviour, Health consciousness, Market growth, Sustainable consumption

Introduction

India is one of the largest producers of organic food in the world, thanks to its diverse agricultural practices. In recent years, the country has experienced significant growth in organic farmland, which now accounts for 78% of its total farmland (Ghosh *et al.*, 2026). By 2025, the global organic food market had exceeded USD 350 billion, showing strong demand for organic products. India has become a major player in the production of certified organic foods (FiBL and IFOAM, 2025). Organic food products are grown and processed without synthetic pesticides, chemical fertilizers, or genetically modified organisms (GMOs). As awareness of health and environmental sustainability increases, consumers are choosing organic food. These products are often viewed as healthier, tastier, and more environmentally friendly (Vasanthi and Preethi, 2026). In emerging economies such as India, organic food consumption is linked to concerns about personal health and the environment. This trend reflects broader sustainability principles, which focus on social, environmental, and economic well-being. Over the years, numerous studies have sought to explain why Indian consumers are increasingly interested in organic food. Factors such as product usefulness, brand reputation, openness to new products, and positive word-of-mouth have contributed to the growth of organic food in the Indian market. However, direct evidence remains limited (Ghosh *et al.*, 2026). Reports indicate that organic food products are increasingly popular among educated and urban consumers in Andhra Pradesh. In fact, 89.33% of respondents are young

adults aged 18-33. This suggests that younger consumers are more likely to incorporate organic food into their daily diets. The study also found that income level significantly shapes attitudes toward organic food ($p < 0.05$). People with higher incomes are more likely to purchase organic products, suggesting that affordability and purchasing power influence the decision to choose organic food (Vasanthi and Preethi, 2026).

Key Drivers of Organic Food Choice

Superior health benefits: Organic food is often associated with freshness and naturalness because it is produced without many of the contaminants typically found in conventional food. Many believe that organic food is healthier because it typically contains higher levels of beneficial compounds, such as polyphenols, vitamin C, carotenoids, and omega-3 fatty acids (n-3 PUFA). These compounds may help lower the risk of metabolic diseases. Plants produce polyphenols naturally in response to stress. Since organic farming generally uses fewer synthetic fertilisers and chemicals, crops might grow in more stressful conditions. This can lead to higher levels of protective compounds. A meta-analysis indicates that organic foods often have more beneficial nutrients, including polyphenols. They also tend to have lower or negligible levels of pesticides and cadmium (Cd). Epidemiological studies report that organic crops typically have higher levels of some bioactive compounds. These compounds may help reduce the risk of chronic diseases, including cardiovascular disease, neurodegenerative diseases, and certain cancers. Moreover, organic foods generally contain lower levels of cadmium and other harmful substances, such as pesticides. These substances have been linked to imbalances in gut bacteria, immune disorders, and toxic effects in humans (Hurtado-Barroso *et al.*, 2019). Several theories explain why consumers prefer organic food. For example, the Health Belief Model (HBM) suggests that people are more likely to choose organic products when they perceive these foods as offering health benefits and reducing health risks relative to conventional options. Similarly, the Protection Motivation Theory (PMT) suggests that heightened awareness of health risks, particularly during crises, can motivate individuals to adopt protective behaviours, such as choosing organic foods. This theory suggests that concerns about chemical exposure and food safety often lead consumers to select safer, healthier food options (Masih *et al.*, 2025).

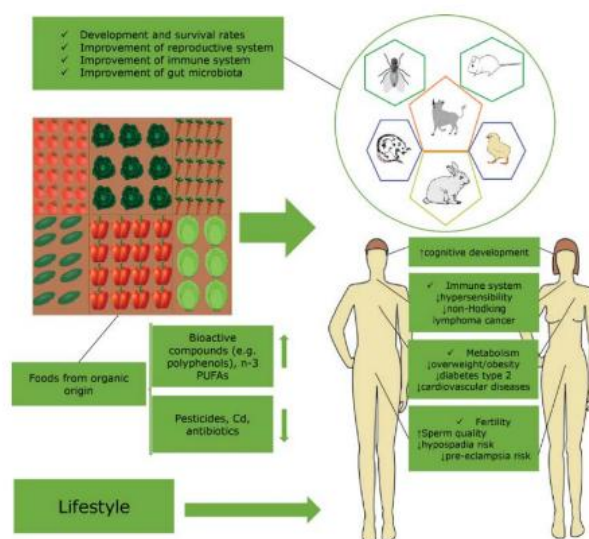


Figure 1: Effects of organic food on animal and human organisms and the possible influence of lifestyle in humans: preliminary results (Masih *et al.*, 2025)

Nature-friendly attributes : Approximately 40% of the world's ice-free land is used for farming. Organic farming is usually better for the environment than conventional farming when looking at land use. However, it is not as effective for output because of lower average yields. Organic farming bans synthetic fertilisers, pesticides, and genetically modified crops, which makes plant nutrition and pest control more difficult and often less effective (Meemken and Qaim, 2018). The studies reviewed show that organic farming has greater potential for biodiversity than conventional farming due to its ability to create different habitats and implement wildlife-friendly practices. The lack of pesticides also supports this benefit. Organic methods, such as using organic matter like green or animal manure and practising longer, more diverse crop rotations with cover and catch crops, can help prevent soil erosion and slow down fertility decline. Environmental awareness involves understanding environmental issues and committing to protecting the environment. This awareness is essential for green consumption. The Theory of Planned Behaviour (TPB) model explains how awareness of health and the environment affect the choice to buy green-packaged organic foods. Consumers who are highly aware of environmental issues tend to have more positive views about green products. They believe these products can help reduce pollution and protect the environment, which makes them more willing to buy. Green packaging shows a commitment to environmentally friendly principles and uses biodegradable and recyclable materials. This method helps cut down on pollution and meets the needs of environmentally conscious consumers. These consumers are also shaped by social norms that influence their support for environmentally friendly actions. Additionally, environmental awareness boosts consumers' confidence and willingness to buy green-packaged organic foods, mainly because they strongly connect with the values behind that behaviour. Research shows that environmental awareness significantly drives consumer behaviour and strongly motivates green buying. In the organic food sector, this awareness leads consumers to pay more attention to the environmental benefits of products and whether they support sustainable development principles. At the same time, health consciousness makes consumers more aware of the health benefits of organic food, which increases their intention to buy. Environmental awareness also strengthens consumers' sense of responsibility towards the environment, further promoting green consumption. When choosing what to buy, consumers often look at both health benefits and environmental impacts; these factors are key in shaping a positive attitude toward purchases (Li and Shan, 2025).

Quality, taste, and social impact: Consumers perceive organic food products as healthier, more natural, and better for the environment, making them more attractive. Consumers' perceptions of organic food depend on their demographic characteristics, social status, and economic background. These beliefs play a key role in shaping buying choices and market trends for organic products. Research from various countries shows that opinions on organic food vary worldwide due to cultural and economic factors. For example, in Germany, consumers value organic certification but often consider organic products too expensive and a luxury. In Italy, local organic products are perceived as authentic and healthier, thereby influencing consumer perceptions. In Poland, high prices and limited awareness constrain consumer choices, although more people are beginning to appreciate organic food (Grzywińska-Rąpca *et al.*, 2025). Some consumers are swayed by community groups, peers, and personal experiences, leading them to prefer organic food products. Some choose organic foods to support local farmers and contribute to their economic well-being. They see this as a personal motivation. Trust in organic certifications and perceived nutritional benefits also drive consumers to buy organic products. Recommendations from nutritionists,

doctors, store staff, and experts in campaigns promoting the benefits of organic foods, along with feedback from influencers, motivate consumers to choose these products (Kalyani and Prabhavathi, 2023).



Figure 2: Consumer perception towards organic food products (Kalyani and Prabhavathi, 2023)

Conclusion

There are various factors affecting the consumption of organic foods in India. It is important to understand the factors behind the growing trend in the consumption of organic foods, which include motivations, behaviours, beliefs, and demographic factors. Understanding this is important to the potential growth of the organic market to become a mainstream product. Access to quality organic foods at competitive prices is important in attracting consumers to this product, which is environmentally friendly since the use of pesticides is minimal. All these factors show that when developing strategies to promote the consumption of organic foods, age groups, awareness, and enhancing accessibility, transparency, and trust are important considerations to bridge the gap between intentions and behaviours in the quest to hasten the move towards sustainable consumption in the growing market. To grow the organic food market, it is essential to implement focused pricing strategies, build consumer trust through clear certification, and enhance awareness campaigns. These insights can help policymakers, retailers, and marketers create more inclusive and effective strategies for promoting organic food consumption in urban areas. Therefore, a concerted effort from all parties, especially the government, to highlight the benefits of organic food can influence consumer behaviour. Future studies should adopt a consumer-based approach, which is vital not only for consumers but also for addressing changes in market dynamics.

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ALLELE MINING: A STRATEGIC TOOL FOR ENHANCING GENETIC GAIN AND CLIMATE RESILIENCE IN CROPS

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Introduction

Modern agriculture faces a critical genetic bottleneck effect, a phenomenon where centuries of domestication and intensive selection for yield have inadvertently led to the erosion of genetic diversity. This narrow genetic base has resulted in the loss of ancestral alleles that originally conferred resilience against biotic and abiotic stressors. As global food systems now face the dual pressures of climate change and evolving pathogen populations, the reliance on a handful of high yielding but vulnerable elite varieties poses a significant threat to global food security.

Allele mining has emerged as a sophisticated reverse genetics approach designed to mine these lost or novel alleles from vast gene banks, wild relatives, and natural populations. Unlike traditional breeding, which often relies on phenotypic observation, allele mining leverages the power of high throughput sequencing and bioinformatics to identify specific DNA sequence variations within candidate genes. By shifting the analytical focus from the entire genome to specific loci of interest, this methodology allows for the targeted and rapid discovery of traits such as drought tolerance, nitrogen use efficiency, and broad spectrum disease resistance.

Methodologies in Allele Mining

The integration of allele mining into modern breeding pipelines facilitates the identification of "superior" haplotypes—specific combinations of SNPs that result in optimized protein function or gene expression. When coupled with advanced assembly technologies like GAANTRY, these mined alleles can be synthesized and precisely stacked to reconstruct complex metabolic pathways. This synergy represents a move toward genomic designing, where the genetic architecture of a crop is not merely inherited but deliberately engineered for sustainability and high performance in fluctuating environments.

Sequencing-Based Allele Mining

This approach relies on the PCR-based amplification and sequencing of a specific gene across a diverse set of genotypes. By comparing the resulting DNA sequences, researchers identify Single Nucleotide Polymorphisms (SNPs) and Insertions/Deletions (InDels). Recent shifts toward Next-Generation Sequencing (NGS) and Whole-Genome Re-sequencing (WGR) have significantly increased the speed and reduced the cost of this process, enabling the discovery of allelic diversity at a pangenomic scale.

EcoTILLING (Ecological TILLING)

EcoTILLING is a molecular technique designed to detect natural mutations in a population. Unlike standard TILLING, which uses chemical mutagens, EcoTILLING analyzes natural variation. It utilizes

the Cel I endonuclease enzyme to identify mismatches in heteroduplex DNA formed between a reference and a test variety. This remains a highly cost-effective method for screening large germplasm collections without the need for full sequencing.

Beyond its utility in mutation discovery, EcoTILLING serves as a powerful bridge between classical germplasm conservation and modern genomic designing. By utilizing high throughput platforms like capillary electrophoresis or LI COR gel systems, researchers can rapidly characterize the allelic architecture of thousands of accessions within a gene bank. This process identifies unique haplotypes associated with environmental adaptation, such as salinity tolerance in coastal landraces or heat resilience in desert cultivars. The ability to categorize natural diversity into distinct allelic groups allows breeders to select the most promising parental lines for crossing, thereby reintroducing "lost" genetic resilience into elite commercial varieties.

The cost effectiveness of EcoTILLING remains its most significant advantage, particularly for orphan crops or in laboratories where expensive deep sequencing infrastructure is unavailable. While whole genome sequencing provides a comprehensive view, it often generates an overwhelming amount of data that requires intensive bioinformatic filtering. In contrast, EcoTILLING provides a targeted "snapshot" of variation within specifically chosen candidate genes known to regulate key agronomic traits. When these precisely identified natural alleles are combined with assembly systems like GAANTRY, it enables the creation of complex, multigene stacks that are grounded in proven ecological success. This integration of ecological screening and synthetic biology ensures that the next generation of crops is not only high yielding but also genetically equipped to handle the shifting pressures of a changing climate.

Applications for Crop Improvement

Biotic and Abiotic Stress Tolerance

Beyond rice blast and submergence, allele mining is increasingly focused on broad spectrum resistance to shifting climate patterns. In wheat, mining for the TaVrn and TaPpd alleles has allowed breeders to fine tune flowering time and vernalization requirements, ensuring crops mature before the onset of terminal heat stress. Regarding biotic pressure, the identification of the mlo resistance allele in barley has provided a template for engineering powdery mildew resistance across various cereal species. By sourcing these "wild" alleles, researchers can move beyond the limited resistance found in modern cultivars, creating a robust genetic shield against both fungal pathogens and the physiological strain of fluctuating temperatures.

Nutritional and Quality Traits

The diversification of grain quality through allele mining extends to the secondary metabolite profiles and micronutrient density of staple crops. In addition to provitamin A in maize, researchers have successfully mined alleles for the GPC-B1 gene in wheat, which significantly increases protein, iron, and zinc content in the grain. Furthermore, in oilseed crops like Brassica, allele mining for fatty acid desaturase (FAD) genes has enabled the development of "designer oils" with reduced erucic acid and increased oleic acid levels.

Integration with Modern Breeding Technologies

The true potential of mined alleles is realized when they are integrated into elite cultivars through a multi-pronged biotechnological approach.

Marker Assisted Selection (MAS): The development of High-Resolution Melting (HRM) and Kompetitive Allele Specific PCR (KASP) markers allows for the high throughput tracking of mined

alleles across thousands of progeny. This ensures that the "superior" version of a gene is retained while the rest of the wild donor's genome is purged through selection.

Genome Editing (CRISPR Cas9): CRISPR technology has revolutionized the "mining to field" pipeline. Instead of a decade of backcrossing to move an allele from a wild relative, researchers can now use "Base Editing" or "Prime Editing" to precisely mimic the beneficial SNP (Single Nucleotide Polymorphism) found during allele mining directly within the elite line's DNA.

Speed Breeding and Genomic Selection: By utilizing controlled environments with extended photoperiods, breeders can achieve up to six generations of a crop per year. When combined with genomic selection models that predict the performance of mined alleles in different genetic backgrounds, the time required to release a new, climate resilient variety is reduced from twelve years to less than five.

Conclusion

Despite its potential, allele mining faces hurdles such as the difficulty of accurately phenotyping wild relatives and the existence of "linkage drag," where undesirable genes are inherited alongside the target allele. However, with the rise of Artificial Intelligence (AI) and Machine Learning to predict protein function from sequence data, the next decade will likely see "In-silico Allele Mining" become the standard for crop design.

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ADVANCES IN PLANT METABOLIC ENGINEERING VIA GAANTRY GENE STACKING

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Introduction

The field of plant biotechnology has transitioned from simple single trait modifications to the complex orchestration of entire metabolic pathways. This shift necessitates gene stacking, the simultaneous introduction of multiple transgenes into a single plant genome. Traditional methods such as sexual crossing of independent transgenic lines or sequential retransformation often suffer from genetic linkage issues, unpredictable expression patterns, and linkage drag. To overcome these hurdles, the GAANTRY (Gene Assembly in *Agrobacterium* by Nucleic acid Transfer using Recombinase technology) system was developed. It represents a shift toward in vivo assembly within the delivery vehicle itself, offering a robust solution for large scale synthetic biology in crops.

The Architecture of Gene Stacking

Gene stacking is essential for developing next generation crops with enhanced nutritional profiles such as biofortified Golden Rice, complex pest resistance, or climate resilience. However, the physical size of these multigene constructs often makes them unstable in standard *E. coli* cloning vectors.

Limitations of Traditional Methods

Sexual Crossing is time consuming and genes integrate at different loci, making it nearly impossible to keep the stack together in subsequent breeding generations. Retransformation requires multiple rounds of tissue culture and different selectable markers, often leading to gene silencing.

During In-Vitro Assembly, powerful methods like Gibson Assembly or Golden Gate face efficiency drops as the total DNA size exceeds 30 kb. Transferring these large blocks into *Agrobacterium* remains a major bottleneck.

GAANTRY: A Paradigm Shift in Assembly

The GAANTRY (Gene Assembly in *Agrobacterium* by Nucleic acid Transfer using Recombinase technology) system solves these stability and transfer issues by performing the assembly directly within *Agrobacterium tumefaciens*. Instead of building a massive plasmid in a test tube and attempting to force it into the bacteria, GAANTRY builds the stack link by link on the T DNA (Transfer DNA) located on a modified virulence plasmid.

The system utilizes a sophisticated stacking cycle powered by site specific recombinases such as Par A, TP901 1, and A118. These enzymes act as precision molecular glue, ensuring that each new gene cassette is inserted at a pre-determined site without causing internal rearrangements. Each

successful integration event switches the antibiotic resistance of the bacteria, ensuring only correctly updated stacks survive. This in vivo assembly allows for cargo capacities exceeding 10 genes, delivered to the plant cell as a single unit to ensure all genes integrate at a single genomic locus for stable inheritance.

The Mechanism of Action

GAENTRY utilizes various recombinases like ParA, TP901 1, and A118 that act like precision molecular glue. Unlike standard recombination, these are highly specific and do not cause internal rearrangements of the stack. The Pin and Donor System, in which a Pin plasmid already in the *Agrobacterium* serves as the foundation. Donor plasmids containing the target genes are introduced one by one.

Alternating Selection: Each successful integration event switches the antibiotic resistance of the bacteria. This ensures that only the colonies containing the correctly updated stack survive the next round. GAENTRY has demonstrated the ability to stack 10 or more genes with high fidelity. Because the stack is built directly on the T DNA, the entire payload is delivered to the plant cell as a single unit, ensuring all genes integrate at a single genomic locus.

Precision Engineering and Regulatory Benefits

One of the most critical aspects of GAENTRY is its ability to produce clean transgenic events. In traditional *Agrobacterium* mediated transformation, fragments of the plasmid backbone often integrate into the plant genome. These extraneous DNA sequences can trigger regulatory scrutiny and potentially interfere with the expression of the target genes.

GAENTRY utilizes a refined T DNA border system that ensures only the intended multigene stack is transferred. Furthermore, the use of site specific recombinases means the stack is assembled in a predictable, linear fashion. This modularity allows researchers to use characterized promoters and terminators to ensure that each gene in the stack is expressed at the desired level without interfering with its neighbors.

Overcoming Metabolic Bottlenecks

In metabolic engineering, simply adding genes is often not enough. One must balance the flux of metabolites to avoid the accumulation of toxic intermediates. GAENTRY supports this by allowing for the inclusion of regulatory elements or RNAi constructs within the same stack. For example, a single GAENTRY construct could introduce four enzymes for a new biosynthetic pathway while simultaneously silencing an endogenous enzyme that would otherwise divert the precursor molecules away from the target product.

This level of control is vital for "stacking" traits like drought tolerance and nitrogen use efficiency, which involve complex signalling networks rather than single protein products. The ability to assemble these components in a single bacterial host reduces the experimental variability that usually plagues large scale plant transformation projects.

Furthermore, the centralized assembly provided by GAENTRY facilitates the implementation of synthetic gene circuits, such as feed forward loops or inducible switches, which are essential for precision metabolic control. In traditional stacking, the random integration of multiple constructs often leads to "transcriptional interference," where the expression of one transgene negatively impacts its neighbor due to chromatin remodelling or promoter competition.

GAENTRY mitigates these spatial effects by allowing researchers to strategically orient genes and insert insulating boundary elements within the T DNA backbone. This architectural precision ensures that complex traits, like C4 photosynthesis machinery or nitrogen fixation clusters, function

as a synchronized module. By providing a predictable genomic environment for large multigene payloads, GAENTRY transforms plant transformation from a game of chance into a disciplined engineering discipline, enabling the development of "smart" crops that can dynamically reallocate metabolic resources in response to environmental cues.

Conclusion

GAENTRY stands as a cornerstone technology for plant synthetic biology. By moving the assembly process into the biological host, it bypasses the physical limitations of in vitro DNA manipulation. Future iterations are expected to integrate CRISPR Cas9 modules within the stack, allowing for simultaneous gene addition and endogenous gene editing. As we move toward engineering climate smart crops, the ability to reliably stack a dozen or more genes will be the difference between incremental improvements and a second green revolution.

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USE OF GIS AND REMOTE SENSING IN MONITORING DEGRADED LANDSCAPES

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Abstract

Land degradation poses a significant threat to agricultural productivity, forest ecosystems, and ecological stability worldwide. Driven by processes such as soil erosion, deforestation, overgrazing, salinity, waterlogging, mining, and desertification, it demands continuous and accurate monitoring for effective sustainable management. Geographic Information Systems (GIS) and Remote Sensing (RS) have emerged as indispensable tools for this purpose. Remote sensing provides timely, large-scale data on vegetation health, soil conditions, and land-use changes through satellite imagery, while GIS enables integration, spatial analysis, and visualization of multi-layered datasets. Together, these technologies facilitate the identification of degraded areas, vulnerability mapping, and informed restoration planning, offering cost-effective and reliable solutions for environmental conservation.

Keywords : Land Degradation, Soil Erosion, Desertification, Deforestation, Overgrazing, Salinity, Waterlogging, Remote Sensing, Geographic Information System, NDVI, Satellite Imagery

Introduction

Land degradation represents one of the most pressing global environmental challenges, impacting soil fertility, biodiversity, and food security. It arises from both natural and anthropogenic factors, including soil erosion, deforestation, overgrazing, unsustainable agricultural practices, salinization, mining activities, and urban expansion. Without timely intervention, degraded landscapes contribute to reduced productivity, loss of ecosystem services, and heightened vulnerability to climate change.

Traditional ground-based monitoring methods are often time-consuming, costly, and limited in spatial coverage. In contrast, Remote Sensing (RS) and Geographic Information Systems (GIS) offer advanced, efficient alternatives. Remote sensing captures synoptic and multi-temporal data on Earth's surface characteristics, while GIS provides robust platforms for data integration and spatial modeling. These technologies have revolutionized land degradation assessment by enabling rapid detection and long-term trend analysis.

Role of Remote Sensing in Monitoring Degraded Landscapes

Remote sensing involves the acquisition of information about the Earth's surface without physical contact, primarily through satellite-based sensors that detect reflected or emitted electromagnetic radiation. Key platforms include Landsat (long-term archive), Sentinel-2 (high spatial resolution and frequent revisit), and MODIS (broad-scale monitoring).

Remote sensing is particularly effective for detecting:

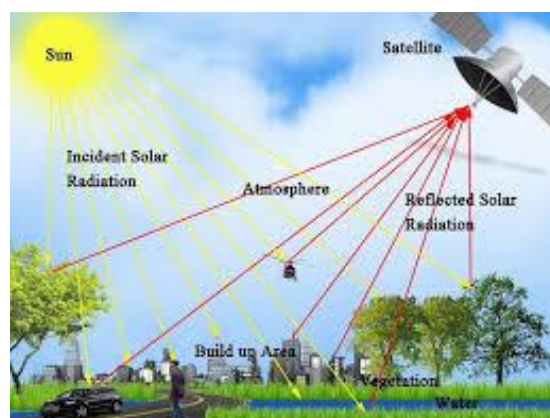
- Changes in vegetation cover and health
- Soil moisture variability and erosion patterns

- Land use/land cover (LULC) transitions
- Indicators of desertification and drought

Vegetation indices derived from multispectral data are central to degradation monitoring. The Normalized Difference Vegetation Index (NDVI), calculated as $(NIR - Red)/(NIR + Red)$, is widely used to assess vegetation density and vigor, with lower values indicating degradation. For areas with sparse vegetation or high soil background influence, the Soil-Adjusted Vegetation Index (SAVI) minimizes soil noise, while the Enhanced Vegetation Index (EVI) improves sensitivity in dense canopies by correcting for atmospheric and soil effects.

Basic Remote Sensing Process

1. Solar radiation interacts with the atmosphere and Earth's surface.
2. Surfaces reflect or emit energy differently (e.g., healthy vegetation strongly reflects near-infrared).
3. Sensors capture reflected radiation as digital data.
4. Data are processed and analyzed to generate indices and change maps.

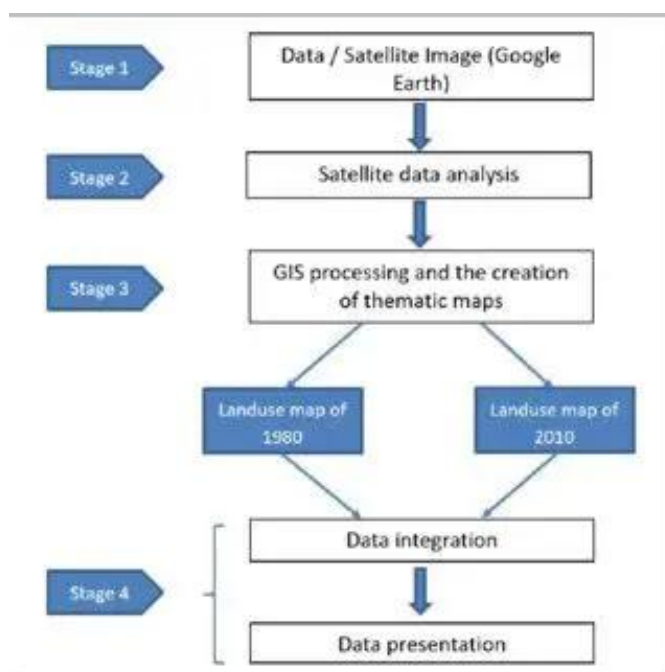


Types of Remote Sensing

- Optical (visible and infrared bands, e.g., Landsat, Sentinel-2)
- Microwave/Radar (all-weather capability, e.g., SAR for soil moisture)

Role of GIS in Monitoring Degraded Landscapes

GIS is a powerful computer-based framework for capturing, storing, analyzing, and visualizing spatial data. By integrating remote sensing outputs with ancillary layers (e.g., soil maps, topography, rainfall, and demographic data), GIS enables comprehensive degradation assessment.



Key applications include:

- Overlay analysis to map degraded zones
- Identification of high-risk areas through multi-criteria evaluation
- Modeling soil and water conservation measures
- Supporting decision-making for restoration and policy formulation

Types of GIS Data Models

- Raster: Grid-based, suitable for continuous phenomena (e.g., elevation, NDVI)
- Vector: Feature-based (points, lines, polygons), ideal for discrete boundaries (e.g., land parcels)

Integrated Applications and Case Studies

The synergy of GIS and remote sensing is most powerful when applied integrally. Multi-temporal satellite data analyzed in GIS environments allow trend detection, vulnerability mapping, and predictive modeling. Recent advancements incorporate machine learning for automated classification and higher accuracy.

In India, GIS and remote sensing have been successfully employed in several regions. For instance, a 2026 study in the Western Agroclimatic Zone of Tamil Nadu used multi-layered GIS analysis to assess land degradation vulnerability across diverse LULC types, integrating environmental indices as ecological indicators. Similar applications in Haryana (Ambala district) and central India have tracked forest loss and mining-induced degradation over decades, highlighting sharp declines in vegetative cover.

Globally, these tools support frameworks like the UN's Sustainable Development Goal 15.3 (Land Degradation Neutrality), providing scalable solutions for early warning and restoration planning.

Conclusion

GIS and Remote Sensing are transformative technologies for monitoring and managing degraded landscapes. By delivering timely, accurate, and spatially explicit information, they enable the detection of vegetation loss, soil erosion, desertification trends, and other degradation processes. Their integration supports evidence-based interventions, making them cost-effective and scientifically robust tools for achieving sustainable land management and environmental conservation in an era of increasing anthropogenic pressure.

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SUSTAINABLE AGRICULTURE AND STRATEGIC COST MANAGEMENT: A REVIEW

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Abstract

India's agriculture sector is demonstrated strong resilience, recording record foodgrain and horticultural output, rising exports, and sustained employment, yet it continues to face cost pressures, climate risks, and structural inefficiencies. In this context, sustainable agriculture has emerged as a strategic imperative, balancing economic viability, environmental protection, and social equity. This paper examines the need for Strategic Cost Management (SCM) in agriculture and highlights the transformative role of Cost and Management Accountants (CMAs) in improving resource efficiency, value chain performance, and sustainability outcomes. It argues that integrating CMAs into agricultural governance can significantly strengthen India's pathway toward sustainable and inclusive growth.

Keywords: Sustainable Agriculture, Strategic Cost Management (SCM), Cost and Management Accountants (CMAs), Agricultural Value Chain Efficiency, Climate-Resilient Farming.

Introduction

Agriculture remains a linchpin of India's economy, underpinning food security, rural livelihoods, and inclusive growth. In the financial year 2024–25, the agriculture and allied sectors contributed approximately 17.94% to the country's Gross Value Added (GVA), underlining its significant role in the economic structure even as services and industry sectors expand rapidly. However, the sector demonstrated robust production performance, with record foodgrain output of 357.73 million tonnes in 2024–25 signifying an 8% increase over the previous year and highlighting the success of improved farming practices, better irrigation, and targeted policy support. In the case of horticultural output has also soared, with garden produce expected to reach 362.08 million tonnes, reflecting diversification beyond staple grains. Agriculture's employment impact is profound: the sector supports nearly 46% of India's workforce, sustaining livelihood opportunities across millions of rural households. Despite its declining share in overall GDP a structural trend common in developing economies its value addition remains significant at over 16% of the national GDP. Further, exports from agriculture and allied sectors have shown encouraging trends, agrifood exports surged from around Rs. 2.49 lakh crore to Rs. 4.33 lakh crore representing a strong 7.8% CAGR, and emphasizing global demand for Indian agricultural products. At the state level, regions such as Maharashtra reported a 15% increase in agricultural and processed food exports in the fiscal year 2024–25, further validating export potential. Growth dynamics within the sector reflect resilience as well as evolving challenges. While the overall economy grew at about 6.5% during the year 2024–25, agriculture's growth often more volatile was buoyed by favourable monsoons, policy interventions such as Minimum Support Price (MSP) enhancements, and expanded credit flows for farmers. Nevertheless, some of the structural issues in the Indian agriculture like productivity gaps,

supply chain inefficiencies, and climatic vulnerabilities continue to constrain long-term stability and exports also face competitive and logistical barriers, with the trade surplus narrowing due to rising agri-imports. In this background, India's agriculture sector in 2024–25 has balanced record production, strong export growth, and continued employment support, while maintaining a substantial role in the economy. Its performance reflects both the vitality of farm outputs and the need for targeted reforms that strengthen value chains, foster innovation, and enhance market linkages ensuring sustained contribution to national goals of food security, rural prosperity, and economic resilience.

Sustainable Agriculture and its Relevance: A Conceptual Overview

Sustainable agriculture represents a transformative approach to food production that harmonizes economic viability, environmental stewardship, and social equity. In an era marked by climate change, resource depletion, biodiversity loss, and growing food demand, the conventional input-intensive farming model has become increasingly unsustainable. However, sustainable agriculture offers a future-ready alternative by ensuring that present agricultural needs are met without compromising the ability of future generations to meet theirs. Conceptually, sustainable agriculture is built on three interconnected pillars such as (i) Economic Sustainability, (ii) Environmental Sustainability, (iii) Social Sustainability.

Economic sustainability ensures that farming remains profitable and resilient to market and climate risks. Environmental sustainability focuses on conserving soil, water, air, and biodiversity through eco-friendly practices such as organic farming, integrated nutrient management, crop rotation, and water-efficient irrigation. Social sustainability promotes inclusive growth, fair incomes for farmers, food security, and improved rural livelihoods. Sustainable agriculture is particularly significant for countries like India, where agriculture supports nearly half of the population and plays a critical role in food security and rural development with shrinking landholdings, rising input costs, erratic monsoons, and soil degradation, the need for sustainable farming practices has become urgent. Sustainable agriculture enhances productivity while reducing dependence on chemical inputs, lowering production risks, and improving long-term farm incomes.

From a broader economic perspective, sustainable agriculture aligns with global development frameworks such as the United Nations Sustainable Development Goals (SDGs), especially those related to zero hunger, climate action, responsible production, and life on land. It also supports national priorities like climate resilience, carbon reduction, and sustainable rural growth. By integrating renewable energy, efficient water use, and low-emission farming techniques, sustainable agriculture contributes to both food security and environmental protection. Further, technological innovations such as precision farming, digital advisory services, climate-smart agriculture, and bio-inputs further strengthen the sustainability framework by enabling farmers to optimize resources, reduce waste, and increase efficiency. When combined with scientific planning and cost management, these innovations make sustainable agriculture both environmentally sound and financially attractive.

Sustainable agriculture is not merely an ecological concept but a comprehensive development strategy. It ensures stable farm incomes, conserves natural resources, enhances food security, and strengthens rural economies. As global food systems face increasing pressure, sustainable agriculture emerges as the cornerstone for building a resilient, inclusive, and future-ready agricultural sector.

Need for Strategic Cost Management in Agriculture

Agriculture today stands at a critical crossroads, facing rising input costs, climate uncertainty, market volatility, and increasing pressure to remain both profitable and sustainable. While farmers are encouraged to adopt modern, eco-friendly, and technology-driven practices, the financial viability of such initiatives often remains uncertain. In this context, Strategic Cost Management (SCM) emerges as a vital tool for transforming agriculture into a resilient, competitive, and sustainable sector.

Unlike traditional cost control, which focuses only on cutting expenses, strategic cost management adopts a long-term, value-oriented approach. It integrates cost planning, performance analysis, and resource optimization with the overall goals of productivity, sustainability, and profitability. In agriculture, where margins are thin and risks are high, SCM enables farmers and agri-enterprises to make informed decisions regarding crop selection, input use, technology adoption, and market participation.

Further, strategic cost management arises primarily from the complex cost structure of modern agriculture. Farmers incur substantial expenditure on seeds, fertilizers, pesticides, irrigation, labor, machinery, energy, transportation, and storage. Additionally, hidden costs such as soil degradation, water depletion, post-harvest losses, and price fluctuations significantly affect farm profitability. Without systematic cost tracking and analysis, these inefficiencies remain invisible, leading to low incomes and financial distress.

Strategic cost management helps identify cost drivers across the agricultural value chain from land preparation and cultivation to harvesting, processing, and marketing. Tools such as activity-based costing, life-cycle costing, and value chain analysis enable farmers and agri-businesses to pinpoint wasteful practices, reduce non-value-adding activities, and allocate resources more efficiently. This ensures that every rupee invested in farming generates maximum output and long-term returns.

Moreover, sustainable agriculture requires investments in technologies such as drip irrigation, renewable energy, organic inputs, and precision farming. While these may involve higher initial costs, strategic cost management evaluates their long-term economic and environmental benefits, helping farmers adopt sustainable solutions without jeopardizing financial stability. In a market-driven and globally competitive environment, SCM also supports better pricing, risk management, and income stability. By improving cost transparency and financial planning, it enhances farmers' bargaining power, access to credit, and ability to integrate with modern agri-value chains.

Role of CMAs in Promoting Sustainable Agriculture

Cost and Management Accountants (CMAs) act as the **financial architects of sustainability** in agriculture by integrating cost efficiency, environmental responsibility, and long-term profitability into farm and agri-business decision-making. Their expertise enables the transformation of traditional farming into a **data-driven, resource-efficient, and financially resilient system**. However, some of the important strategic roles are presented (Figure -1) and a brief discussion of the same.

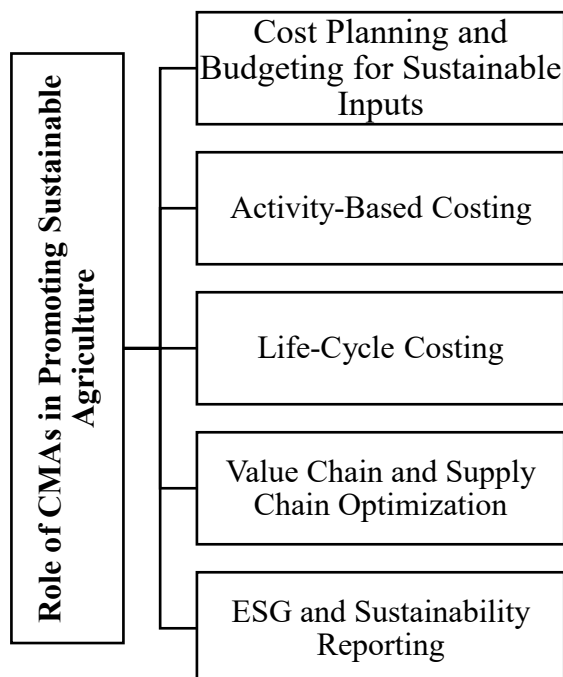


Figure -1: Role of CMAs in Promoting Sustainable Agriculture

- 1) **Cost Planning and Budgeting for Sustainable Inputs:** CMAs design **scientific farm budgets** that compare the cost and returns of conventional inputs (chemical fertilizers, pesticides, diesel pumps) with sustainable alternatives (bio-fertilizers, drip irrigation, solar pumps). By evaluating both short-term expenses and long-term savings, CMAs help farmers adopt eco-friendly practices without compromising profitability, thereby reducing financial risk in sustainable farming.
- 2) **Activity-Based Costing (ABC):** Through **Activity-Based Costing**, CMAs identify the actual cost of specific farming activities such as land preparation, irrigation, harvesting, storage, and transportation. This allows them to pinpoint **high-cost and low-value operations**, enabling farmers to eliminate waste, improve operational efficiency, and optimize resource use critical for sustainable agriculture.
- 3) **Life-Cycle Costing (LCC):** CMAs apply **Life-Cycle Costing** to estimate the total cost of crop production from sowing to marketing, including environmental costs such as water use, soil depletion, and energy consumption. This helps farmers and agri-enterprises select **sustainable crops, technologies, and farming methods** that deliver better long-term returns and lower ecological impact.
- 4) **Value Chain and Supply Chain Optimization:** CMAs analyze the **entire agricultural value chain**, from input suppliers to end consumers, to identify inefficiencies, excessive intermediation, and post-harvest losses. By improving logistics, pricing, storage, and market linkages, CMAs enhance farmers' **share in consumer prices** while reducing waste and carbon footprint.
- 5) **ESG and Sustainability Reporting:** CMAs develop **ESG metrics, carbon accounting, water footprinting, and sustainability reports** for agri-enterprises, FPOs, and cooperatives. These reports enable access to **green finance, climate funds, and impact investments**, making sustainable agriculture financially attractive and globally compliant.

Policy Implications and a Future Ahead

Integrating Cost and Management Accountants (CMAs) into agricultural governance has far-reaching policy implications for strengthening India's farm economy, improving fiscal efficiency, and advancing national development goals. As agriculture increasingly moves towards sustainability, digitalization, and market orientation, professional cost and performance management becomes indispensable for evidence-based policymaking. In the light of the above, the following policy implications are offered: (i) By applying scientific cost analysis, crop-wise budgeting, and activity-based costing, CMAs can help governments identify the **actual cost of cultivation across regions, crops, and farm sizes**. This enables subsidies, minimum support prices, and input support schemes to be designed on realistic cost data rather than broad estimates, ensuring that benefits reach the genuinely deserving farmers while avoiding over or under-compensation; (ii) CMAs play a critical role in **reducing fiscal leakage and inefficiencies** in agricultural spending. With their expertise in audit, cost control, and financial monitoring, CMAs can track the flow of subsidies, grants, and scheme funds across FPOs, cooperatives, and agri-projects. This enhances transparency, minimizes misuse or diversion of funds, and ensures that public money is converted into measurable outcomes such as higher productivity, lower waste, and improved farm incomes; (iii) By developing reliable cost statements, profitability projections, and risk-adjusted financial models for farms and agri-enterprises, CMAs enable banks and financial institutions to assess creditworthiness more accurately. This reduces non-performing assets in the agricultural sector, lowers borrowing costs for farmers, and facilitates the flow of institutional credit to sustainable and viable farm activities; and (iv) CMAs contribute to SDGs such as zero hunger, responsible consumption, climate action, and decent work by embedding sustainability metrics, ESG reporting, and resource efficiency into agricultural planning. Their role ensures that growth in agriculture is not only higher but also greener, more inclusive, and financially sustainable.

Conclusion

India's agriculture sector has demonstrated remarkable resilience through record production, expanding exports, and sustained employment, even amid climate risks and structural challenges. However, long-term sustainability cannot be secured by output growth alone. This study establishes that **sustainable agriculture**, grounded in economic, environmental, and social balance, is the only viable pathway for India's farm sector. In this context, **Strategic Cost Management** and the professional expertise of **Cost and Management Accountants (CMAs)** emerge as powerful enablers of change. By integrating cost efficiency, life-cycle analysis, value chain optimization, and ESG reporting, CMAs make sustainability financially viable and institutionally credible. Their inclusion in agricultural governance can enhance subsidy targeting, credit efficiency, and fiscal transparency while supporting India's SDGs and the **Viksit Bharat** vision. Eventually, CMAs provide the financial intelligence required to transform Indian agriculture into a resilient, inclusive, and future-ready growth engine.

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FARM-TO-FORK VEGETABLE SUPPLY CHAIN: SCOPE, BUSINESS POTENTIAL, AND EMERGING TRENDS IN INDIA AND GLOBALLY

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Introduction

The Farm-to-Fork supply chain in vegetables is emerging as a highly significant and rapidly expanding segment in the global as well as Indian agri-food system. Globally, the fresh vegetable market is estimated at \$700–900 billion and is growing at a 6–8% CAGR, driven by increasing consumer demand for fresh, safe, and traceable food products, along with the expansion of short supply chains and digital agri-logistics systems (FAO, 2023; OECD, 2022). Developed regions such as the USA and Europe are witnessing strong growth in direct farmer-to-consumer and retailer-linked models, supported by cold chain infrastructure, blockchain-based traceability, and sustainability-focused food systems (European Commission Farm to Fork Strategy, 2020).

In the Indian context, the total agri-produce market is estimated at around ₹20–25 lakh crore, with vegetables contributing approximately ₹6–8 lakh crore, indicating a vast domestic demand base (Ministry of Agriculture & Farmers Welfare, 2023). However, organized retail accounts for less than 15% of the market, highlighting immense scope for expansion of corporate-led farm-to-fork models. The online grocery segment is projected to reach ₹2–3 lakh crore by 2030, driven by companies such as Reliance Retail, BigBasket, and Ninjacart (IBEF, 2024). A major challenge in India is the high post-harvest losses in vegetables (20–30%), primarily due to inefficient supply chains, which farm-to-fork models aim to reduce through direct procurement, cold storage, and efficient logistics (NITI Aayog, 2021).

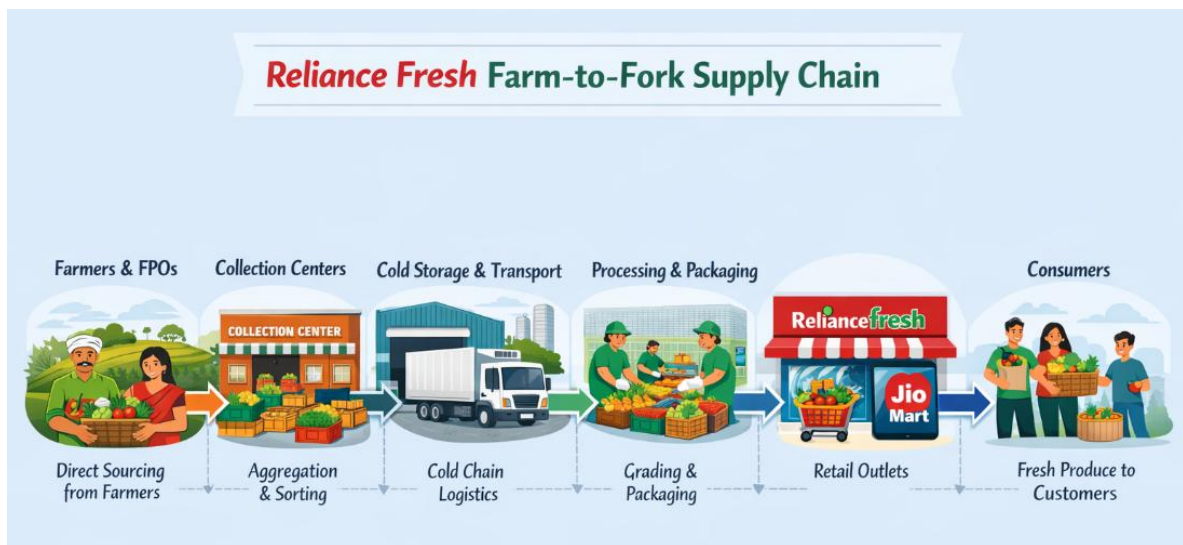
From a business perspective, the farm-to-fork model offers significant opportunities across the value chain. Farmers benefit through 10–30% higher price realization, while companies operate on a high-volume, low-margin model, generating turnovers ranging from ₹5,000 crore to over ₹2 lakh crore, driven by scale, logistics efficiency, and private branding. There is substantial scope for entrepreneurship in aggregation centers, cold chain infrastructure, grading and packaging units, and last-mile delivery systems. The future outlook indicates a gradual transition from traditional mandi-based systems to direct farm procurement models, supported by government initiatives promoting FPOs, agri-logistics, and digital agriculture. Additionally, the integration of AI, IoT, and blockchain technologies, along with the rise of hyperlocal delivery systems, is expected to further strengthen the farm-to-fork ecosystem in the coming years (World Bank, 2022).

The farm-to-fork approach in India is a transformative model connecting farmers directly to consumers, aiming to slash 30–40% post-harvest losses. By integrating production, processing, and logistics, this approach improves traceability, ensures freshness, and boosts farmer income by

cutting out middlemen. Key components include technology-enabled supply chains, cold storage infrastructure, and Farmer Producer Organizations (FPOs) (www.cropin.com/24/3/2026).

What Does Farm-to-Fork Mean?

Simply put, farm-to-fork is about creating a direct, efficient, and transparent journey of food from the farmer's field to the consumer's plate. It reduces unnecessary middlemen, shortens supply chains, and ensures fresher produce reaches consumers while farmers earn better value for their hard work. (www.kirtanepandit.com/24/3/2026).



Why Farm-to-Fork Matters for India

- **Reducing High Post-Harvest Losses:** Due to inadequate cold chain infrastructure, India loses perishables worth ₹92,651 crore annually. (www.global-agriculture.com/24/3/2026)
- **Improving Farmer Income:** The traditional supply chain has too many intermediaries, which lowers the farmer's share of the final consumer price.
- **Ensuring Food Safety and Quality:** Modern consumers demand transparency. Traceability allows for monitoring pesticides and quality from farm to retail.
- **Addressing Supply Chain Inefficiencies:** Fragmentation (small/marginal farmers) and poor infrastructure lead to inefficiencies

The farm-to-fork approach directly addresses these issues by using technology, data, and innovation to streamline the entire agri value chain.

Core Components of the Farm-to-Fork Model:

- **Production & Input Supply:** Focus on technology-driven, sustainable farming, incorporating quality seeds, fertilizers, and precision agriculture.
- **Harvesting and Post-Harvest Handling:** Proper collection, grading, and sorting of crops, often managed by FPOs or agri-startups, to maintain quality.
- **Processing & Value Addition:** Transforming raw materials into finished products (e.g., packaging, grading) to increase market value and extend shelf life.
- **Storage & Transportation:** Investment in cold storage, refrigerated transport, and warehousing to reduce spoilage of perishable goods.
- **Marketing & Distribution:** Digital channels and organized retail directly sourcing from farmers, reducing logistics costs and bypassing traditional, inefficient supply chains.

The top farm-to-fork players in India, including Reliance Retail, BigBasket, and More Retail, are transforming agriculture through integrated supply chains, directly sourcing from farmers to retail, and leveraging quick commerce. These companies focus on enhancing freshness and reducing waste.

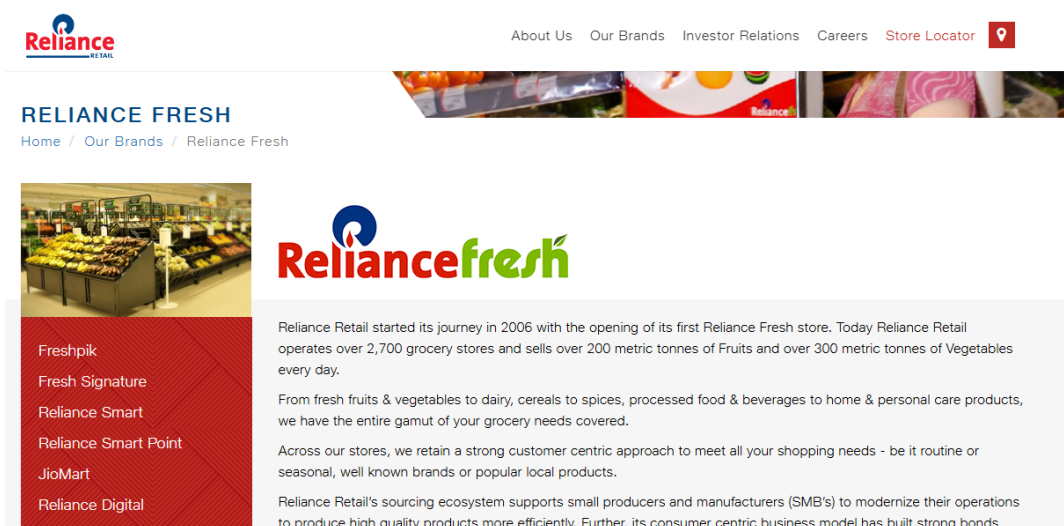
Top 10 Farm-to-Fork Players in India (NITI Ayog, 2023)

1. Reliance Fresh / JioMart (Reliance Retail):

- **Year of Establishment:** 2006
- **Parent Company:** Reliance Industries Limited
- **Retail Formats:** Reliance Fresh, Reliance Smart, JioMart (online platform)
- **Number of Stores:** 18,000+ stores across India
- **Turnover:** ₹2,60,000+ crore (approx., recent financials)
- **Farm Linkage Model:** Direct procurement from farmers & Farmer Producer Organizations (FPOs)
- **Collection Centres:** 1,500+ farm collection centers across sourcing regions
- **Supply Chain Strength:** Integrated cold chain, warehousing, and logistics network
- **Key Focus Products:** Fruits, vegetables, staples, dairy, and FMCG

Farm-to-Fork Strategy:

- Eliminates intermediaries
- Ensures better price to farmers
- Delivers fresh produce to consumers via stores & JioMart



2. BigBasket (Tata Enterprise): A pioneer in online grocery with a robust farm-to-fork model. It serves 40+ cities, handling huge volumes of fresh produce, and operates BB Now for rapid delivery.

- **Year of Establishment:** 2011
- **Parent Company:** Tata Digital (Tata Group)
- **Business Model:** Online grocery platform with farm-to-fork integration
- **Cities Covered:** 40+ cities across India
- **Turnover:** ₹10,000+ crore (approx.)
- **Farmer Linkage:** Direct sourcing through “Farmer Connect” program
- **Collection Centres:** 100+ aggregation & collection hubs

Supply Chain Strength:

- Modern warehouses & cold storage
- Strong last-mile delivery network
- AI-driven demand forecasting

Key Services:

- BigBasket (scheduled delivery)
- BB Now (quick/rapid delivery model)

Key Products: Fruits, vegetables, staples, dairy, organic products

Farm-to-Fork Strategy:

- Direct procurement from farmers/FPOs
- Quality grading, sorting, and packaging
- Efficient delivery to urban consumers



3. More Retail (Aditya Birla Group): A prominent supermarket and hypermarket chain, offering a wide range of fresh produce sourced directly from farmers.

- **Year of Establishment:** 2007
- **Current Ownership:** Samara Capital & Amazon
- **Business Formats:** Supermarkets (More), Hypermarkets (More Mega Store)
- **Number of Stores:** 700+ stores across India
- **Turnover:** ₹4,500+ crore (approx.)
- **Cities Covered:** 150+ cities
- **Farmer Linkage Model:**
 - Direct procurement from farmers & Farmer Producer Organizations (FPOs)
 - Contract farming and aggregation models
- **Collection Centres:** 200+ sourcing & aggregation centres
- **Supply Chain Strength:**
 - Centralized distribution centers
 - Cold chain logistics for perishables
 - Efficient inventory and retail management
- **Key Products:** Fresh fruits & vegetables, staples, dairy, FMCG
- **Farm-to-Fork Strategy:**

- Reduces intermediaries
- Ensures fresh produce at competitive prices
- Strengthens farmer-market linkage



4. **Blinkit (Zomato):** A leading quick-commerce platform delivering groceries in 10-20 minutes, with a strong focus on fresh produce and daily essentials.
5. **Swiggy Instamart (Swiggy):** Rapidly growing quick-commerce player with a strong focus on farm-fresh fruits, vegetables, and dairy products.
6. **Zepto (KiranKart):** A prominent quick-commerce player in India known for its 10-minute delivery model, expanding its direct-from-farm fresh produce.
7. **DMart (Avenue Supermarts):** A leading value-focused supermarket chain, known for efficient supply chains that bring high-volume staples and produce to consumers.
8. **Star Bazaar (Tata Trent):** A major hypermarket/supermarket chain with a strong emphasis on fresh produce, bakery, and dairy items.
9. **Spencer's Retail (RP-Sanjiv Goenka Group):** A major retail chain with over 150 stores, specializing in a wide assortment of fresh produce and gourmet products.
10. **Amazon Fresh (Amazon India):** E-commerce giant offering a large-scale online grocery and fresh produce service across major cities.

How the farm-to-fork model helps the farming community

1. Increased Farmer Income and Better Margins

- **Reduced Middlemen:** Traditional supply chains often involve multiple intermediaries, reducing the share of the final price received by farmers. F2F models (such as direct-to-consumer apps, community-supported agriculture (CSAs), and farmers' markets) allow farmers to capture a higher percentage of the final selling price.
- **Profit Surge:** Businesses adopting the farm-to-fork approach enable primary producers to earn higher profit margins, often ranging from 30% to 45%, compared to traditional models.
- **Direct Value Addition:** By processing, packaging, or branding directly on the farm, farmers can add value to their produce and gain 10-20% more value than selling raw commodities.

2. Reduced Post-Harvest Losses and Waste Management

- **Lower Wastage:** In developing nations, post-harvest losses can be high. F2F initiatives, including cold storage and fast transport, reduce these losses, which are estimated to be 13.3% globally at the post-harvest stage.

- **Improved Infrastructure:** Investments in cold chain logistics—often a part of comprehensive farm-to-fork programs—help reduce the spoilage of perishable goods like fruits, vegetables, and dairy.

3. Improved Access to Technology and Finance

- **Digital Transformation:** The model utilizes digital marketplaces and agtech to connect farmers with retailers and consumers, ensuring wider market access.
- **Reduced Risk:** F2F platforms help farmers monitor crops, optimize irrigation, and reduce input costs, sometimes resulting in 40% lower crop losses due to pest detection systems.
- **Digital Payments:** The integration of Agri-Fintech provides farmers with easier access to credit, crop insurance, and immediate digital payments, strengthening their financial stability.

4. Promotion of Sustainable Practices and Better Prices

- **Higher Demand for Organic:** As consumers seek healthier food, the demand for organic produce has increased. India's organic crop production reached 3.2 million metric tons in 2020-2021, an increase of 36% from the previous year, which allows farmers to command premium prices.
- **Eco-friendly Incentives:** F2F models often pay farmers more for adopting sustainable practices (e.g., lower pesticide use), which reduces input costs and improves long-term soil health.

5. Enhanced Traceability and Market Credibility

- **Consumer Trust:** Blockchain and QR code-based tracking allow consumers to see where their food comes from, enabling farmers to command premium prices for traceable produce.
- **Brand Building:** Farmers can build direct relationships with consumers and restaurants, allowing them to market their produce based on quality rather than just competitive prices.

Key Challenges from a Farming Perspective:

- **Infrastructure Deficits:** Lack of cold chain, storage facilities, and efficient transportation results in high post-harvest losses and reduced product quality, particularly for fruits and vegetables.
- **Small Land Holdings & Fragmentation:** High fragmentation of farmland inhibits economies of scale, making it difficult for farmers to meet bulk order requirements.
- **High Traceability and Certification Costs:** Implementing farm-to-fork traceability (e.g., blockchain) is complex, expensive, and requires skills often lacking, creating a high barrier for smallholders.
- **Stringent Quality and Safety Standards:** Compliance with global food safety standards and certification (e.g., GAP) is difficult, limiting access to high-value markets.
- **High Intermediary Influence:** Numerous middlemen often lead to unfair pricing, reducing the profit share of the primary producer.
- **Adoption of Sustainability Standards:** Shifting to sustainable practices (organic fertilizers, reducing chemicals) requires high upfront investment and can lead to yield losses during the transition.
- **Market Volatility & Climate Risks:** Extreme weather events and price fluctuations disrupt supply, reducing income security for farmers.

- **Limited Access to Information/Technology:** Lack of technical knowledge and modern agricultural infrastructure prevents farmers from optimizing production or improving efficiency

Key challenges from an industry perspective

1. Infrastructure and Logistics Deficits

- **Cold Chain Inefficiency:** A severe lack of adequate cold storage and refrigerated transport leads to high post-harvest losses, with roughly 15–20% of fresh produce wasted.
- **Logistics Bottlenecks:** Inadequate transportation networks, poor road conditions, and inefficient handling facilities increase transit times and costs, which are particularly critical for fast-moving consumer goods (FMCG).
- **High Operational Costs:** Energy costs for cold storage in developing regions can be significantly higher than in the West, limiting the scalability of necessary infrastructure.

2. Technological and Data Challenges

- **Slow Adoption of Digital Tools:** The industry faces a high initial investment cost for advanced technologies like IoT, blockchain, and AI, which are crucial for real-time tracking.
- **Lack of Traceability:** The absence of end-to-end traceability systems hinders the ability to quickly identify sources of contamination, increasing the risk during food recalls.
- **Data Silos:** A lack of standardized data sharing protocols among stakeholders prevents effective demand forecasting and planning, resulting in oversupply or shortages.

3. Supply Chain Fragmentation and Structure

- **Smallholder Domination:** In many regions, fragmented, small-scale farming makes aggregation difficult, leading to inconsistent quality and higher logistics costs.
- **Excessive Intermediaries:** An unorganized network of middlemen increases transaction costs and reduces farmers' profit margins, limiting their ability to invest in better practices.

4. Regulatory, Food Safety, and Compliance

- **Quality Standard Mismatch:** Inability to meet strict international food safety and quality standards (e.g., GAP, GMP, HACCP) hampers export potential and local brand trust.
- **Complex Regulatory Environment:** The need to comply with changing environmental, social, and governance (ESG) standards, such as carbon footprint reduction, adds administrative pressure on producers.
- **Food Fraud and Security:** The rise in complex, globalized supply chains provides opportunities for food adulteration, requiring intense monitoring.

5. Sustainability and External Shocks

- **Climate Change and Disruptions:** Extreme weather events (floods, droughts) directly disrupt production and logistics, causing extreme price volatility.
- **Decarbonization Pressure:** The industry faces pressure to shorten supply chains to reduce carbon footprints, forcing a rethink of centralized, long-distance distribution models.
- **Rising Input Costs:** High prices for fertilizers, energy, and labor are compressing margins for both farmers and downstream operators.

Strategies for Farmers

- **Adoption of Sustainable Practices:** Implementing regenerative agriculture, organic farming, reduced pesticide use, and precision irrigation to lower carbon footprints and satisfy consumer demand for sustainable products.

- **Technology Integration:** Leveraging AI and, remote sensing, and in-soil sensors for precision farming to optimize input usage, enhance productivity, and improve soil health.
- **Direct Marketing Channels:** Using digital platforms for direct-to-consumer sales, increasing profit margins and strengthening relationships with buyers.
- **Crop Diversification:** Using crop rotation and choosing stress-tolerant seed varieties to enhance resilience against climate change and reduce reliance on chemical inputs.

Strategies for Industry (Processors/Retailers)

- **Enhanced Traceability and Transparency:** Implementing blockchain technologies to track food from origin to consumption, reducing risks of fraud, and improving food safety management.
- **Cold Chain Development:** Investing in robust refrigerated transport and storage to reduce post-harvest losses, particularly for perishables.
- **Collaborative Supply Chain Management:** Building strategic partnerships with farmers to ensure a sustainable, traceable, and efficient flow of produce, managing the supply chain to minimize time-to-market.
- **Sustainable Packaging and Processing:** Adopting eco-friendly packaging and processing technologies to align with circular economy goals.

Conclusion

The farm-to-fork supply chain in vegetables represents a transformative shift in both global and Indian agri-food systems, bridging the gap between farmers and consumers through efficiency, transparency, and technology. With a rapidly expanding market size, increasing demand for fresh and traceable food, and the growing role of organized retail players such as Reliance Retail, BigBasket, and Ninjacart, the model offers immense scope for economic growth and supply chain modernization. In India, where post-harvest losses and fragmented supply chains remain major challenges, the farm-to-fork approach provides a viable solution by integrating farmers into structured markets, enhancing price realization, and reducing wastage through cold chain and digital logistics.

Despite challenges such as infrastructure gaps, small landholdings, and technological barriers, the sector holds strong potential for entrepreneurship, employment generation, and sustainable agriculture. The integration of advanced technologies like AI, IoT, and blockchain, along with supportive government initiatives and the rise of agri-tech startups, is expected to further strengthen this ecosystem. Ultimately, the farm-to-fork model is not only a business opportunity but also a pathway toward improving farmer livelihoods, ensuring food security, and building a resilient, efficient, and sustainable agricultural economy for the future.

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INTRODUCTION OF MUSTARD APHID *Lipaphis erysimi* (KALTENBACH): A SUMMARY

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Introduction

One of the most dangerous and devastating pests in the world is the mustard aphid, also called the turnip aphid (*Lipaphis erysimi*). Perennial yearly threats to crops such as mustard (*Brassica* spp.) and rapeseed. *L. erysimi* (Kalt.) is found all over the world (Martin 1983; Pradhan and Moorthy, 1995) and is recognized as a major cruciferous pest (Atwal *et al.*, 1976). It is a minor pest of the bean, beet, spinach, pea, celery, onion, stock, cucumber, and potato (Scmutterer, 1978). When fully grown, this species, which has a short body and is yellowish and green or greenish in color, measures 2-2.5 mm in length. Adults might have two pairs of hyaline wings (Alate) or no wings (Apterae).

The fifth segment of the abdomen has two cornflakes. Adults with wings typically have a blackish head and black body patterns. They occupy nearly the entire plant with a high population and are primarily seen on the host plants' developing points, such as the tips, blossoms, and immature pods (Nelson and Rosenheim, 2006). With the aid of stylets, piercing sucking mouthparts that resemble needles, and a phloem sieve element, they draw sap from the host plant, causing infected plants to eventually become stunted and deformed.

Plant wilting, yellowing, and stunting are among their main infection symptoms (Khan *et al.*, 2015). The preventable yield losses everywhere because to 20–50% aphid infection, with the possibility of reaching 78% (Prasad and Phadke, 1983). Because of its rapid proliferation, adaptable reproductive mechanism, and significant agricultural output losses, it has been regarded as the primary pest status in the brassica family. A review's goal is to provide a broad understanding of biology, climate, host plant range, extent of yield losses and damage, and management.

Recognition

Adult apterae of *Lipaphis erysimi* are small to medium-sized aphids that typically have an olive, It has a thin white wax bloom and a grey or yellowish-green hue. The wax covering on them could be thicker in humid conditions. Two rows of black bands run along the apterae's thorax and abdomen, joining to form a single band near the abdomen's tip. The mature The body length of *Lipaphis erysimi* apterae ranges from 1.4 to 2.4 mm, and they have whitish siphunculi with black ends.

Damage Symptoms

Symptoms of severe infestations include leaf drying, curling, and yellowing, which results in to the development of tiny seeds and feeble pods. Additionally, the aphids release honeydew, which promotes the development of sooty mold and lessens the rate of photosynthetic energy. As a result,

it is Mustard crops must be routinely observed. during the season when aphids breed. In situations where extreme infestation, chemical management turns into the only practical way to control mustard aphids outbreak. Thus, the purpose of this investigation was to evaluate the bioefficacy of each pesticide against This is the mustard aphid, *Lipaphis erysimi*.

Taxonomic Position of Mustard Aphid

Kingdom	: Animalia
Class	: Insecta
Sub-Class	: Pterygota
Division	: Exopterygota
Order	: Homoptera
Family	: Aphididae
Subfamily	: Aphinidae
Genus	: Lipaphis
Species	: Lipaphis erysimi Kalt.

Biology and Life Cycle

This aphid has two methods of reproduction: sexual reproduction, in which males fertilize females to create eggs, and Parthenogenesis is the process by which mature females produce living female nymphs without the need for male fertilization. Due to the rarity of males, parthenogenesis is the major way of reproduction. Males are only seen in the cooler months, while females are nearly always viviparous (give birth to live young).

Eggs

Typically, this aphid lays its eggs along the leaf veins. However, there is no proof of Eggs of this species of aphid have been discovered in Hawaii.

Nymphs

This aphid species has four nymphal stages, or instars. Every stage seems comparable in overall appearance, growing larger in later instars. The first, second, third, and fourth nymphal stages last 1-2 days each, for a total of roughly 8-9 days during the nymphal stage, according to Sachan and Bansal. There are minor variations in these durations between winged and wingless forms when reared on cabbage, cauliflower, mustard, and radish for a detailed explanation of the first and fourth instars.

Adults

Apterae are wingless female aphids that range in color from yellowish-green to their bodies are gray-green or olive-green, with a white waxy bloom covering them. In humid environments, this waxy coating gets denser. Aphids with wings, known as alates, have dark lateral stripes that divide body segments, a darkish green abdomen, and dusky wing veins. The antennae are all black, except for the base Alate forms are roughly 1.4-2.2 mm (3/50-1/12 inch) long, whereas female apterae are roughly 1.2-2.4 mm (3/50-1/10 inch) long.

The Host Crop

In India, brassicas, which are primarily grown during the rabi season, are members of the Cruciferae family. Season for their use as medicinal, oilseed, and condiment crops. As supplies of vegetables, oilseeds, fodder, green manure, sauces, and feed, they have a special agricultural value. Brassica seed oil is used in the food, lubricant, and polymer industries; the cake is utilized in agriculture as organic manure and animal feed. The high oil content of mustard-rape seed seeds, which ranges

from 32% to 42% and is mostly used for gastronomic reasons, makes them particularly valuable. Furthermore, stem plants and mustard's lush leaves are abundant sources of oil.

Damage

Aphids consume their host plants' sap. As colonies expand, they can cause the plants to become distorted, resulting in yellowing, shriveling, and curling leaves. In example, the turnip aphid frequently gathers in large quantities on the undersides of the outer leaves or in the flowers (inflorescences). In severe cases, there may be a significant infestation on both sides of the leaves. High cabbage populations can reduce yield and change leaf size. The mustard plants' flowers above the leaves are preferred by these aphids. Wasps, ants, bees, and other insects consume honeydew, a sweet, liquid secretion secreted by aphids and other soft-bodied insects including mealybugs, scales, and leafhoppers.

Honeydew encourages the establishment of sooty mold, a black sooty fungus that gives cabbage plants a dirty look and reduces their market worth. Additionally, aphids spread a variety of plant diseases, frequently doing more harm through disease transfer than through direct eating. For example, about ten non-persistent plant viruses, including those that cause turnip, radish, and cauliflower mosaic diseases as well as cabbage black ring spot, are spread by the turnip aphid. During non-persistent transmission, the virus grows inside the plant, and aphids facilitate the infection and spread of the virus.

Conclusion

A significant barrier to the production of mustard and other brassica crops, particularly during the rabi season, is the mustard aphid (*Lipaphis erysimi*). Because parthenogenesis allows for rapid multiplication, populations can grow rapidly, resulting in large infestations in a short period of time. The aphid damages the plant, causing yellowing, curling, stunting, and poor seed development, by sucking sap from sensitive plant parts like shoots, flowers, and developing pods. Yield losses might be significant in extreme situations.

In addition to causing damage through direct feeding, the insect releases honeydew, which promotes the growth of sooty mold, inhibiting photosynthesis and lowering produce's market value. Additionally, it serves as a vector for a number of plant viruses, which increases crop losses. Its broad host range and ability to adapt to many environmental conditions make management difficult.

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BEYOND THE DOLLAR: CAN THE INDIAN RUPEE BECOME A GLOBAL CURRENCY?

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Introduction: A Whisper in a World That Shouts in Dollars

Imagine you run a business in Mumbai that exports beautiful textiles to a buyer in Paris. You agree on a price, produce the goods, and send them off. But when the payment arrives, it's not in Rupees. It's in US Dollars. Before you can use that money to pay your weavers in India, you have to convert it. If the Dollar weakened against the Rupee while your goods were in transit, you could actually lose money on the deal, even though you sold your products. This is the daily reality for countless businesses in a world where the US Dollar is the undisputed king of international trade. For decades, the "big four" currencies—the US dollar, the Euro, the Japanese yen, and the British pound sterling—have dominated global finance. But the ground is shifting. The 2008 global financial crisis exposed the risks of relying so heavily on one currency. More recently, geopolitical tensions and sanctions have made countries like China, Russia, and now India, question the existing monetary order. They are asking a bold question: why should one nation's currency dictate the terms of trade for the entire world? This brings us to India and its ambitious quest: the internationalization of the Indian Rupee (INR). It's a concept that sounds like it belongs in an economics textbook, but its implications touch everything from the price of petrol at your local pump to India's power on the world stage. As of March 2026, this journey has entered a new phase—one marked by quiet but steady progress, persistent challenges, and a strategic vision that looks decades ahead.

What Does It Mean to "Internationalize" a Currency?

In simple terms, internationalizing the Rupee means making it usable and acceptable outside India's borders, just like the Dollar. It's about increasing the number of cross-border transactions—trade, loans, investments—that are settled in Rupees instead of a foreign currency.

Think of it in three steps:

1. **Trade Settlement:** An Indian company buys oil from the UAE and pays in Rupees. The UAE company accepts it.
2. **Investment:** That UAE company, now sitting on a pile of Rupees, decides to invest them in Indian stocks or government bonds, rather than converting them back to Dollars.
3. **Reserve Currency:** The central bank of the UAE decides to hold a portion of its national reserves in Rupees, trusting its stability and value for the long term.

Currently, the Rupee is a lightweight in this arena. While India accounts for nearly 2% of global goods trade, the Rupee's share in global foreign exchange market turnover hovers around just 1.6–2%. The US dollar, by contrast, is involved in nearly 88% of all forex trades according to the Bank for International Settlements' latest 2025 Triennial Survey, which recorded global daily forex turnover at a staggering \$9.6 trillion. The journey from 1.6% to even 5% is a monumental task—one that the Reserve Bank of India (RBI) acknowledges will take generations, not years.

Why Does India Want This? The Significance of a Global Rupee

You might wonder, why bother? Why not just stick with the comfortable, if imperfect, system of using Dollars? The reasons are compelling and strategic.

1. Reducing Dependency on the Dollar (The "Russia" Effect): This remains the biggest driver. The sanctions imposed on Russia in 2022, which cut off its banks from the SWIFT payment system, served as a stark warning. If a nation can be financially "switched off" by the West, every other country takes note. For India, which imports a massive amount of oil, paying in Rupees insulates it from such geopolitical shocks. It's a form of economic insurance. This was the trigger for the RBI to aggressively push for a Rupee trade settlement mechanism, and the momentum has only grown through 2026.

2. Eliminating Currency Risk for Indian Businesses: This brings us back to our textile exporter. If that Parisian buyer could pay in Rupees, the Indian business would have zero currency risk. They would know exactly how much money they are getting. This predictability lowers the cost of doing business, makes exports more competitive, and shields companies from the wild swings of the forex market.

3. Enhancing India's Bargaining Power: A currency that is widely accepted is a symbol of economic strength. If countries hold Rupees, they have a stake in India's economic well-being. It gives India greater "soft power" and a stronger voice in international financial institutions like the International Monetary Fund (IMF).

4. Reducing the Need for Forex Reserves: India's central bank spends billions of dollars buying and selling foreign currency to keep the Rupee stable. It needs a huge war chest of foreign exchange reserves (mostly Dollars) to do this. If a significant chunk of India's trade was in Rupees, the demand for Dollars would fall, and the RBI wouldn't need to maintain such a massive safety net.

How Much Progress Have We Really Made? The Latest Numbers

The RBI's February 2026 Bulletin offers the clearest picture yet of where things stand. For the period of April to December 2025 (the first three quarters of financial year 2025–26), the data shows modest but genuine progress:

- **Exports invoiced in rupees:** 6.08% of all goods and software exports
- **Imports invoiced in rupees:** 4.82% of all imports
- **Exports actually settled in rupees:** 2.84%
- **Imports actually settled in rupees:** 2.36%

Compare this to the previous year, when export invoicing stood at 5.84% and import invoicing at 4.18%. The growth is slow—painfully slow for those hoping for rapid change—but it is moving in the right direction. What these numbers reveal is that while Indian businesses are increasingly willing to *invoice* in rupees, the actual *settlement*—the moment money changes hands—remains more challenging. The gap between invoicing and settlement (6.08% vs 2.84% for exports) tells us that many deals still get converted to Dollars or other major currencies by the time payment is made.

The Big Hurdle: What's Stopping the Rupee?

Despite the clear benefits and incremental progress, the path to a global rupee is blocked by some formidable roadblocks. It's not as simple as just declaring it so.

1. Partial Convertibility: This is the most technical but crucial barrier. A currency can be "convertible" on two accounts: the **current account** (for trade in goods and services) and the **capital account** (for investments like buying stocks, bonds, or real estate). India has full convertibility on the current account—you can freely exchange Rupees to pay for imports. However, the Rupee is **only partially convertible on the capital account**. There are strict limits on how much money can flow in and out of the country for investment purposes. For a currency to be truly international, it must be freely movable in and out for any reason, without restrictions. India has kept these controls to protect itself from the "hot money" of speculators that can cause massive financial instability.

2. Limited Global Demand & The Russia Problem: Why would a foreign company want to hold Rupees? They need to be able to use them. If a Russian company receives Rupees for its oil, what can it do with them? It can buy Indian goods, but if India isn't selling enough, the Rupees pile up. This is precisely what happened in 2023–24. Talks to settle trade with Russia in Rupees stalled because Russia ended up with a massive surplus of Rupees and not enough to buy from India. They preferred to be paid in Chinese Yuan or UAE Dirham—currencies they could spend more easily elsewhere. For a currency to be desired, there must be deep and liquid financial markets where it can be invested or exchanged.

3. India's Persistent Trade Imbalances: India typically buys more from the world (imports) than it sells (exports). This creates a trade deficit. When India runs a deficit with a country—whether it's China, Russia, UAE, or Saudi Arabia—that country accumulates Rupees. As the Russia example shows, they are often reluctant to hold them, leading them to sell Rupees and buy their own currency or Dollars, which pushes the Rupee's value down. For the Rupee to be in high demand, India needs to export more, creating a global need for its currency.

4. Exchange Rate Volatility: The year 2025 was a turbulent one for the Rupee. Global uncertainties, US trade tensions, and record foreign portfolio investor (FPI) outflows of approximately \$17–18 billion put immense pressure on the currency. The Rupee hit record lows before the RBI stepped in with interventions. By early March 2026, the Rupee was trading around 91–92 INR/USD, with the RBI's reference rate at 91.68 on March 6. While this represents a slight recovery, the underlying downward bias from trade uncertainties remains.

What's New? Key Developments in 2024–2026

Despite these challenges, the RBI has been quietly but systematically building the infrastructure for a more international rupee. Several key developments have occurred in the past two years:

The SRVA Network Expands: The Special Rupee Vostro Account (SRVA) framework, which allows foreign banks to hold rupee accounts in India, has now been extended to approximately 30 countries. By mid-2025, 156 such accounts had been opened by 123 correspondent banks. Partners now include Bangladesh, Bhutan, Nepal, Sri Lanka, UAE, Indonesia, Maldives, Mauritius, Russia, and Malaysia—a diverse mix of neighbors and key trading partners.

Regional Focus Intensifies: In October 2025, the RBI announced a significant policy shift: authorized dealer banks can now lend rupees to non-residents in Bhutan, Nepal, and Sri Lanka specifically for trade purposes. This targeted approach recognizes that internationalization often begins in one's own backyard. The same announcement expanded the uses of SRVA balances, allowing them to be invested in Indian corporate bonds and government securities—giving foreign holders of rupees more options.

Reference Rates for Partners: To make transactions smoother, the RBI has introduced transparent reference rates for major partner currencies, including the UAE dirham and Indonesian rupiah. This eliminates one of the practical barriers to rupee trade: knowing what your currency is worth at any given moment.

The Tug-of-War: What Makes the Rupee Rise and Fall?

The value of the Rupee isn't static. It fluctuates daily against the Dollar, a constant tug-of-war between various economic forces. Understanding these drivers is key to understanding the challenge of internationalization. Think of the Rupee's price (say, 91.68 Rupees to 1 US Dollar on March 6, 2026) as being set by supply and demand. If demand for Rupees is high, its value appreciates (you need fewer Rupees to buy a Dollar). If supply is high or demand is low, it depreciates.

Factors that make the Rupee APPRECIATE (Strengthen):

1. **Strong Economic Growth (GDP):** If India's economy is booming, foreign investors want a piece of the action. They sell Dollars to buy Rupees to invest in Indian companies, driving up demand for the Rupee.
2. **Higher Interest Rates:** If the RBI raises interest rates, foreign investors can get a better return on Indian bonds. They flock to India, buying Rupees and pushing its value up.
3. **High Foreign Investment (FDI/FPI):** A surge in foreign companies setting up factories (FDI) or portfolio investors buying stocks (FPI) creates a constant demand for Rupees.
4. **Low Inflation:** If Indian inflation is low, the Rupee retains its purchasing power, making it a more attractive store of value.

Factors that make the Rupee DEPRECIATE (Weaken):

1. **High Trade Deficit:** This is a big one. To pay for all the imported goods (especially oil), Indian companies need to sell Rupees and buy Dollars. This massive supply of Rupees in the forex market pushes its value down.
2. **High Inflation:** If prices in India are rising faster than in the US, Indian goods become less competitive. This reduces demand for exports and, consequently, for Rupees.
3. **Global Risk-Off Sentiment:** When there's a global crisis (like trade wars or geopolitical tensions), investors flee "riskier" emerging markets like India and rush to the "safe haven" of the US Dollar. This causes a mass selling of Rupees and a sharp depreciation. The \$17–18 billion FPI outflow in 2025 is a perfect example.
4. **Speculation:** If currency traders believe the Rupee will weaken, they will sell it, creating a self-fulfilling prophecy.

The RBI's Balancing Act

The RBI isn't a passive observer in all this. It steps into the market to manage this volatility. It plays the role of a shock absorber. If the Rupee is falling too fast, the RBI will sell Dollars from its massive reserves and buy Rupees, soaking up the excess supply and propping up the value. If the Rupee is rising too much (hurting exporters), it will do the opposite: buy Dollars and sell Rupees.

This intervention is a delicate dance. The RBI's primary goal isn't to fix the Rupee at a particular level, but to prevent "jerky" movements that can destabilize the entire economy. In 2025, as the Rupee came under pressure, the RBI sold dollars to curb volatility, demonstrating its continued commitment to stability over a free float.

Conclusion: An Ongoing Journey, Not a Destination

The story of the Indian Rupee is a story of India itself. It reflects the nation's growing economic might, its policy adaptability, and its ambition to be a leading voice in a multipolar world. The push for rupee internationalization, turbocharged by the geopolitical shocks of 2022 and sustained through 2026, is a strategic move to assert economic sovereignty and build resilience against global financial storms.

The latest data from the RBI's February 2026 Bulletin tells a story of slow but genuine progress. Six percent of exports now invoiced in rupees, up from under five percent just a year ago. A network of 156 Special Rupee Vostro Accounts spread across 30 countries. New mechanisms allowing neighboring countries to borrow in rupees and invest surplus balances in Indian bonds. These are not revolutionary changes, but they are real, tangible steps forward.

Yet the journey is fraught with challenges that no policy declaration can simply wish away. The fundamental problem of India's trade imbalance remains: why would a country with a surplus against India want to hold rupees if it can't easily spend them? The Rupee's partial convertibility, maintained to protect the economy from speculative shocks, also limits its usefulness as a truly global currency. And the volatility of 2025—with record foreign investor outflows and the Rupee touching new lows—serves as a reminder that internationalization can be a double-edged sword, exposing the currency to global forces beyond any single central bank's control.

The case of Russia, once seen as the great hope for rupee trade, now stands as a cautionary tale. The mechanism was created, the accounts were opened, but the fundamental economics didn't align. Russia accumulated rupees but wanted to spend them elsewhere. It's a perfect illustration of the gap between policy ambition and on-the-ground economic reality.

So where does this leave the Rupee in March 2026? It leaves it exactly where a prudent, gradualist approach would want it to be: making progress, learning from setbacks, and building infrastructure for the long haul. The RBI has consistently emphasized that this is a multi-decade journey, not a sprint. The goal is not to dethrone the Dollar—an impossible task for any single currency—but to create genuine alternatives, to reduce dependence, and to ensure that when the next global financial storm hits, India has more options than simply hoping the Dollar remains stable.

The internationalization of the Indian Rupee is not an event with a clear finish line. It is an ongoing evolution. With each new bilateral trade agreement signed in Rupees, with every step towards deeper financial markets, and with every policy that boosts exports, India takes another step on this long road. The nation is demonstrating its capacity to adapt, innovate, and collaborate on a global scale. While the Rupee may not become a reserve currency anytime soon, its journey towards greater global recognition is a testament to India's determination to not just participate in the global financial landscape, but to help shape it. For the textile exporter in Mumbai, the benefits remain distant but visible on the horizon. For policymakers at the RBI, the work continues—patient, persistent, and purposeful. And for the Rupee itself, the march towards international acceptance goes on, one small step at a time.

11. CASE STUDY-I

A Study on Exchange Rate Volatility and its Macro-Economic Determinants in India

- **Author:** Swati Thakur and Rakesh Kumar Srivastava
- **Year:** 2016

OBJECTIVES:

- To identify macro-economic determinants that affect the exchange rate of INR-US \$ and linearity in their correlation during 2005-2015.
- To examine the factors causing fluctuations of INR against the US\$ in the same time period.

Results:

- It is observed that exchange rate is highly correlated with the selected independent variables taken up for this study, except with the Inflation ($r = -0.003$).
- There is huge positive correlation between the Exchange rate of INR/USD and external debt ($r = 0.904$). A negative correlation exists between exchange rate and lending interest rate ($r = -0.432$).
- The correlation between the exchange rate and GDP is also high at ($r = 0.809$). And, a mild positive correlation exists between exchange rate and FDI ($r = 0.293$).

Research Implications: A strong correlation between the dependent variable exchange rate & independent macroeconomic variables suggests improving Export to GDP ratio along with promoting foreign capital especially FDI to improve the INR/US \$ exchange rate.

CASE STUDY-II

An ARIMA analysis of the Indian rupee/USD exchange rate in India

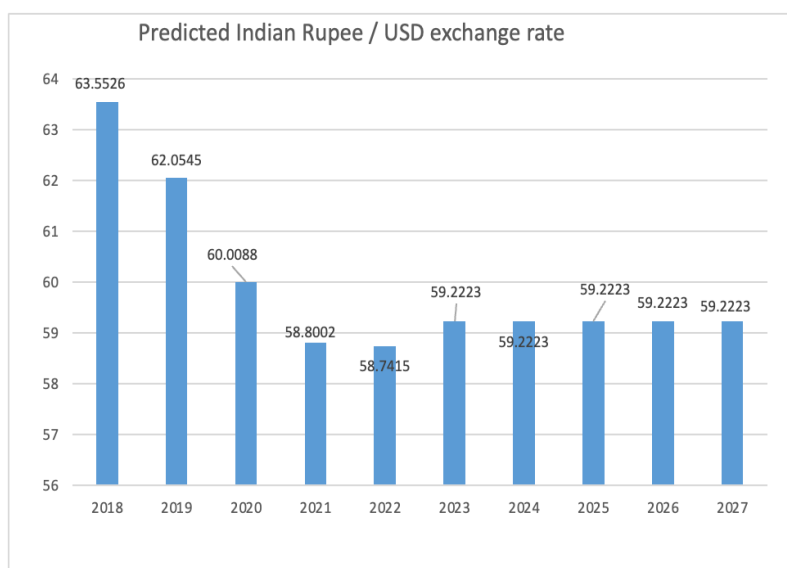
- **Author:** Thabani Nyoni
- **Year:** 2019

Research objectives:

- To develop an optimal ARIMA model for the analysis of the Indian rupee / USD exchange rate.
- To predict the Indian rupee / USD exchange rate over the period 2018 – 2027

Methodology: The study used annual time series data on the Indian Rupee / USD exchange rate from 1960 to 2017, to model and forecast exchange rates using the Box-Jenkins ARIMA technique.

RESULTS:



- Indian Rupee / USD exchange rate will appreciate over the period 2018 – 2022, after which it will depreciate slightly until 2027.

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ABSCISIC ACID AS A CENTRAL REGULATOR OF PLANT TOLERANCE TO ABIOTIC CONSTRAINTS

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Introduction: Plants Under Environmental Stress

Plants, unlike animals, cannot move away from unfavorable environments. They remain rooted in place and must endure fluctuations in water availability, temperature, soil salinity, radiation, and pollutants. These non-living environmental challenges—collectively known as abiotic stresses—are major factors limiting agricultural productivity worldwide. Even under irrigated conditions, stresses such as drought, heat, and heavy metal toxicity can substantially reduce crop growth and yield. To survive such hostile conditions, plants rely on sophisticated internal signaling systems. Among the various plant hormones, abscisic acid (ABA) plays a particularly crucial role. Often referred to as the “stress hormone” of plants, ABA coordinates a wide range of physiological, biochemical, and molecular responses that enhance tolerance to adverse environments. It not only helps plants cope with stress but also regulates key developmental processes such as seed dormancy, germination, and growth.

Nature and Production of Absciscic Acid

Absciscic acid is a small organic molecule belonging to the terpenoid family. It is synthesized in various plant tissues, particularly in roots and young shoots, and its production increases rapidly when plants experience stress. During dehydration or water deficit, ABA is synthesized *de novo*, whereas rehydration leads to its degradation. The biosynthesis of ABA originates from carotenoid precursors. Several enzymes participate in this pathway, converting compounds such as violaxanthin and neoxanthin into xanthoxin and ultimately into active ABA. Key enzymes involved include zeaxanthin epoxidase (ZEP), 9-cis-epoxycarotenoid dioxygenase (NCED), and abscisic aldehyde oxidase (AAO). Among these, NCED is considered the rate-limiting step, and its gene expression rises sharply during stress conditions such as drought. Thus, plants possess the ability to rapidly adjust ABA levels according to environmental cues, enabling timely activation of protective responses.

ABA as a Master Signal in Stress Response

Abiotic stresses often lead to cellular dehydration, osmotic imbalance, and oxidative damage. ABA functions as a central signaling molecule that detects these disturbances and initiates adaptive responses. When stress occurs, ABA concentration rises in plant tissues, triggering changes in gene expression, metabolism, and physiology. One of the most important roles of ABA is regulating stomatal behavior. Stomata are microscopic pores on leaf surfaces that control gas exchange and water loss. Under drought conditions, ABA signals guard cells to close the stomata, thereby reducing

transpiration and conserving water. This mechanism is essential for plant survival during water scarcity. However, stomatal closure also restricts carbon dioxide entry, leading to reduced photosynthesis. Therefore, ABA balances survival against growth, prioritizing water conservation when conditions are severe.

ABA Signaling Pathway: From Perception to Response

The ABA signaling pathway involves a series of molecular interactions that translate hormone perception into cellular responses. Specific receptors detect ABA and initiate downstream signaling cascades involving protein phosphatases, protein kinases, and transcription factors. These components regulate stress-responsive genes that produce protective proteins and metabolites. For example, ABA activates transcription factors that induce the synthesis of osmolytes small molecules that help maintain cell turgor and protect cellular structures. It also stimulates antioxidant systems to counteract reactive oxygen species generated during stress. Importantly, ABA signaling operates through both rapid responses (such as stomatal closure) and slower long-term adaptations (such as altered gene expression and growth patterns).

Role of ABA in Drought and Water Stress

Drought is the most widespread abiotic stress affecting agriculture. It causes osmotic stress, reduces water uptake, and disrupts metabolic processes. ABA accumulation is one of the earliest responses to drought.

During water deficit:

- ABA levels can increase dramatically in leaves and roots
- Stomata close to minimize water loss
- Root growth may be maintained or enhanced to access deeper water
- Protective proteins accumulate

Metabolism shifts toward stress tolerance

Studies have shown that plants with impaired ABA synthesis are highly susceptible to drought, while those with enhanced ABA production exhibit improved tolerance. Interestingly, ABA may inhibit shoot growth while allowing root development, enabling plants to allocate resources toward water acquisition rather than canopy expansion.

Response to Salinity and Osmotic Stress

High soil salinity creates conditions similar to drought because it limits water availability to plant roots. Salt stress also leads to ionic toxicity and oxidative damage. ABA helps plants cope by regulating ion balance, osmotic adjustment, and antioxidant defenses. Osmotic stresses such as drought, salinity, and cold share common signaling pathways involving ABA. This overlap allows plants to deploy a coordinated response to diverse environmental challenges. Calcium ions often act as secondary messengers in these pathways, amplifying ABA signals and facilitating cross-talk between different stress responses.

ABA and Temperature Stress

Both heat and cold can severely disrupt plant physiology. Elevated ABA levels have been associated with improved tolerance to temperature extremes. The hormone promotes the synthesis of protective proteins and stabilizes cellular structures under stress conditions. Cold stress, in particular, induces gene expression patterns similar to those activated by drought and salinity, highlighting the central role of ABA in integrating stress responses.

Protection Against Heavy Metal Toxicity

Industrial pollution and agricultural practices have increased heavy metal contamination in soils. Metals such as cadmium, copper, and lead interfere with photosynthesis, enzyme activity, and nutrient uptake. Exposure to heavy metals often results in elevated ABA levels. This hormone contributes to tolerance by:

- Activating antioxidant defenses
- Regulating water relations
- Modulating gene expression
- Influencing metal uptake and transport

ABA and Ultraviolet Radiation

Ultraviolet-B radiation can damage DNA, proteins, and membranes through the production of reactive oxygen species. ABA participates in protective responses by promoting stomatal closure, enhancing antioxidant activity, and interacting with other signaling molecules such as nitric oxide. Plants exposed to UV-B often show increased ABA synthesis, which contributes to improved tolerance not only to radiation but also to drought.

Influence on Seed Dormancy and Germination

Beyond stress responses, ABA plays a vital role in plant development. One of its classic functions is maintaining seed dormancy. High ABA levels prevent premature germination, ensuring that seeds sprout only under favorable conditions. During germination, ABA levels decline, allowing growth to proceed. Mutations affecting ABA sensitivity can result in abnormal germination behavior, highlighting the hormone's regulatory importance.

Balancing Growth and Survival

While ABA enhances stress tolerance, excessive levels can inhibit growth. This trade-off reflects an adaptive strategy: during unfavorable conditions, survival takes precedence over biomass production. ABA coordinates resource allocation by reducing processes such as cell expansion and photosynthesis while promoting protective mechanisms. Once favorable conditions return, ABA levels decrease, allowing growth to resume.

Future Perspectives: Harnessing ABA for Crop Improvement

Understanding ABA signaling has significant implications for agriculture. Climate change is expected to intensify abiotic stresses, making crop resilience a priority. Manipulating ABA biosynthesis, signaling components, or responsive genes could lead to the development of stress-tolerant cultivars. However, translating laboratory findings into field performance remains challenging. Stress tolerance is a complex trait involving multiple pathways, and excessive ABA responses may reduce yield under non-stress conditions. Therefore, future research aims to achieve an optimal balance between tolerance and productivity.

Conclusion

Abscissic acid serves as a central coordinator of plant responses to abiotic stress. By integrating environmental signals with physiological and molecular processes, ABA enables plants to survive drought, salinity, temperature extremes, heavy metal toxicity, and radiation. Its influence extends beyond stress tolerance to fundamental developmental processes such as seed dormancy and growth regulation. As global agriculture faces increasing environmental challenges, a deeper understanding of ABA signaling offers promising avenues for improving crop resilience and ensuring food security.

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CLIMATE SMART STRATEGIES FOR RESILIENT COFFEE PRODUCTION

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Abstract

Climate change is pushing coffee growers into tough territory. Higher temperatures, unpredictable rainfall and increased pest populations are reducing yields, lowering quality, and shrinking areas where coffee thrives. Farmers and scientists aren't sitting back. They are turning to shade-based agroforestry, working on better soil and water management and breeding new climate-resilient varieties. There's even talk of promising species like *C. Liberica* and *C. Stenophylla* joining the mix. India's layered shade systems and new grafting methods stand out, showing practical ways to keep production steady in a shifting climate.

Keywords: Coffee, Climate-smart, Sustainable production, Varieties of Coffee, Challenges.

Coffee in a Warming World

Coffee is of global economic and cultural importance, supporting the livelihoods of over 120 million people. However, it is becoming increasingly difficult and expensive to produce as climate change pushes temperatures beyond the critical 30°C threshold, disrupting flowering and reducing bean quality. Between 2021 and 2025, the top five coffee-producing countries experienced an average of 57 additional heat-stress days each year, while India recorded around 30 extra days linked to carbon pollution. These climate changes, along with shifting rainfall patterns, are making traditional coffee-growing regions less suitable. As a result, yields and quality are declining, contributing to rising global prices for both Arabica and Robusta coffee.

Climate Change Threats to Coffee Farms

Climate change poses serious direct and indirect threats to coffee agroecosystems. The global area suitable for Arabica cultivation is projected to decline by at least 50% by 2050, with countries like Ethiopia potentially losing 65–100% of suitable land. Changing rainfall patterns lead to unseasonal flowering, while excessive rains can damage crops by causing berries to burst or fall prematurely, as seen in the Western Ghats. At the same time, rising temperatures accelerate the spread of pests and diseases, increasing coffee berry borer populations by around 8.5% for every 1°C rise and allowing coffee leaf rust to expand into higher elevations that were once too cool. In addition, the decline of key pollinators such as bees, estimated at 8–18%, further threatens coffee productivity and overall yields.

Climatic Resilience in Coffee Farming Practices

Climatic resilience in coffee farming is advancing through research-driven and field-level innovations, notably by the Central Coffee Research Institute (CCRI) during its centenary (1925–2025). Improved techniques like grafting Robusta scions onto Arabica rootstocks (such as S.4595 and SIn. 5B) enhance drought resistance by sustaining photosynthesis and efficient water use under stress. Farmers are also adapting through altitudinal shifts, moving cultivation to cooler

elevations—around 150–200 meters higher in Tanzania and 700–1800 masl in India—though such transitions are often restricted by soil limitations and protected forest zones. Alongside this, adaptive farm management practices, including flexible planting times and the use of solar dryers, play a crucial role in reducing risks from unpredictable rainfall and excess moisture, thereby supporting more stable yields.

Shade Trees: Coffee's Natural Climate Protector

Shade trees are an essential natural defence mechanism in coffee farming, especially in traditional Indian coffee plantations, which are more akin to layered forests. Shade trees control regional climate conditions by controlling fluctuations in temperature by 2-3°C and raising leaf warmth by 2-4°C during nights, thereby ensuring that frost damage is prevented. Additionally, they provide defence cover by significantly reducing wind speed by 22-99% and moisture loss through evapotranspiration from the soil by 38%. It is also important to preserve indigenous tree species since replacing them with exotic species such as silver oak compromises ecological stability, and indigenous species encourage biodiversity by supporting beneficial insects, natural pest controllers, and pollinators such as giant honeybees.

Soil Health and Efficient Water Management

In the Western and Eastern Ghats of India, coffee farming has to deal with weather that is getting harder to predict, so soil and water management are key for keeping things sustainable. I think the monsoons play a big role here, with all that heavy rain washing away nutrients and topsoil, which is why farmers build terraces on the slopes. They also plant this elephant grass that has deep roots, *Pennisetum purpureum*, believed to hold everything in place and stop landslides from happening. Water is another challenging aspect, especially since larger estates have the money for bore wells and sprinkler systems to give the coffee plants those blossom showers when needed. But most small farmers just can't swing that kind of setup, so they rely on simpler stuff like digging ponds to catch rainwater right on the farm. Organic mulching helps too, cutting down evaporation from the soil by maybe 30 per cent or so, which lets the plants make it through dry periods without needing fancy irrigation. Those shaded areas where coffee grows store a lot of carbon, like 70 to 80 tonnes per hectare, and keep the air cooler for better beans. It seems like that microclimate is important, but it is not sure how it all ties back to the water issues exactly. Some repetition in methods across farms might help build resilience overall, though smaller ones still face more challenges.

Newly Released and Future Versions of Row Crop Greenhouses

These greenhouse crop varieties have been bred for their "endurance to resist" pests and to endure the extreme temperature fluctuations. Selection 15 (S.5086) is a first-generation hybrid of Chandragiri and Sln. 10. It was created as a better version of Chandragiri, with an extra gene for coffee rust tolerance. It offers nearly 10% higher yield than Chandragiri while keeping excellent cup quality, scoring 79 to 80. This makes it a promising option for areas affected by climate stress. Selection 14 (S.4594), a new tall variety, was bred to resist attacks from the coffee white stem borer. This pest has become more common due to rising temperatures. Chandragiri (Sln. 13), although released earlier, remains an important climate-resilient choice because of its outstanding cold tolerance. It can thrive at elevations above 1800 meters, where pest pressure is lower. Elite varieties like Sln. 9 are also vital for adapting to climate challenges because of their strong drought resistance. Recent observations show that over 25% of Chandragiri seedlings have very high coffee rust resistance, ranging from 95 to 98%. This highlights the growing importance of resilient planting material in future coffee landscapes.

Diversity, Climate Benefit, Current State (as of 2026)

The plant *Coffea stenophylla* thrives in hot climates because it can withstand extended periods without rainfall. Current research is being conducted at field locations, and initial results from CCRI and Greve et al. research show a flavour profile that closely resembles Arabica. *Coffea excelsa* grows in humid tropical areas and can tolerate unpredictable rain patterns, while the speciality "tree coffee" has begun to be exported from India to both the USA and European markets. The deep-rooted trees of *Coffea liberica* establish strong roots, enabling them to draw water from challenging clay environments, and the species can withstand moderate storms, which contributes to its increasing use as a full plantation crop for farmers. The CCRI research team focuses on hybridisation studies of *Coffea racemosa* because the species exhibits excellent drought resistance and thrives in dry, marginal environments.

Climate Adaptation Strategies

Indian farmers also employ other methods to adapt to climate change, such as grafting. Indian coffee growers plan to graft Robusta scions (S. 274 and CxR) onto Arabica rootstocks (Sln. 6 and Sln. 9) between 2025 and 2026. This innovative technique will combine the drought resistance of certain Arabica rootstocks with the resilience of Robusta. Regarding the Natural Canopy Shade, India will continue using the "two-tier" shade system that employs Erythrina and Ficus as its two layers. This system can lower the temperature in the coffee plantation by as much as 3 to 5 degrees Celsius below the ambient temperature, thus reducing some negative effects caused by the 30 extra hot days.

Challenges and the Future of Sustainable Coffee Production

India's coffee production is transitioning from high-input monocultures to biodiversity-rich agroforestry, due to an increasing 30-65 heat-stress (>30°C) days annually in the major growing states. With unseasonal rains leading to premature fruit drop, farmers are switching to the "Shade-to-Standards" framework, whereby traditional shade species like Jackfruit and Ficus reduce temperature by up to 4°C, in addition to curbing the coffee white stem borer. Supported by India's first home-grown sustainability standard, INDICOFs, which bridges small holders to international demands like the EU Deforestation Regulation (EUDR), AI-based irrigation and soil-health sensors are complemented by regenerative approaches to help India's coffee to be recognised as high-quality, climate-resilient and origin-specific.

Conclusion

The major challenges that still exist, despite the innovations, include a lack of adaptation finance for small-scale farmers and stricter environmental regulations. However, the future of coffee depends on scientific breakthroughs, equitable policy support, networking, and the inclusion of indigenous ecological knowledge to create resilient and sustainable coffee systems.

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CLEAN ENERGY THROUGH AGRICULTURE: PATHWAYS TO A SUSTAINABLE AND LOW-CARBON FUTURE

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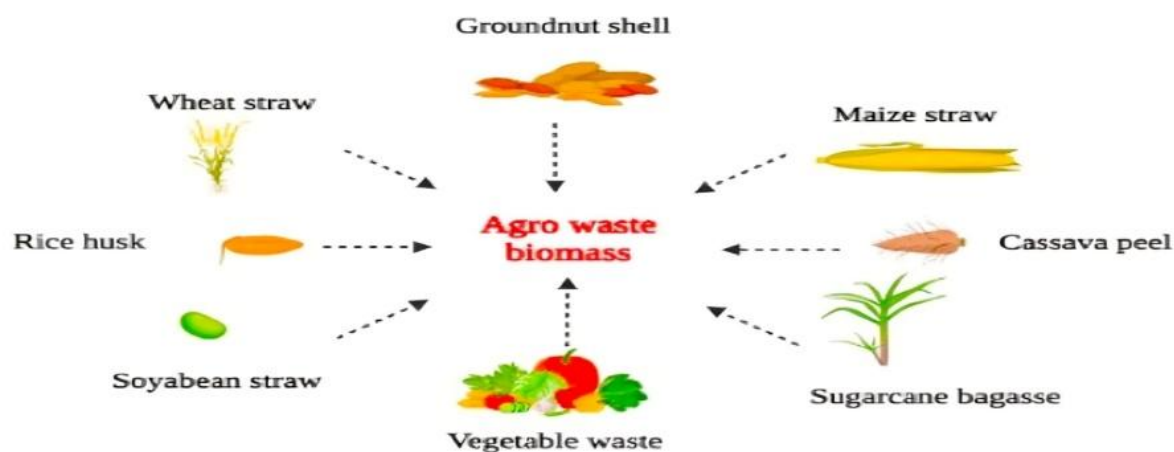
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Introduction

Energy demand across the world is increasing rapidly due to population growth, industrialization, and modernization of agriculture. Conventional fossil fuels such as coal, petroleum, and natural gas contribute significantly to greenhouse gas emissions, environmental degradation, and climate change. Therefore, the transition toward clean and renewable energy sources has become essential for sustainable development. Agriculture plays a dual role in this transition: it is both an energy consumer and a potential energy producer. Agricultural systems generate vast quantities of biomass, organic waste, and renewable resources that can be converted into clean energy. Integrating energy production with farming activities not only reduces carbon emissions but also enhances farmers' income and strengthens rural economies.

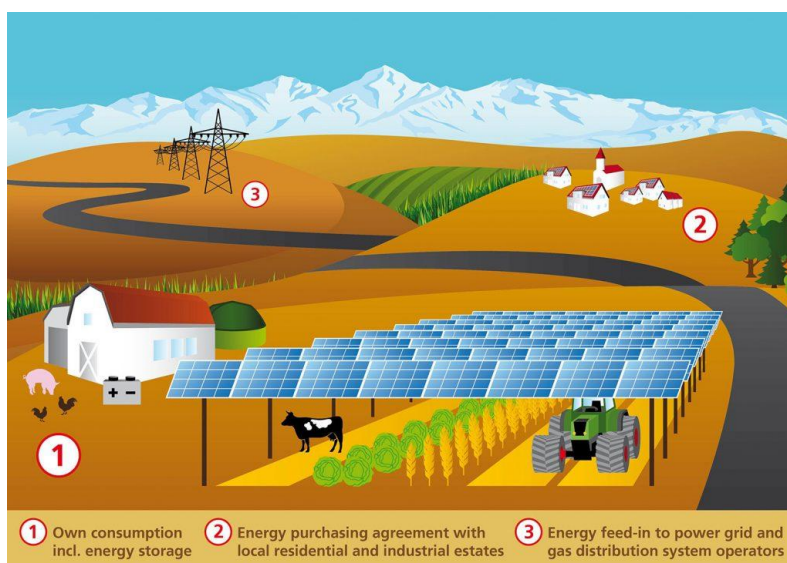
Bioenergy from Agricultural Biomass

Agricultural biomass is one of the most promising renewable energy sources. Crop residues such as rice straw, wheat straw, maize stalks, and sugarcane bagasse can be converted into bioenergy through various technologies. Biogas production from organic residues and animal dung provides clean cooking fuel and electricity generation in rural areas. Bioethanol produced from crops like sugarcane and maize serves as an alternative fuel blended with petrol, reducing dependence on fossil fuels. Similarly, biodiesel derived from oilseed crops such as soybean and jatropha can replace conventional diesel in agricultural machinery. Efficient utilization of agricultural biomass also prevents residue burning, thereby reducing air pollution and improving soil health.



Solar Energy in Agriculture

Solar energy has emerged as one of the most accessible renewable energy options for farmers. Solar-powered irrigation pumps reduce electricity costs and dependence on diesel engines while ensuring reliable water supply. Solar dryers help farmers preserve fruits, vegetables, and spices by reducing post-harvest losses and improving product quality. Agrivoltaic systems, where crops are grown beneath solar panels, allow simultaneous food and energy production on the same land. These systems enhance land-use efficiency, provide shade to crops, and generate additional income through electricity production.



Wind and Small-Scale Hydropower

Small-scale wind energy systems installed at farm level can generate electricity for irrigation, storage, and processing operations in regions with adequate wind potential. These systems are especially useful in remote rural areas where grid connectivity is limited. Micro-hydropower technologies utilize flowing water from canals or small streams to produce electricity without major environmental disturbance. Such decentralized renewable energy systems support sustainable agriculture by reducing operational costs and promoting energy self-sufficiency among farmers.

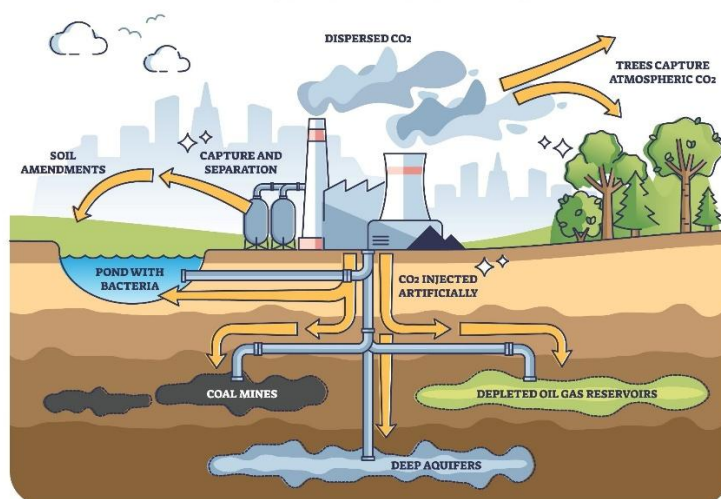
Waste-to-Energy Technologies

Agricultural and livestock wastes present valuable opportunities for energy generation. Livestock manure can be processed in biogas plants to produce methane gas for cooking, heating, and electricity generation. The remaining slurry acts as nutrient-rich organic manure, improving soil fertility. Composting technologies convert organic waste into stable fertilizers while reducing environmental pollution. Waste-to-energy approaches help manage farm waste efficiently, minimize methane emissions, and promote circular agricultural systems.

Carbon Sequestration and Climate Benefits

Agriculture has significant potential to mitigate climate change through carbon sequestration. Practices such as conservation tillage, cover cropping, agroforestry, and organic farming enhance soil organic carbon storage. Increased carbon sequestration improves soil structure, water retention, and productivity. Adoption of renewable energy technologies in agriculture reduces greenhouse gas emissions by replacing fossil fuels. These climate-smart practices contribute to achieving global sustainability goals while maintaining agricultural productivity.

CARBON SEQUESTRATION



Economic and Policy Aspects

Government policies play a crucial role in promoting clean energy adoption in agriculture. Various schemes encourage installation of solar pumps, biogas units, and renewable energy technologies through subsidies and financial assistance. Clean energy integration improves farm profitability by reducing fuel expenses and generating additional income through energy sales. Access to credit facilities, training programs, and technical support further enhances adoption among farmers. Policy frameworks focusing on renewable energy and rural development create opportunities for sustainable agricultural transformation.

Challenges and Future Prospects

Despite its potential, clean energy adoption in agriculture faces several challenges, including high initial investment costs, limited technical awareness, and lack of infrastructure in rural regions. Technological gaps in biomass conversion efficiency and storage systems also restrict large-scale implementation. However, advancements in smart farming technologies, energy-efficient equipment, and innovative financing models offer promising solutions. Future research and collaboration among scientists, policymakers, and farmers can accelerate the transition toward energy-efficient agricultural systems.

Conclusion

Clean energy integration within agriculture offers a sustainable pathway toward a low-carbon future. By utilizing biomass, solar power, wind energy, and waste-to-energy technologies, agriculture can transform from an energy-dependent sector into a renewable energy producer. These approaches reduce environmental pollution, enhance farm income, and strengthen rural resilience against climate change. With supportive policies, technological innovation, and farmer participation, agriculture can become a cornerstone of global clean energy solutions and sustainable development.

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COLD PLASMA TECHNOLOGY: A PROMISING NON-THERMAL APPROACH FOR MODERN FOOD PROCESSING

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Abstract

The modern food industry seeks innovative methods to preserve food safety and freshness without compromising natural taste and nutrition. While traditional heat-based preservation effectively eliminates harmful microbes, it can adversely affect texture, flavor, and nutrients, particularly in sensitive items like seafood. Cold plasma, a technology operating near room temperature by energizing gases, offers a novel solution. It generates highly reactive particles that destroy bacteria and slow spoilage without significantly heating the food. For seafood such as sea bass, cold plasma treatment has demonstrated reduced microbial growth, delayed spoilage signs, and extended refrigerated shelf life while preserving sensory qualities. Although precise control is necessary to prevent unwanted oxidation, this environmentally friendly technology holds great promise. Cold plasma may soon become a key method for delivering safer, fresher, and higher-quality seafood globally.

Keywords: Cold plasma; Innovative food preservation; Seafood safety; Shelf life improvement; Microbial control; Sustainable technology; Quality retention; Sea bass preservation.

Introduction

The global food industry is undergoing significant changes due to shifting consumer preferences, stricter food safety regulations, and a growing demand for more sustainable methods of preserving food without harming the environment. Shoppers are choosing food items that appear fresh, as if they haven't been processed, have been handled with care, and offer a high level of nutrients. At the same time, businesses need to make sure food stays safe from germs and lasts longer as it moves through complex supply chains. Traditional ways of preserving food, especially those that use heat, still work well to get rid of harmful microbes. But these methods often cause problems like changes in the food's texture, flavour, look, and nutritional value. These problems are especially clear in foods that go bad quickly, like seafood, because the weak muscle structure and a lot of unhealthy fats cause the quality to drop fast. To deal with these challenges, non-thermal processing techniques have become a big focus of research, and cold plasma has emerged as one of the most promising innovations.

Cold plasma, also called non-thermal plasma, is a type of gas that is only partly ionized. It contains electrons, ions, radicals, and molecules that are in an excited state. This kind of plasma is created using carefully controlled electrical conditions. Unlike thermal plasma systems, cold plasma works at temperatures close to room temperature, so it can treat food without causing much heating. This feature has attracted a lot of attention because it allows for good control of microbes while keeping the taste and nutritional value intact. In the last ten years, more and more studies have looked into how cold plasma can be used to clean food, make it last longer, and improve its quality, showing that it works well with many different types of food. Research shows that how well it works depends

on more than just how sensitive the microbes are. It also depends on things like how the treatment is done, what's in the product, and how it's stored. This shows that the way plasma interacts with food is quite complicated.

Principles and Generation of Cold Plasma

Cold plasma is made when energy is given to a gas, which leads to some of the gas particles losing electrons and forming a mix of charged and neutral particles that move around actively. Cold plasma is known for the fact that electrons and the heavier gas particles are not in balance with each other. Electrons gain enough energy to start chemical reactions, but the gas stays cool enough so it doesn't hurt the food. This physical process makes cold plasma a good choice for treating materials that can't handle heat, and it's different from traditional methods that use heat to preserve things.

Many different systems for creating plasma have been made for use in food processing. Systems that work at normal air pressure are especially useful because they can easily fit into industrial settings. Dielectric barrier discharge systems are one of the most commonly studied types. They have electrodes that are separated by a layer of insulating material. The dielectric barrier stops too much electrical current, which helps create a steady and even plasma on surfaces. Plasma jets are another common setup that creates focused streams of plasma used for treating specific areas. Corona discharge systems make ionized areas using uneven electric fields and are popular because they are easy to use and don't cost much. Each system has different levels of plasma density, how evenly the treatment is applied, and how complicated it is to operate, which affects how well it works for certain uses.

The ability of cold plasma to kill microbes mostly comes from creating reactive oxygen species and reactive nitrogen species. These are things like ozone, hydroxyl radicals, hydrogen peroxide, nitric oxides, and other chemicals that are active and can react with the cells of microorganisms. The harmful substances damage the cell membranes, cause proteins and fats to break down, and affect the genetic material, which leads to cells not working properly and the microorganism dying. Ultraviolet light released when plasma is created helps kill microbes by harming their DNA and stopping them from multiplying. Using several different methods at the same time makes it less likely for microbes to become resistant, which is different from other preservation methods that only target one thing.

The creation and how well reactive species work depend a lot on factors like the type of gas used, the electrical frequency, the voltage applied, how long the exposure happens, and the level of moisture in the environment. Oxygen-based gases can lead to the creation of oxidative substances, while nitrogen-based gases create reactive nitrogen compounds. Both types of gases can influence how microbes are controlled and may affect the quality of food. So, applying it well needs careful tuning that matches the particular product and the goals of the process. Understanding these interactions is still being studied to find a good balance between keeping microbes safe and maintaining product quality.

Applications of Cold Plasma in Food and Seafood Preservation

In recent years, the real-world uses of cold plasma in food processing have grown a lot. One of its main uses is cleaning surfaces, where plasma treatment helps lower the number of microbes on fresh fruits, vegetables, meat, and fish without causing much of a temperature rise. Its ability to kill harmful microbes and bad bacteria while keeping the product safe and unchanged meets what customers want in foods that are processed as little as possible. Cold plasma has also been studied

for turning off enzymes, changing how packaging works, and getting rid of bad chemicals, showing that it can do many things in food systems.

Seafood preservation is a great area where cold plasma can be used because fish and shellfish are naturally easy to spoil. High moisture levels, a neutral pH, and plenty of unsaturated fatty acids make it easier for microbes to grow and for oxidation to happen. Regular ways to keep food fresh, like putting it in the freezer or using chemicals, can make it last longer. But these methods might change how good the food tastes or looks, and they can also cost more to do. Cold plasma offers a different way to fight bacteria on the surface of food without changing how fresh the seafood looks, which is important for customers in the market.

Studies with chilled sea bass show that using cold plasma in the air can help lower the number of bacteria at first and slow down how microbes grow when the fish is stored in the fridge. Samples that were treated with plasma kept their better taste ratings for longer and had a slower rise in signs of spoilage like trimethylamine nitrogen and thiobarbituric acid reactive substances over time. These results show that cold plasma can help keep food fresh longer without changing how it looks or feels much, which makes it a good option for use in real stores.

Challenges, Quality Considerations, and Future Perspectives

Even though cold plasma shows promise, there are still some issues that make it hard to use this technology widely in the food industry right now. One of the biggest worries is about possible changes in quality because of oxidation reactions. The same chemicals that help kill microorganisms can also react with food parts, especially fats, causing them to oxidize. In seafood that has a lot of polyunsaturated fatty acids, too much contact with plasma can cause bad tastes or make the nutrients break down. However, studies show that when treatment conditions are not too harsh, they can reduce unwanted side effects, and in some cases, a little oxidation might not harm the taste or smell.

Another challenge is that the effectiveness of treatments can vary depending on the type of food they are applied to. Things like how wet the surface is, how rough it feels, how much protein is present, and the conditions inside the packaging can all affect how plasma moves through and how the reactive particles act. So, it's hard to create standard treatment rules, and each product often needs its own special adjustments. Industrial implementation also needs to think about how the equipment is designed, keeping people safe during operation, and making sure it's cost-effective. Even though weather patterns can make infrastructure easier to manage, some uses might need special gases or fancy tools that make things more expensive to run.

In short, cold plasma technology is a major step forward in preserving food without using heat, providing a good balance between keeping food safe from harmful microbes and maintaining its quality, which matches what the food industry is looking for today. Its use in seafood systems shows how it can help solve long-term problems related to food spoilage and getting products to the right places.

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CROP YIELD MONITORING IN PRECISION AGRICULTURE

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Introduction

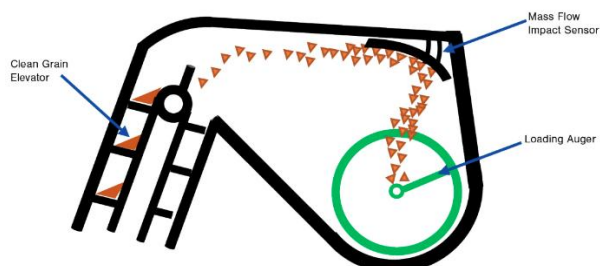
In traditional farming, decisions were often based on assumptions - that every part of a field will respond uniformly, or that practices successful in the previous season will deliver the same results again. However, crop yield monitoring and mapping reveal a different reality - fields are highly variable, and inputs do not always generate equal returns across all areas. Even adjacent sections of the same field can produce significantly different yields despite receiving identical treatment. These variations are not random; they are influenced by underlying factors such as soil health, drainage conditions, and pest management practices. Ignoring this variability, especially across large farming areas, can lead to increased costs and lost opportunities. This article explores how crop yield monitoring and mapping can be effectively used to identify such differences and make more informed, cost-efficient decisions in the field.

A yield monitoring system helps identify high-yielding and low-yielding zones, allowing farmers to apply inputs like fertilizers, water, and pesticides more efficiently and only where needed. This not only reduces input costs but also increases overall profitability. Additionally, it forms the backbone of precision agriculture by supporting technologies such as GPS-based mapping and variable rate application, leading to site-specific crop management. Yield monitoring also helps in detecting problem areas like poor soil conditions or drainage issues, enabling timely corrective actions. Over time, the collected data can be used to analyze trends, improve future planning, and evaluate the effectiveness of different farming practices. Furthermore, it promotes sustainable agriculture by minimizing resource wastage and environmental impact. Overall, this system transforms farming from a generalized approach to a precise, efficient, and sustainable practice, ultimately improving productivity and farm income.

Key Components of a Crop Yield Monitoring System

Crop yield monitoring system relies heavily on sensors, remote sensing and data driven models, from individual field to global scales. These tools support food security, input optimization, and risk management by providing timely, spatially explicit information on crop growth and expected production. A typical yield monitoring system (especially in combine harvesters) includes following sensors:

- 1. Yield Sensor:** It is the most critical component as it measures the flow rate of harvested grain inside the combine harvester. It is usually installed in the clean grain elevator and works by measuring the force exerted by the grains when they strike an impact plate or by using optical sensors. The sensor converts this physical interaction into electrical signal, which is then used to calculate the mass or volume of grain harvested per unit time. Proper calibration and routine maintenance of the yield sensor is essential for accurate measurements.



Impact Type Mass Flow Sensor



Optical Mass Flow Sensor

Fig. 1: Grain Flow Sensor

2. **Moisture Sensor:** The moisture sensor is used to determine the moisture content of the harvested grain. Since grain weight varies with moisture level, this sensor ensures that yield data is standardized to a specific moisture content for accurate comparison. It typically works by measuring electrical conductivity or capacitance, as these properties change with moisture content. This correction is crucial for obtaining reliable yield values.
3. **GPS Receiver:** It provides the geographical location of the harvester in real time. It records latitude and longitude coordinates continuously as the machine moves across the field. This spatial information allows yield data to be linked with specific locations, enabling the creation of detailed yield maps that show variability within the field.
4. **Header Position Sensor:** The header position sensor detects whether the harvesting header is engaged or not. When the header is lowered, it indicates active harvesting, and the system records data. When the header is raised, data recording is paused to avoid collecting false yield information during turning or non-harvesting movements. This improves the accuracy of the dataset.
5. **Ground Speed Sensor:** This sensor measures the forward speed of the harvester. Yield is often calculated as mass flow per unit area, so accurate speed measurement is necessary to determine how much area is being covered over time. Speed can be measured using wheel sensors, radar, or GPS-based systems.
6. **Data Logger/Monitor:** The data acquisition system (data logger or monitor) collects signals from all sensors, processes them, and stores the information. It provides a real-time display of yield, moisture content, and other parameters to the operator. Advanced monitors also allow data transfer to external devices for further analysis and mapping.
7. **User Interface:** The display unit (in-cab monitor) is the interface through which the operator interacts with the system. It shows real-time yield values, field coverage, and system status, helping the operator monitor performance during harvesting and make immediate adjustments if needed.

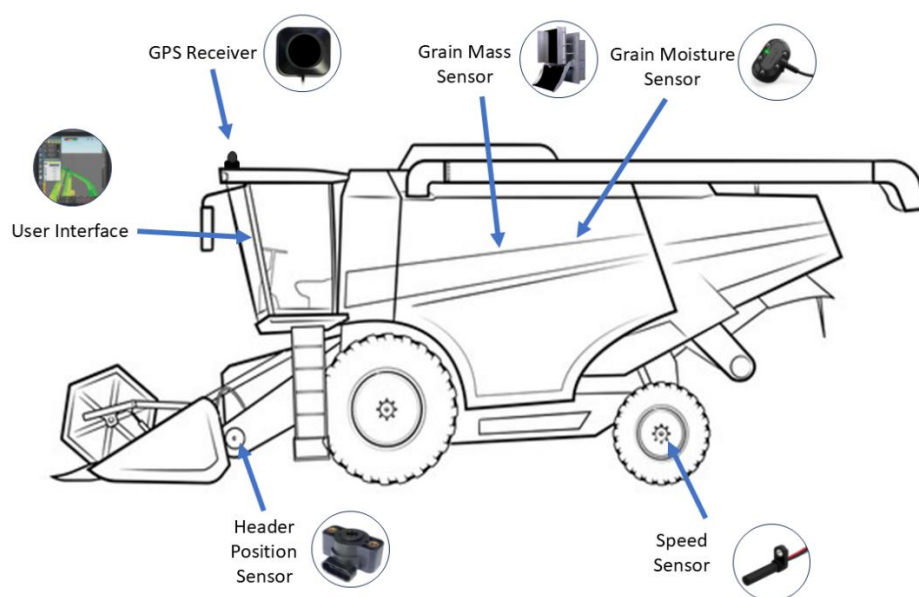


Fig. 2: Different Components of Crop Yield Monitoring System

Working Principle

The working principle of a crop yield monitoring system is based on the continuous measurement of grain flow, correction for moisture content, and integration with positional data to calculate yield over a specific area during harvesting. When the combine harvester operates in the field, the crop is cut and fed into the machine, where the grain is separated from the straw. As the cleaned grain moves through the clean grain elevator, it passes through the yield sensor, which measures the rate of grain flow. In most systems, this is done using an impact plate: as grains strike the plate, they exert a force proportional to their mass flow rate, and this force is converted into an electrical signal. This signal represents the amount of grain being harvested per unit time. Simultaneously, a moisture sensor measures the moisture content of the grain. Since grain weight varies with moisture, the system corrects the measured yield to a standard moisture level to ensure accuracy and consistency in yield calculations.

At the same time, a GPS receiver continuously records the exact position of the harvester in the field. Along with this, the system tracks the ground speed and the effective width of the harvester header to determine the area being covered per unit time. By combining grain flow rate with the area covered, the system calculates yield in terms of mass per unit area (such as kg/ha or tons/acre). The header position sensor ensures that data is recorded only when actual harvesting is taking place, avoiding errors during turning or idle movement.

All these data inputs - grain flow, moisture content, position, and speed are sent to a data acquisition system, which processes and stores the information in real time. As the harvester moves across the field, this process repeats continuously, generating a large dataset of yield values linked to specific locations. After harvesting, specialized software uses this data to create detailed yield maps, which visually represent spatial variability in crop productivity across the field.

Recent Advancements

Traditionally, ground-based crop yield monitoring system relies on the sensors, mounted directly on the harvesting machine. Recent advancements allow yield monitoring and estimation not only

with installed sensor but also using remote sensing (satellite) data. The satellite-based systems provide a wide view of fields, capturing various growth and health parameters of the plant. The detailed map is then generated, showing where the field is expected to produce more or less yield.

Table 1: Satellite-based vs. ground-based yield monitoring

Method	Satellite-based monitoring	Ground-based monitoring
Data coverage	Covers the entire field and even multiple fields at once	Limited to areas where the equipment is operating
Measurement method	Estimation based on crop reflectance and model correlations	Manual data collection through machine-based sensors
Historical data	Easy access to past seasons' data through archived satellite imagery	Only available if precision yield monitors were used in previous years
Frequency	Regular image acquisition during the growing season	Only during harvest
Setup requirements	No need for on-field hardware; only software and satellite data	Requires specialized machinery, sensors, and calibration
Costs	Cost-effective for large-scale monitoring across multiple fields	High initial investment and maintenance costs
Field variability	Detects spatial variability in crop performance early and consistently	Provides accurate data, but only after harvest
Scalability	Easily scalable to monitor tens of thousands of hectares remotely	Limited by the number of equipped machines and operators
Use cases	Scalable harvest estimation, early detection of growth trends, strategic decision-making across regions	Detailed tracking at harvest for individual

Source: EOS Data Analytics

Table 2: Major Categories of Crop Yield Monitoring Technologies

Approach	Main data sources	Typical use cases	Related Study
Satellite RS	Landsat, Sentinel, MODIS; multispectral, SAR	Regional–global yield monitoring, early warning	(Joshi <i>et al.</i> , 2023)
UAV / drones	High-res multispectral/ RGB	Field-scale LAI/biomass and yield mapping	(Fu <i>et al.</i> , 2020)
Proximal / on-harvester	Load cells, optical counters, capacitance sensors	Deterministic yield maps at harvest	(Longchamps <i>et al.</i> , 2022)
Crop models + RS	LAI, phenology + process models (e.g., SAFY, DSSAT, APSIM)	Mechanistic growth & yield simulation	(Lungu <i>et al.</i> , 2020)
Vision / photos	Ground or phone imagery	Low-cost yield estimation, especially in smallholder systems	(Li <i>et al.</i> , 2025)

Conclusion

Crop yield monitoring systems are an essential component of modern agriculture, enabling farmers to accurately measure, analyze, and manage crop productivity. By providing real-time and location-

specific data, these systems help in understanding field variability, optimizing input use, and improving overall farm efficiency and profitability. They play a crucial role in advancing precision agriculture and promoting sustainable farming practices. Although challenges such as high cost, technical complexity, and data management exist, the benefits of improved decision-making and resource optimization far outweigh these limitations. Future progress should focus more on better ground data acquisition, fusion strategies, and transparent, scalable models that work across crops, regions, and climate extremes. With continued technological advancements and proper training, crop yield monitoring systems will become more accessible and effective, contributing significantly to the future of smart and sustainable agriculture.

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CUSTOM HIRING CENTRES IN AGRICULTURE: THE NEED OF THE HOUR FOR EVERY FARMER

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Abstract

With every kharif season, millions of smallholder farmers face a familiar double bind scarce agricultural labour and unaffordable farm machinery competing for the same brief planting window. Custom Hiring Centres (CHCs) have emerged as the most practical answer to this annual crisis, making tractors, seed drills, transplanters, harvesters, and precision drones available to every farmer on a simple pay-per-use basis. This article argues that CHCs are not merely a convenience they are an agronomic imperative. By reducing cultivation costs by 20-40%, ensuring timely field operations, cutting post-harvest losses, and generating rural entrepreneurship, CHCs are transforming the economics of smallholder farming. As the kharif season of 2026 approaches, understanding and strengthening the CHC network has never been more urgent.

Keywords: Custom Hiring Centres, Agricultural Mechanization, Kharif Season, Farm Machinery, Drone in Agriculture, Rural Entrepreneurship

Introduction

As the kharif season draws near, a familiar anxiety grips farming communities across the country. Paddy nurseries are being prepared, soybean fields lie ready for the first furrow and cotton growers are watching the sky for the southwest monsoon, yet the tractors, transplanters and seed drills needed to capitalize on each precious window of opportunity are already overbooked. Farm labourers, increasingly drawn to better-paying urban construction and industrial jobs, are harder to find and costlier to hire than ever before. This seasonal scramble for machines and manpower is not a new problem but it is an intensifying one and it demands a structural solution rather than another year of makeshift compromise.

That solution already exists and its name is the Custom Hiring Centre (CHC). A CHC is an organized rural service enterprise that owns a fleet of farm machinery tractors, power tillers, seed drills, transplanters, combine harvesters, sprayers and drones and makes it available to farmers on hire, on demand, at the time they need it most. By converting expensive capital assets into affordable pay-per-use services, CHCs democratize access to modern agricultural technology for the millions of smallholder farmers for whom individual ownership is simply not an economic option.

The urgency of the *kharif* window perfectly illustrates why CHCs are not a luxury but a necessity. Delayed sowing of paddy, maize or soybean beyond the optimal planting window can reduce yields by 10-20%. Every day a field sits unploughed because a tractor is unavailable or every transplanting job done late because labour did not show up is a yield loss that no amount of fertilizer or irrigation can recover. In this context, a well-functioning CHC network is as essential to *kharif* crop success as timely rainfall itself.

What is a Custom Hiring Centre

A Custom Hiring Centre is a rural mechanization service hub owned by an individual entrepreneur, farmer-producer organization (FPO), cooperative, or supported by the government that maintains a pool of agricultural implements and rents them to farmers as and when needed. The 'custom' in

custom hiring reflects the tailored, on-demand nature of the service: a farmer books the exact machine needed, for the field size and specific operation required, at the time that fits the crop calendar.

A typical CHC offers tractors with interchangeable attachments (ploughs, rotavators, disc harrows), seed-cum-fertilizer drills, paddy transplanters, combine harvesters, multi-crop threshers, boom sprayers, laser land levellers, and increasingly, agricultural drones for precision spraying, crop monitoring, and nutrient application. In India, over 50,000 CHCs are operational across the country, supported under the Sub-Mission on Agricultural Mechanization (SMAM) with subsidies of 40–80% on approved equipment.



Tractor FM Reaper



Rotavator



Combine Harvester



Straw Chopper



Tractor and Wagon



Thresher



4 Row Spring Type



9 Tyne Spring Automatic Seed Drill

Role and Importance of CHCs in Agriculture

Ensuring Timely Kharif Field Operations

Timeliness is everything in kharif agriculture. CHCs ensure that land preparation, sowing, transplanting, and crop protection happen within the narrow agronomic windows that determine whether a crop succeeds or fails. A transplanter hired from a nearby CHC can complete in one day what twenty labourers would take three days to accomplish and at a lower cost. In districts where combine harvesters from CHCs are readily available, paddy is harvested in hours instead of days, avoiding the catastrophic losses that follow unseasonal rain on a standing mature crop.

Reducing the Cost of Cultivation

Cost reduction is the most immediately felt benefit of CHC services. Mechanized transplanting costs 30–35% less than hiring manual labour; combine harvesting cuts harvest and threshing expenses by over half; precision zero-till drills reduce seed use by 20–25% through accurate placement; and drone-based spraying trims pesticide consumption by 15–30% through uniform, targeted coverage. These savings translate directly into improved net income for farm families.

Addressing Critical Labour Scarcity

Rural labour migration to cities has made farm labour not merely expensive but genuinely scarce during *kharif* peak periods. CHCs substitute machine power for absent human labour, sustaining cultivation viability in areas where manual operations have become impractical. A CHC-based

transplanter or combine harvester does not ask for advance payment, does not take festival leave during harvest, and does not bargain up wages when every farmer in the village needs workers on the same day.

Promoting Resource-Use Efficiency and Sustainability

Laser land levellers available through CHCs reduce irrigation water requirements by 25–35% through uniform field grading. Zero-till drills eliminate the need to burn crop residues, conserving soil carbon and reducing air pollution. Agricultural drones deliver nano-urea and nano-DAP fertilizers with up to 50% greater efficiency than broadcast methods, while simultaneously providing crop health intelligence through multispectral imaging. Each of these technologies accessible through CHC services makes the *kharif* crop more resource-efficient and environmentally sustainable.

Creating Rural Entrepreneurship and Livelihoods

A well-managed CHC is a thriving rural business. An operator running a tractor with attachments and a drone service can earn a net annual income of USD 4,000–15,000 two to three times the earnings of an average farm labourer in the same district. India's Drone Didi initiative, which trains women from self-help groups as drone pilots and CHC operators, is opening transformative economic pathways for rural women while simultaneously expanding CHC service coverage into underserved communities.

Challenges and the Way Forward

Despite their proven impact, CHCs face significant barriers. Access to institutional finance even with government subsidy remains difficult for first-generation rural entrepreneurs lacking collateral. Seasonal revenue concentration, where most earnings arrive in two or three peak months, creates year-round cash flow stress. Skill gaps in operating drones and precision machinery require structured training. Poor rural road infrastructure limits machinery movement, while fragmented small fields restrict large implement manoeuvrability. Timely after-sales service and spare parts availability in remote areas remain chronic weaknesses.

Addressing these constraints requires sustained policy commitment: priority lending for CHC operators, mandatory skill certification programmes for drone pilots and machinery technicians, investment in rural road infrastructure, and incentives for private AgriTech companies to extend service networks into underserved regions. Digital platforms for real-time machinery booking and GPS-based fleet tracking already operational in several states need to scale nationally to maximize equipment utilization and farmer access.

Conclusion

As the kharif season of 2026 gathers momentum, the pressures of labour scarcity and machinery competition are once again testing the resilience of Indian farming. Custom Hiring Centres stand as the most practical, proven and scalable answer to this perennial challenge. They put the right machine in the right field at the right time and in agriculture, timing is everything.

CHCs reduce the cost of growing food, improve yields through timely and precise operations, conserve water and soil, cut post-harvest losses and generate dignified rural livelihoods. They are not a stop-gap they are the future architecture of smallholder agriculture. Strengthening CHC networks before and during the kharif season is not merely sound agricultural policy; it is an act of solidarity with every farmer who wakes before dawn to watch the monsoon clouds and wonders whether help will arrive in time.

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PHLOEM LOADING AND UNLOADING MECHANISMS: CONTROL OF PHOTOASSIMILATE DISTRIBUTION

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Introduction

Photosynthesis in mature, fully expanded leaves generates carbohydrates, with sucrose being the principal transport form in most higher plants. These mature leaves function as “source” organs because they produce more assimilates than they consume for their own metabolism. In contrast, actively growing tissues such as roots, young leaves, shoot apices, flowers, fruits, and developing seeds act as “sink” organs that rely on imported carbon. The movement of assimilates from sources to sinks occurs through the phloem, a living vascular tissue specialized for long-distance translocation of organic compounds. Phloem transport is driven by a pressure gradient established between source and sink regions, consistent with the Münch pressure-flow hypothesis.

Phloem loading in source leaves involves the active or passive transfer of sucrose from mesophyll cells into sieve element–companion cell complexes. This loading may occur via symplastic pathways through plasmodesmata or via apoplastic pathways requiring membrane transporters. Once inside the phloem, sucrose and other solutes are transported rapidly over long distances to sink tissues. At the sink end, phloem unloading delivers photoassimilates into surrounding cells, where they are metabolized, stored, or used for growth. Sink strength, determined by metabolic activity and developmental stage, strongly influences the direction and rate of assimilate flow. Efficient coordination between loading, transport, and unloading ensures optimal carbon partitioning within the plant. Under stress conditions such as drought or nutrient deficiency, phloem function may be altered, affecting assimilate supply to critical organs. Impaired transport can result in accumulation of sugars in source leaves, feedback inhibition of photosynthesis, and reduced biomass production. In crop plants, efficient source–sink relationships are closely associated with yield potential and harvest index. Therefore, understanding phloem loading and unloading mechanisms is essential for improving carbon allocation, stress resilience, and productivity in agricultural systems.

Source–Sink Concept in Plants

The concept of source and sink is fundamental to understanding assimilate transport. Source tissues are those that export carbohydrates, typically mature leaves performing active photosynthesis. Sink tissues are those that import carbohydrates because their demand exceeds their photosynthetic capacity. These include young expanding leaves, root systems, reproductive organs, and storage tissues. Importantly, organs can switch roles during development; for example, a young leaf initially acts as a sink but becomes a source upon maturation. Sink strength—the ability of a tissue to attract assimilates is determined by its size, metabolic activity, rate of cell division, and capacity for storage.

During reproductive stages, developing grains or fruits often become dominant sinks, drawing large quantities of sucrose and thereby influencing overall plant productivity.

Structure of the Phloem Tissue

Phloem tissue is structurally specialized for efficient transport. The primary conducting cells are sieve tube elements, which form elongated tubes connected end-to-end. These cells lack nuclei and many organelles at maturity, minimizing resistance to flow. Closely associated companion cells provide metabolic support, regulate loading and unloading, and supply energy required for active transport processes. Numerous plasmodesmata connect companion cells to sieve elements, enabling rapid exchange of metabolites and signals. Phloem parenchyma cells contribute to storage and lateral transfer of assimilates, while fibers provide mechanical strength. The coordinated functioning of these cell types allows the phloem to serve both as a transport pathway and a communication network within the plant.

Pressure–Flow Mechanism of Transport

Long-distance movement of sucrose through the phloem is explained by the pressure–flow hypothesis. At source tissues, active loading of sucrose into sieve tubes increases osmotic concentration, causing water to enter from adjacent xylem vessels. This influx generates high turgor pressure. At sink tissues, removal of sucrose lowers osmotic pressure, leading to water efflux and reduced turgor. The resulting pressure gradient drives bulk flow of phloem sap from source to sink. This mechanism allows rapid transport over long distances without continuous energy expenditure along the pathway. Phloem sap can be partitioned among several sink organs at the same time because bulk flow follows pressure gradients created by unloading at each sink. Organs with greater sink strength due to higher metabolic demand or storage capacity maintain steeper gradients and therefore receive a larger share of assimilates.

Mechanisms of Phloem Loading

Phloem loading is the process by which sucrose moves from photosynthetic mesophyll cells into the sieve element–companion cell complex. In apoplastic loading, sucrose is exported into the cell wall space and actively transported into companion cells via sucrose/H⁺ symporters. These transporters utilize proton gradients generated by ATP-dependent pumps, allowing sucrose to accumulate to high concentrations in the phloem. This mechanism provides strong control over transport rates and is common in many crop species. In symplastic loading, sucrose moves directly through plasmodesmata from cell to cell without crossing membranes. This pathway relies on cytoplasmic continuity and concentration gradients rather than active transport. In certain species, sucrose is converted into larger oligosaccharides in intermediary cells, preventing back diffusion and maintaining directional flow through a polymer-trap mechanism. Some plants exhibit intermediate strategies that combine both pathways, allowing flexibility in response to developmental or environmental conditions.

Long-Distance Transport in the Phloem

After loading, sucrose travels through sieve tubes as part of the phloem sap. Transport velocities can be remarkably high, enabling distribution from leaves to distant organs such as roots or fruits. Along the transport pathway, assimilates may be temporarily exchanged with surrounding tissues to meet local metabolic needs. In addition to sugars, the phloem carries amino acids, hormones, proteins, and signaling molecules, making it a major conduit for systemic communication. Efficient long-distance transport ensures coordinated growth across the entire plant.

Mechanisms of Phloem Unloading

Phloem unloading refers to the removal of sucrose from sieve tubes at sink tissues. In symplastic unloading, sucrose moves directly into sink cells through plasmodesmata. This pathway predominates in rapidly growing tissues such as root tips and young leaves, where cell connectivity is high. In contrast, apoplastic unloading involves release of sucrose into the extracellular space followed by uptake into sink cells via transport proteins. This mechanism is common in developing seeds, fruits, and storage organs. Cell wall invertases often hydrolyze sucrose into glucose and fructose in the apoplast, maintaining a concentration gradient that promotes continuous efflux from the phloem. The glucose and fructose produced from sucrose hydrolysis serve as immediate substrates for cellular respiration, supplying energy (ATP) for growth and metabolism. They also act as carbon skeletons for the synthesis of structural components and storage compounds such as starch, lipids, and proteins.

Regulation of Sink Strength

Sink strength determines how effectively a tissue can attract assimilates from the phloem. It depends on both structural factors, such as sink size, and physiological factors, including metabolic demand and enzymatic activity. High activities of enzymes like invertases and sucrose synthase enhance sucrose utilization, thereby maintaining steep concentration gradients that favor import. Storage capacity also plays a role; organs capable of accumulating starch, oils, or proteins can sustain strong sink activity over extended periods. During grain filling in cereals or fruit development in horticultural crops, sink strength largely dictates final yield.

Hormonal Regulation of Photoassimilate Distribution

Plant hormones coordinate assimilate transport with developmental processes. Auxins promote vascular differentiation and establishment of new sinks, particularly in developing organs. Cytokinins enhance sink activity by stimulating cell division and delaying leaf senescence, thereby maintaining source capacity. Gibberellins promote growth and mobilization of stored reserves, increasing demand for assimilates. Absciscic acid plays a key role under stress conditions, modulating carbohydrate partitioning and phloem function. Through complex interactions, hormonal signals ensure that carbon resources are directed toward tissues most critical for survival and reproduction.

Environmental Influences on Phloem Transport

External environmental conditions strongly affect photoassimilate distribution. Drought stress reduces photosynthesis and alters turgor pressure, often shifting carbon allocation toward roots to enhance water uptake. Temperature extremes influence membrane properties and enzyme activities, thereby affecting transport efficiency. Nutrient deficiencies can weaken sink activity, while light intensity determines source strength by controlling carbohydrate production. Plants continuously adjust loading and unloading processes to maintain metabolic balance under fluctuating environmental conditions.

Molecular Regulation of Transport Processes

At the molecular level, phloem transport is controlled by the expression and activity of specific proteins. Sucrose transporters mediate uptake into phloem cells, while SWEET proteins facilitate sucrose efflux into the apoplast. Hexose transporters enable uptake of glucose and fructose in sink tissues. Enzymes such as invertases and sucrose synthase regulate sucrose metabolism, influencing concentration gradients and sink strength. Additionally, the permeability of plasmodesmata can be dynamically regulated, affecting symplastic transport. Advances in molecular biology have revealed that these components are tightly regulated by developmental cues and environmental signals.

Role in Crop Productivity and Yield Formation

Efficient distribution of photoassimilates is a major determinant of agricultural yield. Grain filling in cereals, tuber formation in potato, sugar accumulation in sugarcane, and fruit growth in horticultural crops all depend on adequate assimilate supply. Even when photosynthesis is high, limitations in phloem transport can restrict yield formation. Therefore, improving carbon allocation efficiency is a key objective in crop improvement programs.

Phloem Transport Under Stress Conditions

Under abiotic stress, plants often reprogram carbon allocation to support survival. For example, drought conditions may enhance assimilate transport to roots, while salinity can alter carbohydrate metabolism and partitioning. Heat stress may accelerate leaf senescence, reducing source capacity and impairing grain filling. Understanding how stress affects loading and unloading processes is crucial for developing resilient crop varieties.

Conclusion

Phloem loading and unloading mechanisms govern the distribution of photoassimilates throughout the plant and thus play a central role in growth, development, and productivity. Through coordinated regulation involving structural features, metabolic processes, hormonal signals, and environmental responses, plants ensure efficient carbon allocation to organs with the greatest demand. A comprehensive understanding of these processes provides valuable opportunities for enhancing crop yield and stress tolerance, making phloem transport a critical focus in plant physiological research and agricultural innovation.

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DRAGON FRUIT: FROM ROCKY LANDS TO REVENUE – A PRACTICAL GUIDE

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Abstract

Dragon fruit (*Hylocerus undatus*), which was introduced as a new crop for low rainfall areas and rocky, barren land, is quickly becoming popular among farmers. It is a nutritious fruit that can be used as pulp in many ways, comprising 70–80% of the ripe fruit. Dragon fruit (*Hylocereus* spp.), a herbaceous perennial climbing cactus, often called Pithaya fruit or Kamlam fruit, has recently attracted Indian growers because of its attractive red or pink color and its economic value as a fruit. It is also appreciated for its high antioxidant potential, vitamins and minerals content. It is known to prevent colon cancer, diabetes, and neutralise heavy metals and toxic substances; it reduces cholesterol and high blood pressure. The fruit tastes like kiwi fruit and is high in calcium, phosphorus, and vitamin C. The crop becomes profitable in four to five years, despite the comparatively large initial investment. When kept at room temperature, fruits stay fresh. The crop is hardy and may thrive in any climate that is conducive to fruiting and flowering as long as the soil has adequate drainage.

Keywords: Dragon fruit, Antioxidants, Nutritional value, Low rainfall cultivation, Shelf life.

Introduction

The dragon fruit (*Hylocereus* and *Selenicereus* species) is a member of the Cactaceae family and has a chromosomal number $2n=22$. It is native to Central and South America. In India, it is sometimes referred to as Kamalam fruit, while it is commonly recognised as "Pitahaya fruit" throughout the world (as stated by the Hon'ble. Prime Minister of India in his Maan ki Baat on July 26, 2020). This fruit is called "**Dragon fruit**" because it has green scales, just like a dragon, and it is a striking reddish-pink tint that represents fire.



**Figure : 1 Mature dragon fruit
(*Hylocereus* sp.) ready for harvest.**

Dragon fruit (*Hylocerus undatus*, family Cactaceae) is a climbing cactus originally from Central and South America. Today, it is grown in many tropical and subtropical areas. In India, states such as Gujarat, Maharashtra, Karnataka, West Bengal, and Bihar are starting to grow dragon fruit as a new crop option. However, even though demand is rising, most of the supply still comes from imports because local production is limited. Dragon fruit grows well in dry and semi-dry climates and needs less water than many other crops, which makes it a good fit for Bihar's weather. As more people want to buy dragon fruit and the government supports its cultivation, farmers have a good chance to increase their income and grow crops in a more sustainable way. The area under cultivation of this crop has been continuously growing since it was brought to India in the early 1990s. It is also known by names like "Nobel women," "Queen of the night," "Strawberry pear" and "Jesus in the cradle" in other countries. The fruit's amazing taste and high antioxidant content make it one of the most popular fruits among customers. Additionally, the fruit has a number of therapeutic benefits. For example, eating the fruit can assist a dengue patient's immunity and platelet count. It also helps with serious cardiac conditions, blood pressure, and many other things. The adaptable traits, simple cultivation, and management techniques demonstrate how scientific farming techniques will increase the income of small and marginal farmers. Dragon fruit is grown in several Indian states, including Bihar, Gujarat, Maharashtra, Kerala, Tamil Nadu, and portions of the North East Hill region.

Ideal Growing Condition

To ensure optimal growth and prevent root rot, the environmental and soil conditions must be carefully managed.

Table 1. Ideal environmental and soil requirements for dragon fruit (*Hylocereus* spp.) cultivation.

Parameter	Ideal Requirement
Temperature	20–30°C.
Shade Requirement	20–30% shade is necessary if daytime temperatures exceed 40°C to prevent leaf scorching.
Soil Type	Rich in organic matter, completely free of compaction, and well-drained. It cannot survive waterlogging.
Soil pH	5.5 to 6.6.
Intercropping Options	Chickpea, Cowpea, Chilli, Lentils, and Tomato (helps smother weeds and adds nitrogen to the soil).

Propagation and Nursery Management:

- Using mature, one-year-old stem cuttings that were collected post-harvest during the September–October pruning phase is the main technique of propagation.
- Although cuttings should ideally be 25–30 cm long, studies show that longer cuttings (>35 cm) result in superior root and shoot development because of stronger photosynthetic absorption.
- Cuttings are treated with natural aloe vera extract or dipped in IBA (2.5 ppm) for 30 seconds to promote rapid roots.
- They are planted in polybags measuring 12 by 30 cm and containing a 1:2 mixture of cocopeat and vermicompost. To get rid of pathogens, this media needs to be fumigated with 0.5% Cypermethrin or formaldehyde before being planted.

- The saplings are prepared for field transplanting at a spacing of 2 m x 2 m, once new buds usually emerge within a month.

Field Management: Training, Pruning, and Fertiliser Support Structures (Trellising):

The vines grow quickly, reaching 4-5 meters in height and 30-50 branches in a few years. Farmers use trellises to keep the stems from breaking down. IIHR Bangalore's popular design uses a 6-foot concrete pillar topped with a used bicycle tyre or scooter to support the heavy vines.



Figure 2. Vegetative growth of dragon fruit plants propagated from one-year-old stem cuttings.



Figure 3. Dragon fruit vines trained on a concrete pillar with tire support (trellis system) in the field support

Pruning

To encourage the formation of lateral branches, the primary vertical stem is trimmed. Only after the fruiting season ends in October or November should unhealthy or damaged vines be removed.

Fertiliser

As humans, we need a balanced diet to maintain a healthy body and mind so that we can carry out our daily tasks as effectively as possible. Similarly, for healthy vine development and increased yield, the plant also needs a balanced dosage of nutrients. A normal dose of 540:720:300 grams per plant is provided, albeit the amount of N:P:K will differ depending on the location.

Table 2. Key species of dragon fruit (*Hylocereus* spp.), their fruit characteristics, and notable global varieties.

Key Species	Appearance	Notable Global Varieties
<i>Hylocereus undatus</i>	Red skin & White flesh	Taiwan Pink, Thai Dragon, Australian Red
<i>Hylocereus megalanthus</i>	Yellow skin & White flesh	Valdivia Raja, Natural Mystic, Isis Yellow
<i>Hylocereu spurusii.</i>	Red skin & Red flesh	Dark Star, Vietnamese Giant, Pepino Dulce
<i>Hylocereus polyrhizus</i>	Red skin & Red-Purple flesh	<i>H. Costaricensis</i> , Thompson, Caribbean Pink

Dragon fruits are harvested in the months of September and October. The plants start bearing fruit after three years of transplanting. At the time of ripening, the colour of the epicarp changes from green to reddish-pink. The TSS of the fruit is 15-18% . The Average weight of one fruit is around, 300-400gm. Harvesting must be done early in the morning by using a sharp knife or with the help of secateurs. After harvesting, the fruits must be stored at a temperature of 10 degrees Celsius to

increase the shelf life as compared to room temperature. Packaging of the fruits must be done in a Punnett box or Cardboard boxes. Value-added products like jam, juices and squashes can be prepared using the pulp, and the outer rind can also be used in the extraction of natural dyes.

Conclusion

Growing dragon fruit offers farmers a very profitable opportunity to raise their socioeconomic status, particularly in the current market environment where demand greatly exceeds supply. In order to successfully expand farming into more degraded regions, the agricultural sector should concentrate on building better marketing networks and creating bio-fortified, stress-tolerant cultivars in the future.

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ECOLABELLING IN AQUACULTURE: ENSURING SUSTAINABLE SEAFOOD

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Abstract

Ecolabels function as market-based tools designed to incentivize sustainable fishing and responsible aquaculture. By providing a visible certification, these bridge the gap between environmentally conscious consumers and producers. For producers, ecolabelling offers enhanced market access and potential price premiums, while ensuring the long-term viability of aquatic resources. However, challenges persist regarding the high costs of certification and the data-heavy requirements that often disadvantage small-scale fisheries in developing regions. Despite these hurdles, ecolabelling remains a cornerstone of the Blue Economy, driving transparency through chain-of-custody tracking. Ultimately, these programs harmonize international trade with conservation goals, fostering a seafood industry that balances global food security with ecological integrity.

Keywords: Certification, Sustainability, Conservation, Responsible aquaculture.

Introduction

The fastest-growing food industry in the world is aquaculture (Bray, 2018). As a source of seafood for human consumption, the industry has now surpassed wild fisheries, accounting for 57% of global consumption in 2022. Its expansion has also contributed to a notable rise in per capita seafood consumption, which went from 9 kg in 1961 to 20.7 kg in 2022. The industry is also linked to a number of environmental issues. Aquaculture is now a significant component of seafood production due to rapid technological innovation, increased productivity, and rising global demand for aquatic products. However, a number of issues accompany the aquaculture industry's phenomenal expansion, including social issues if left uncontrolled and environmental effects such as disease outbreaks, water pollution, mangrove destruction, and the depletion of natural resources. This raises questions about customers' understanding of the need for sustainable aquaculture products and the role aquaculture plays in sustainable development. One such well-known market management tactic is ecolabelling, an economic tool that seeks to convince customers to take into account factors other than price when making purchases. It is provided through an optional third-party certification for seafood products, which has been established since the 1990s and is believed to be a market-based strategy for reducing any adverse effects and boosting benefits for consumers and society. "Development that meets present needs without compromising the ability of future generations to meet their own needs" is how the commission defined sustainable development.

Feature	Environmental Labels	Ecolabels
ISO Standard	ISO 14021	ISO 14024
Claim Nature	Self-declared by the manufacturer/retailer.	Awarded by an independent third party.
Verification	No mandatory external audit; based on the company's own data.	Strict, mandatory third-party verification.
Scope of the product	Often focuses on a single attribute (e.g., "Recyclable").	Comprehensive Life Cycle Assessment (LCA).
Assessment Criteria	Determined internally by the company.	Pre-set by an impartial body with stakeholder input.
Examples	A "100% Recycled" logo on a box; "CFC-free" sprays.	EU Ecolabel, ASC (Aquaculture Stewardship Council).

Customers are willing to pay a premium for sustainable seafood because they often associate seafood certifications with product quality and sustainability, thereby supporting sustainable aquaculture (Kim and Lee, 2018; Yi, 2019). The proportion of certified aquaculture goods in the global market has remained low, despite many attempts to create markets for them. According to Potts et al. (2016), it made up 6% of the world's aquaculture supply in 2015 and was the most common in industrialized nations, making up more than 50% of the total with Norway, Chile, and Spain.

An ecolabel is a mark, logo, label, or product endorsement affixed to a seafood product at the point of sale that implies to a purchaser that the product has been produced through ecologically sustainable procedures and is from a well-managed source. Ecolabels are normally applied as labels or tags, such as a recognisable logo, to a seafood product as product endorsement at the point of retail sale. Thus, the message that the eco-labelled product is more environmentally sustainable is conveyed to consumers.

Difference between ecolabels and environmental labels

Since ecolabels apply to a specific category of products, environmental labeling is the general practice of providing information about a product's environmental impact, which is quite vague and imprecise.

Under the International Organization for Standardization (ISO), these are classified into three types categories of Ecolabelling: Ecolabelling is classified into three main categories:

- 1. First Party:** Individual producers establish these based on their own product standards and criteria related to specific environmental issues. It is a form of ecolabelling often termed as "self-declaration", e.g., "biodegradable".
- 2. Second Party:** Industry associations for members' products establish these criteria, and the organization determines them. The members elucidate the certification requirements, often by seeking guidance from academic institutions and environmental advocacy groups. External certifying companies or industry-specific internal certification processes are involved in verifying conformance.
- 3. Third Party:** These certificates are created by the external organizations (public or private), independent from the producers, distributors, and sellers of the labelled products. Products

provided by certified organizations or resources are then labelled to inform customers that they were made in an "environmentally friendly" manner. The label, also known as the seal, is usually licensed to a producer and can be found on or in conjunction with a product that comes from a certified producer or fishery. It is multi-criteria, which is third-party verified.

Objectives of Ecolabeling

- Communicate verifiable and accurate information.
- Encourage demand and supply of eco-friendly products and services.
- Stimulate a continuous market -driven environmental improvement.
- Reduce ecosystem degradation.
- Biodiversity Conservation.
- Social Responsibility.
- Pollution Control.

The guidelines for aquaculture certification mainly include four broad ranges of issues that are considered relevant for certification, as follows

1. Animal Health and Welfare Aquaculture.
2. Food Safety and Quality in Aquaculture.
3. Environmental Integrity of Aquaculture.
4. Social Responsibility Aquaculture.

Some of the examples of global ecolabels:

Sl. No.	Name of the Ecolabel	Logo	Description
1.	Australian Certified Organic		• Provides certification services to operators from all sectors of the organic industry. • Certification ensures compliance with national production standards. • Allows traceability of all products to their origin.
2.	B Corporation		▪ B Corporations' transparent and comprehensive performance standards enable consumers to support businesses. ▪ It uses the power of business to solve social and environmental problems.
3.	Best Aquaculture Practices		▪ Tells consumers that seafood came from BAP-certified aquaculture facilities that are marked on the retail packages. ▪ The standards specifically protect biodiversity and worker rights within a program that addresses environmental, social, food safety, and traceability issues throughout producers' operations.

Sl. No.	Name of the Ecolabel	Logo	Description
			BAP certification is currently available for shrimp farms and hatcheries, and seafood processing plants.
4.	Bio Suisse		Indicates fully organic, produced in Switzerland.
5.	BIO Hellas		- Provides the research and promotion of Organic Agriculture. inspection and Certification services for organic products according to: - The Regulation EC 834/2007 & 889/2008 - The NOP/ USDA Regulation. - Naturland standard - Biosuisse standard - Demeter standard - KRAV standard.
6.	Biokreis		- The Biokreis is a non-governmental organisation. - to help farmers to grow organically, - to inform consumers about organic agriculture and a healthy lifestyle.
7.	Certified Green Restaurant		Green Restaurant Association Seal is an ecolabel for restaurants that have committed to sustainability.
8.	Dolphin Safe		The Earth Island Institute monitors tuna companies around the world to ensure the tuna is caught by methods that do not harm dolphins and protect the marine ecosystem.

Sl. No.	Name of the Ecolabel	Logo	Description
9.	Earthsure		- The purpose of the program is to provide comprehensive environmental data to purchasers. - Earth Sure declarations (EPDs) can cover a portion of the life cycle of a product or an entire life cycle.
10.	Eco-Leaf		- The eco-leaf is an environmental product declaration based on a life cycle analysis consisting of three parts: 1. environmental aspects declaration 2. Environmental Information Data Sheet 3. product data sheet.
11.	EcoMark Africa		- It will consist of threshold criteria and indicators suitable for the African continent. - EMA will provide one continent-wide and cross-sectoral label to mark sustainably produced African products.
12.	Marine Stewardship Council		The MSC fisheries standard has 3 principles that every fishery must meet: Principle 1: Sustainable fish stocks Principle 2: Minimising environmental impact Principle 3: Effective management The MSC traceability makes sure that the label is only displayed on seafood from an MSC-certified sustainable fishery.
13.	Ocean Wise		Ocean Wise works with restaurants and markets, ensuring that they have the most current scientific information regarding seafood and helping them make ocean-friendly buying decisions to make environmentally friendly seafood choices.
14.	SeaChoice		- SeaChoice is a program of Sustainable Seafood Canada that produces sustainable seafood advisory lists. - It is designed to raise consumer awareness about the importance of

Sl. No.	Name of the Ecolabel	Logo	Description
			buying seafood from sustainable sources, and guide consumers for responsible seafood purchasing.
15.	Ø-label: Norway		All providers of organic products in Norway are part of Debio's inspection scheme, which includes all activities from farm to table.
16.	Naturland e.V.		- It is a private certification body and an organic farmers' association since 1982. - Certification standards range from organic food-production, organic aquaculture, sustainable capture fishery, to processing and trade, as well as non-food areas like organic forest management, organic cosmetics, and organic textiles.

Conclusion

Ecolabelling is a transformative approach to fisheries management worldwide, moving away from strictly regulatory methods toward market-driven conservation. These programs have effectively raised the standards for stock management, bycatch reduction, and habitat protection by establishing a clear connection between sustainable harvesting methods and customer choice. The versatility of ecolabelling in incorporating the objectives of the Blue Economy, while balancing ecological integrity with economic profitability, is what makes it successful. However, the industry must address the current "certification gap," which frequently excludes small-scale and data-deprived fisheries in developing nations, if these programs are to have a genuine global impact. Ecolabelling remains an essential tool in the larger Integrated Coastal Zone Management toolkit. It guarantees that the seafood sector can meet the growing global demand for protein without compromising the health of aquatic ecosystems for future generations, provided robust national and international regulations support it.

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THE CURRENT STATE AND FUTURE OUTLOOK OF INDIA'S VEGETABLE SEED INDUSTRY

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Introduction

India's vegetable seed industry is a critical component of the country's agricultural economy, driving both food security and productivity. Over the years, the sector has shifted from traditional farmer-saved seed systems to a modern, science-driven industry, powered by innovative breeding technologies. As a global leader in vegetable seed production and export, India's vegetable seed industry plays a pivotal role in the country's agricultural GDP. With its position as the world's second-largest vegetable producer, India has seen significant changes in seed production, distribution and consumption. The rise in demand for high-quality hybrid seeds, especially for crops like tomatoes, onions, cabbage and cauliflower, has transformed the industry. Hybrid seeds are now indispensable due to their superior yield potential, pest resistance and climatic resilience, cementing India's place as a key player in the global vegetable seed market. This article explores the current state of India's vegetable seed industry and outlines its future prospects, examining the opportunities and challenges that lie ahead in the evolving landscape of agricultural innovation.

Evolution of the Industry

1960s – Mid 1980s: Limited Private Sector Participation

- During this period, the vegetable seed industry was primarily driven by public sector entities.
- Research and development activities were mainly carried out by government-run research centers.
- Strict regulatory frameworks hindered foreign investments and limited the exchange of germplasm.

Mid 1980s – 1990s: Policy Reforms and Growth of the Sector

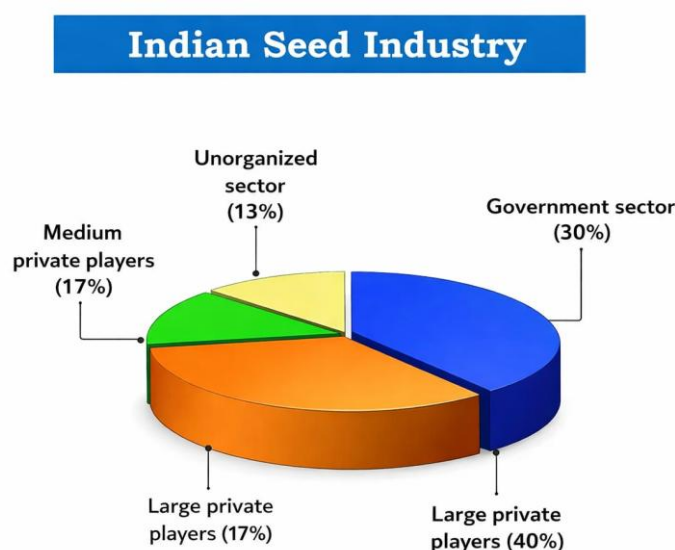
- In the mid-1980s, the Indian government began to liberalize the seed sector, opening up avenues for private sector involvement.
- The government introduced policies that encouraged Foreign Direct Investment (FDI), facilitating global partnerships.

- Relaxed import regulations allowed Indian seed companies to gain access to international breeding lines, enhancing local seed quality and variety.

Current Status and Market Growth of India's Vegetable Seed Industry.

The private sector now plays a dominant role in India's vegetable seed industry, contributing 80% of the total revenue generated within the domestic market. This shift has led to India being recognized as a key player in the global seed industry, with considerable market influence. Approximately one-third of Indian seed firms have established global technology and financial partnerships, enhancing their reach and capabilities. Private companies in India allocate 10-12% of their revenue towards research and development (R&D). Notably, smaller and mid-sized firms are ramping up their R&D investments, with an annual 20% increase in spending. This growing commitment to innovation is helping drive advances in seed technology and agricultural practices.

India's vegetable seed market is set for significant growth. Projections indicate the market will grow from US\$ 689.33 Million in 2024 to US\$ 1,136.24 Million by 2033, reflecting a CAGR of 5.71% from 2025 to 2033. This growth is driven by several factors, including the increasing demand for high-yield and hybrid seeds, government support for the horticulture sector, the adoption of modern agricultural methods and ongoing advancements in seed technology. Additionally, the country's expanding population, emphasis on food security and the development of climate-resilient seeds are key drivers fueling the industry's progress and shaping its future trajectory.



The government entities involved in seed production and research & development in the Indian seed industry include:

- 1) National Seeds Corporation
- 2) State Seed Corporations
- 3) ICAR institutes
- 4) State Agriculture Universities

Top Private Vegetable Seed Companies in India

1. Syngenta Group
2. Maharashtra Hybrid Seeds Company (Mahyco)
3. UPL Limited (Advanta Seeds)

4. VNR Seeds Pvt. Ltd.
5. BASF SE (Vegetable seed division)
6. Rijk Zwaan India Seeds Pvt. Ltd.
7. Namdhari Seeds
8. Right Seeds Pvt. Ltd.
9. ACSSEN HyVeg (ACSSEN Agriscience)
10. Ankur Seeds Pvt. Ltd.
11. Vokkal Seeds
12. Inventive Seeds Pvt. Ltd.
13. Iris Hybrid Seeds Pvt. Ltd.
14. Tropica Seeds
15. R.K. Seed Farms

Market Growth and Technological Advancements

The demand for vegetable seeds in India is primarily driven by the rising popularity of hybrid seeds, which offer better yields, consistent quality and enhanced disease resistance compared to traditional varieties. These seeds are essential in ensuring high productivity and profitability, especially for crops like tomatoes, onions, cabbage and cauliflower. Hybrid varieties also allow farmers to increase the number of cropping cycles per year, further boosting income potential.

As urbanization accelerates and the population grows, the need for year-round vegetable production has become more pressing. This trend is supported by established retail channels that make it easier for farmers to access quality seeds, while technological innovations in seed development have led to the creation of varieties that are disease-resistant, climate-resilient and biofortified for better nutritional value.

Growth Drivers in the Vegetable Seed Market

Rising Demand for Hybrid and High-Yield Seeds

Hybrid seeds have become increasingly popular due to their higher yield, pest resistance and longer shelf life. These seeds are particularly attractive to both commercial and small-scale farmers as they maximize agricultural income and productivity. With population growth and shifting dietary habits, the market for hybrid vegetable seeds continues to expand.

Modern Farming Techniques

The adoption of modern farming methods, including vertical farming, drip irrigation and precision farming, has amplified the demand for high-quality vegetable seeds. These methods require seeds that can perform well in controlled or intensive farming systems, such as hydroponic or greenhouse environments. Government programs and subsidies further promote the use of superior seeds to optimize yields and farming efficiency.

Technological Advancements in Seed Development

Innovations in biotechnology and molecular genetics have revolutionized the vegetable seed sector, leading to the development of disease-resistant, drought-tolerant and biofortified vegetable cultivars. These advances help minimize losses from pests and extreme weather, while enabling farming in diverse agro-climatic zones. Technologies such as gene editing and CRISPR are expected to further accelerate this trend, introducing faster crop development cycles and more resilient seed varieties.

Challenges in the Vegetable Seed Market**Dependence on Monsoon and Climate Variability**

India's reliance on monsoon rainfall poses significant risks to vegetable farming, especially during droughts or floods. Unpredictable weather events can disrupt seed germination, plant growth and overall yield. To mitigate these risks, farmers require access to better irrigation systems, weather forecasting technologies and climate-resilient seed varieties. However, high costs and limited infrastructure hinder widespread adoption.

High Cost of Hybrid and Certified Seeds

Although hybrid seeds offer improved performance, their higher cost remains a barrier for many smallholder farmers. The initial purchase cost of hybrid seeds is higher compared to traditional open-pollinated varieties and hybrid seeds need to be purchased every season, as they cannot be saved for future planting. This recurrent expense may deter farmers, especially those in rural and financially constrained areas. Financial support programs or subsidies could help overcome this hurdle and increase adoption.

Future Outlook and Growth Prospects**Market Potential**

India's vegetable seed industry presents significant growth potential, both domestically and internationally. As the population grows and urbanization increases, the demand for nutritious, high-yielding vegetables will continue to rise. Additionally, India's growing export market for vegetable seeds presents an excellent opportunity for the industry to expand its reach globally.

Technological Innovations

Future growth will be driven by technological innovations such as precision agriculture, digital farming and the increasing role of biotechnology in developing disease-resistant, high-yield varieties. The integration of smart technologies and AI-powered decision-making processes will streamline seed production and improve efficiency. Furthermore, breakthroughs in gene-editing technologies like CRISPR and genomics are expected to revolutionize the seed industry.

Sustainability Focus

With growing environmental concerns, the future of the vegetable seed industry will focus on sustainable practices. The development of climate-resilient seeds capable of withstanding extreme weather events is crucial. Additionally, the demand for organic vegetable seed varieties is increasing, pushing the industry to develop sustainable and eco-friendly seed solutions.

Private Sector Involvement

The private sector is expected to play an increasingly important role in the future of India's vegetable seed industry. As demand for hybrid and genetically modified seeds continues to grow, collaborations between seed companies and research institutions will foster innovation. Private sector investments in seed technology and distribution channels will help reach untapped rural markets.

Regulatory and Policy Changes

Future regulatory changes may focus on improving seed quality standards and addressing concerns regarding GM seeds. More robust policies for seed certification and distribution will help ensure the availability of high-quality seeds.

Key Drivers for Growth**Rising Food Demand**

India's growing population, coupled with increasing urbanization, will drive the demand for high-quality, nutritious vegetables. This presents a tremendous growth opportunity for the vegetable seed industry.

Shift to Hybrid Seeds

Farmers are increasingly adopting hybrid seeds due to their high yield, disease resistance and shorter growth cycles. The shift towards hybrid varieties will continue to drive the industry's growth.

Government Support and Initiatives

Government initiatives, such as subsidies and support for research and development, will continue to foster the growth of the vegetable seed industry. These programs will help improve the quality of seeds and make them accessible to smallholder farmers.

Adoption of Technology

The continued adoption of digital technologies in farming, including data analytics, sensors and automation, will streamline the vegetable seed industry, making it more efficient and cost-effective.

Conclusion

India's vegetable seed industry is poised for significant growth, driven by technological innovations, rising food demand and an increased focus on sustainability. While challenges such as price volatility, seed quality control and regulatory hurdles persist, the industry has immense potential to shape the future of Indian agriculture. To ensure continued growth, it is vital to address the challenges through improved policies, technology adoption and private sector involvement. The future of the vegetable seed industry looks promising, with increasing opportunities in both domestic and international markets.

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FINANCIAL INCLUSION: INDIA'S PATH TO SUSTAINABLE GROWTH IN 2026

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Introduction

In a nation as diverse and dynamic as India, bridging the gap between economic opportunity and everyday people has long been a challenge. Back in 2022, a groundbreaking study highlighted how financial inclusion—making basic banking services accessible to all—could supercharge sustainable development. Researchers analyzed data from 28 states and three union territories over 2018-2020, focusing on cooperative banks as a key driver. Their findings? A strong, positive link between expanding cooperative bank networks and India's progress toward the United Nations' Sustainable Development Goals (SDGs). By providing affordable loans, savings accounts, and other services to rural and low-income groups, these banks weren't just boosting wallets; they were fueling poverty reduction, gender equality, and environmental resilience.

Fast-forward to 2026, and that vision is evolving faster than ever. India's financial inclusion story has exploded, powered by digital innovations, government schemes, and a resilient cooperative sector. With the latest data showing remarkable leaps in banking access and digital payments, the country is not only sustaining its momentum but accelerating toward a more equitable future. Let's dive into the updates and see how this ties back to sustainable development.

The Rise of India's Financial Inclusion Index

One of the clearest signs of progress is the Reserve Bank of India's (RBI) Financial Inclusion Index (FI-Index), which measures access, usage, and quality of financial services on a scale of 0 to 100. In March 2025, the index hit 67, up from 64.2 the previous year—a 4.3% jump that reflects gains across all categories. Since its launch in 2021, the FI-Index has climbed 24.3%, underscoring the government's push for inclusive growth.

Financial Inclusion Index Score of India (2017-2025)

Year	FI-Index Score
2017	43.4
2018	49.7
2019	53.6
2020	60.8
2021	61.6
2022	64.1
2023	67.8
2024	64.2
2025	67.0
CAGR	5.59%

Source: Reserve Bank of India (2025)

This growth isn't just numbers on a page. It's driven by real-world initiatives like the Pradhan Mantri Jan Dhan Yojana (PMJDY), which has opened over 55.98 crore bank accounts by August 2025, with more than 55% held by women. As of early 2026, that figure has crossed 57 crore, with deposits nearing Rs 2.7 lakh crore. These zero-balance accounts come with perks like accident insurance and overdraft facilities, pulling millions out of the informal economy and into formal banking. Rural and semi-urban areas have seen the biggest boost, with 36.63 crore accounts opened there by March 2025.

But the real game-changer? Digital tools. The Unified Payments Interface (UPI) has turned smartphones into wallets, processing a staggering 172 billion transactions worth Rs 247 trillion in 2024 alone—a 46% increase from the prior year. By October 2024, UPI handled 16.58 billion transactions monthly, accounting for nearly half of global digital payments. In 2025, volumes surged further, with UPI dominating 80% of India's digital transactions. This isn't elite tech—it's for everyone, from street vendors to farmers, reducing cash dependency and cutting costs.

These strides echo the 2022 study's emphasis on cooperative banks but amplify it through the "JAM Trinity"—Jan Dhan accounts, Aadhaar IDs, and mobile connectivity. What once took decades now happens in years: India hit 80% financial inclusion 41 years ahead of schedule, thanks to this digital backbone.

Cooperative Banks: Still the Backbone, Now Stronger

The original research spotlighted cooperative banks as a proxy for financial inclusion, showing their branch networks directly lifted SDG scores by enabling credit for the poor. In 2026, these institutions remain vital, especially in rural India where commercial banks often fall short. Recent RBI measures have supercharged their role. Urban Cooperative Banks (UCBs) can now open branches up to 15% of their existing network annually, without prior approval, to expand reach. Housing loan limits have doubled to 25% of total advances, making homeownership more accessible. To boost doorstep services, over 12,624 Micro-ATMs have been distributed to dairy and fisheries cooperatives acting as "Bank Mitras" in Gujarat alone, with plans for nationwide rollout.

A simplified Aadhaar framework now lets cooperative banks offer Aadhaar-enabled payments, extending digital services to remote areas. RuPay Kisan Credit Cards are being issued to milk cooperative members, providing low-interest credit and transaction ease. These steps address the 2022 study's call for better governance and expansion, reducing non-performing assets (NPAs) to Rs 23,000 crore and fostering cautious revival. Cooperative banks are uniquely positioned for sustainable impact. They support local economies, from agriculture to small businesses, aligning with SDGs like zero hunger (SDG 2) and decent work (SDG 8). A 2025 study reaffirmed their role in rural financial inclusion, noting community-focused operations bridge gaps left by big banks.

Linking Financial Inclusion to Sustainable Development

The 2022 paper proved financial inclusion via cooperatives elevates SD levels, and 2026 data backs this up. India's global SDG Index score rose to 66.95 in 2025, landing the country at 99th out of 167 nations—its first top-100 entry. Domestically, NITI Aayog's SDG India Index hit 71 in 2023-24, up 14 points from 2018. Progress is fastest in East and South Asia, with India leading on goals like affordable energy (SDG 7) and sustainable cities (SDG 11). Financial inclusion directly fuels this. Digital payments have slashed poverty by enabling direct benefit transfers—over Rs 45,974 crore in Atal Pension Yojana corpus by April 2025. Women now hold 89% of bank accounts (up from 35% in 2011), closing gender gaps. UPI's rural penetration jumped to 65% by 2024, boosting economic

growth and reducing inequality (SDG 10). Yet challenges persist. Only 35% of global SDG targets are on track, and India lags in areas like climate action (SDG 13). Financial literacy remains key—campaigns like RBI's Centres for Financial Literacy have reached millions, but more is needed for full usage.

Looking Ahead: A Viksit Bharat by 2047?

As India eyes "Viksit Bharat" (Developed India) by 2047, financial inclusion is the engine. Cooperative banks, blended with digital giants like UPI, are creating resilient communities. Recent fintech analyses show a 10% rise in digital adoption lifts inclusion by 7-8%, with rural gains strongest. Global UPI expansion—to France, Malaysia, and beyond—positions India as a model for emerging economies.

The 2022 study was prescient: Stronger cooperative networks mean better SD. In 2026, with 107 Digital Banking Units and 13.55 lakh Bank Mitras, that vision is reality. But success demands ongoing reforms—tackling data privacy, cybersecurity, and urban-rural divides. If India keeps this pace, sustainable development won't just be a goal; it'll be the norm.

Conclusion: Charting a Sustainable Future through Inclusive Finance

As India marches toward its centennial independence in 2047, the synergy between financial inclusion and sustainable development stands as a cornerstone of national progress. The 2022 study on cooperative banks' role in advancing SDGs has proven prescient, with real-world metrics in 2026 underscoring transformative gains. The RBI's Financial Inclusion Index reaching 67 in March 2025 reflects deepened access, usage, and quality of services, driven by initiatives like PMJDY, which now boasts 57.71 crore accounts and deposits exceeding Rs 2.94 lakh crore as of February 2026. UPI's meteoric rise to 228 billion transactions worth Rs 300 lakh crore in 2025 alone has democratized payments, fueling economic resilience and reducing inequality.

Cooperative banks remain pivotal, bolstered by RBI reforms allowing Urban Cooperative Banks to expand branches and increase housing loan limits to 25% of advances, enhancing rural credit and governance. These efforts align with India's SDG Index score of 66.95 in 2025, securing a historic top-100 global ranking at 99th—progress fastest in East and South Asia on goals like clean energy and sustainable cities. Yet, challenges like financial literacy gaps and climate vulnerabilities persist. By sustaining digital momentum and cooperative strengthening, India can not only meet but exceed SDG targets, fostering a "Viksit Bharat" where prosperity is truly inclusive. The journey from exclusion to empowerment proves that finance, when accessible, is a powerful lever for sustainable growth.

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FISH PROCESSING: PRESERVING FRESHNESS FROM CATCH TO CONSUMER

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Abstract

Fish is one of the most nutritious and widely consumed food sources in the world. It provides high-quality proteins, essential fatty acids, vitamins, and minerals essential for human health. However, fish is highly perishable and begins to spoil soon after harvest. Therefore, proper handling and processing are necessary to maintain its quality and safety. Fish processing includes several operations, such as handling, cleaning, preservation, packaging, and distribution, that help extend the shelf life of fish products. Various traditional and modern preservation methods, such as chilling, freezing, drying, salting, smoking, and canning, are commonly used in the fisheries sector. In addition, the development of value-added fish products has increased the economic value of fish and provided convenient food options for consumers. This article highlights the importance of fish processing and describes the different techniques used to ensure that fish reaches consumers in a safe, nutritious, and high-quality form.

Introduction

Fish and fish-based products contribute significantly to global nutrition and food security. Fish is regarded as one of the most nutritious animal protein sources since it provides important amino acids, omega-3 fatty acids, vitamins, and minerals that are helpful to human health. Because of these nutritional benefits, fish consumption has exploded worldwide (Noreen *et al.*, 2025).

The benefits of its nutritional value, fish is extremely perishable. Biochemical processes and microbial activity start to deteriorate fish almost immediately after they are caught. If fish is not properly managed, its quality quickly deteriorates, resulting in economic losses and food safety problems (Speranza *et al.*, 2021).

Fish processing is a crucial part of the fishing industry. It includes plenty of processes that help preserve fish, increase its shelf life, and turn it into a variety of consumable products. Several processes, including handling, shipping, cleaning, preservation, packaging, and distribution, are involved from the time fish are harvested until they are placed on a consumer's plate. In addition to minimizing post-harvest losses, efficient fish processing raises the market value of fish products. Additionally, the seafood industry now has more potential due to the development of value-added products and advanced processing technology.

Importance of Fish Processing

Fish processing is essential to preserving the safety and quality of fish products. Fish decay quickly, so adequate processing methods are needed to slow down the enzymatic changes and microbial

growth that lead to deterioration. Fish processing makes it possible to keep and ship fish to far-off markets by extending their shelf life. Additionally, it minimizes post-harvest losses, particularly in developing nations, brought on by improper handling and insufficient preservation. Additionally, by generating employment and raising the value of fisheries products, fish processing promotes economic growth.

Handling and Transportation of Fish

To preserve freshness and quality, fish must be handled properly as rapidly as they are caught. Fish should be handled delicately to prevent physical damage that may accelerate spoilage, such as bruising or crushing. One of the best ways to maintain fish quality is rapid chilling. In order to lower the temperature, fish are typically placed in crushed ice shortly after harvest. Lower temperatures slow down microbial growth and enzymatic activities that cause spoilage (Wang & Zheng, 2025). Another vital component of transportation is keeping the cold chain maintained. Until they arrive at processing facilities or markets, fish are carried in refrigerated vehicles or insulated containers to maintain a low temperature.

Primary processing operation

To prepare fish for additional processing, several preliminary procedures are carried out when they arrive at the processing facility. Sorting, grading, washing, scaling, gutting, and filleting are some of these procedures. To ensure consistent processing and higher market value, distinct fish are sorted and graded according to species, size, and quality. Washing aids in removing slime, debris, and microbes from the fish's surface. Filleting separates the fish into boneless pieces for consumer convenience, while gutting removes the internal organs to stop bacteria and enzymes from causing spoilage. To guarantee food safety and preserve product quality, it is crucial to maintain appropriate cleanliness throughout all these processes.

Method of fish preservation

To retain product quality and increase the shelf life of fish, the fish processing industry uses a variety of preservation procedures. These preservation techniques help prevent spoilage caused by microbes, enzymes, and environmental factors because fish is extremely perishable. The type of fish, available facilities, and the demands of the market all influence the choice of preservation technique (Nateras-Ramírez *et al.*, 2026).

Chilling

One of the easiest and most popular ways to preserve fresh fish is by chilling. This method uses crushed ice to keep fish at a low temperature, often between 0 °C and 4 °C. The microbial activity and enzymatic activities that lead to spoilage are slowed down by the low temperature. Fish can be transported and sold in nearby areas since chilling helps preserve its flavor, texture, and freshness for a short period (Erikson *et al.*, 2021).

Freezing

Freezing is one of the most important preservation techniques used in fish processing. This technique considerably slows down enzymatic reactions and microbiological growth by freezing fish at a temperature below – 18 °C. Fish that is frozen retains its nutritional content, flavor, and texture for an extended period. In both domestic and international markets, frozen fish items such as fillets, shrimp, and entire fish are extensively traded. Frozen fish can be kept for several months without losing much of their quality if stored properly.

Drying

Fish are traditionally preserved by drying, which has been done for decades, particularly in rural and coastal areas. This process uses either mechanical or sun drying to remove moisture from fish. Lowering the water content helps prolong the product's shelf life by preventing the growth of microorganisms. Dried fish Products are lightweight, easy to store, and can be transported over long distances (Singh *et al.*, n.d.).

Smoking

Fish are exposed to smoke produced by burning wood or other natural materials in the preservation process known as smoking. The smoke deposits substances that inhibit microbial growth and aid in lowering the moisture content of fish. Smoking also gives the fish a distinctive flavor, color, and aroma that many consumers enjoy. Smoked fish products are valued for their distinct flavors and enjoyed in many cultures.

Canning

Fish are placed in airtight containers, such as metal cans, and then cooked to high temperatures to kill microorganisms in a modern preservation method called canning. The product is made safe for long-term storage and shelf-stable by this method. Tuna, sardine and mackerel are examples of canned fish products that can be kept at room temperature for extended periods of time without going bad. Additionally, canning makes it easier for consumers to use and carry seafood (Rout *et al.*, 2026).

Vacuum Packaging

Vacuum packaging involves removing air from the container before sealing the fish product. Many spoilage microorganisms grow more slowly when oxygen is removed. Fish products' flavor, texture, and freshness are all preserved via vacuum packaging. This method is commonly used for fresh, chilled, and smoked fish products in supermarkets and seafood markets (Siddiqui *et al.*, 2024).

Modified atmosphere packaging (MAP)

Modified atmosphere packaging (MAP) preserves perishable foods like seafood, meat, and produce by replacing atmospheric air with a tailored mixture of CO₂, nitrogen, and oxygen to inhibit bacterial growth, prevent oxidation, and extend shelf life significantly. MAP is widely used in the seafood industry to extend the shelf life of fresh fish and fish fillets while maintaining their quality and appearance (Czerwiński *et al.*, 2021).

Value addition in Fish processing

Value-added fish products have become more well-known in recent years as a result of shifting consumer tastes and the need for quick meals. Value addition is the process of turning raw fish into processed products that are easier to prepare and more appealing. Fish fillets, fish fingers, fish cutlets, fish pickles, fish sausages, and ready-to-eat or cook meals are a few examples of value-added fish products. These products raise fish's market value and give fish processors more income opportunities. Value addition also contributes to waste reduction and more effective use of fish resources.

Role of packaging and storage

Packaging is crucial to preserving the safety and quality of fish products. Fish that are packaged properly are adequately protected against physical harm, contamination, and moisture loss during storage and transportation. The seafood industry is progressively using modern packaging

techniques, including vacuum packaging and modified atmosphere packaging. By lowering oxygen levels and suppressing microbial growth, these methods aid in extending the shelf life of fish products. Proper storage conditions, including temperature control and hygienic handling, are essential to ensure the safety and quality of processed fish products.

Conclusion

Fish processing is an essential component of the fisheries industry, ensuring that fish captured from natural waters and aquaculture farms reach consumers in a safe and high-quality form. Fish is highly perishable; therefore, appropriate handling, preservation, and processing techniques are required to maintain freshness and prevent spoilage. Various preservation processes, such as chilling, freezing, drying, salting, smoking, and canning, help to extend the shelf life of fish and prevent post-harvest losses. Furthermore, the development of value-added fish products has expanded the economic potential of the fisheries sector. With the world's expanding demand for seafood, efficient and sustainable fish processing technologies are becoming increasingly important. By implementing enhanced processing technologies and maintaining appropriate good hygiene practices, the fisheries sector can ensure that customers have access to safe, nutritious, and high-quality fish products.

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FOLIAR NUTRITION IN PLANTS: A SMART WAY TO FEED CROPS

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Abstract

Foliar nutrition is an efficient technique of supplying essential nutrients directly to plant leaves to enhance growth and productivity. Unlike soil application, foliar feeding allows rapid absorption and immediate utilization of nutrients, especially under deficiency conditions or unfavorable soil environments. Nutrients penetrate the leaf surface through pathways such as cuticle, stomata, aqueous pores, and ectodesmata, followed by their translocation via xylem and phloem to different plant parts. The effectiveness of foliar application depends on factors like environmental conditions, spray composition, and plant characteristics. Key nutrients such as nitrogen, iron, phosphorus, and zinc exhibit specific absorption behaviors that influence their mobility within plants. Foliar feeding plays a crucial role in correcting micronutrient deficiencies, improving nutrient use efficiency, and supporting crop yield and quality, making it an important component of modern sustainable agricultural practices worldwide.

Keywords: Foliar nutrition, nutrient uptake, cuticle, stomata, crop productivity

Introduction

Plants require essential nutrients for proper growth, development, and yield production. Traditionally, nutrients are supplied through soil application, but this method often faces challenges such as nutrient loss, fixation, and slow availability. To overcome these limitations, foliar nutrition has been developed as an effective technique. In this method, nutrients are directly applied to plant leaves in the form of sprays. This allows plants to absorb nutrients quickly and efficiently. Foliar feeding is especially useful during critical growth stages and under nutrient deficiency conditions. It provides a rapid response compared to soil fertilization. Environmental factors like soil pH and moisture do not limit foliar absorption significantly. This method is widely used in modern agriculture to enhance productivity. It also helps improve nutrient use efficiency. Therefore, foliar nutrition plays an important role in sustainable crop management.

What is Foliar Nutrition?

Foliar nutrition refers to the application of nutrients directly onto plant leaves to supplement their nutritional requirements. These nutrients are usually sprayed in liquid form and absorbed through the leaf surface. It is not intended to replace soil fertilization but to complement it. Foliar feeding is particularly beneficial when root uptake is restricted due to unfavorable soil conditions. It provides an immediate supply of nutrients to plants. This method is commonly used to correct micronutrient deficiencies. It is also helpful during periods of high nutrient demand in plants. Farmers use foliar sprays to improve crop quality and yield. The efficiency of this method depends on the type of nutrient and plant species. Proper formulation and application techniques are essential for success. Overall, foliar nutrition is a quick and effective way to nourish plants.

How Do Leaves Absorb Nutrients?

Leaves have specialized structures that enable them to absorb nutrients from external sources. The primary barrier is the cuticle, which is a waxy layer covering the leaf surface. Despite being protective, the cuticle allows certain substances to penetrate, especially when hydrated. Stomata are small pores on the leaf surface that also facilitate nutrient entry. In addition, aqueous pores provide pathways for water-soluble substances. Ectodesmata act as microscopic channels connecting external solutions to internal tissues. Nutrients enter through these pathways and reach the epidermal cells. The efficiency of absorption depends on the size and charge of nutrient molecules. Environmental conditions such as humidity can enhance absorption. The leaf surface characteristics also influence uptake. Thus, leaves play an active role in nutrient absorption.

Mechanism of Foliar Nutrient Uptake

The mechanism of foliar nutrient uptake involves several sequential steps. First, the nutrient solution is deposited on the leaf surface, where it adheres through adsorption. Then, nutrients penetrate the cuticle or enter through stomata and pores. After penetration, they move into the internal tissues of the leaf. The nutrients are then absorbed into the cells and become part of metabolic processes. Following absorption, nutrients are translocated to different plant parts. This movement occurs through vascular tissues such as xylem and phloem. The efficiency of this process depends on the chemical nature of the nutrient. Factors like concentration and environmental conditions also influence uptake. Proper formulation improves penetration and absorption. Overall, this mechanism ensures effective utilization of foliar-applied nutrients.

Why is Foliar Feeding Important?

Foliar feeding is important because it provides a rapid and efficient way to supply nutrients to plants. It helps in quickly correcting nutrient deficiencies, especially micronutrients. This method ensures that nutrients are directly available to plant tissues. It reduces losses caused by leaching, volatilization, or soil fixation. Foliar feeding is particularly useful during critical growth stages such as flowering and fruiting. It enhances plant health and improves crop yield and quality. Farmers can use this method to address nutrient stress conditions effectively. It also allows precise nutrient application. Foliar sprays are economical and require smaller quantities of fertilizers. They improve overall nutrient use efficiency. Thus, foliar feeding is a valuable tool in modern agriculture.

Key Nutrients and Their Behavior

Different nutrients exhibit different behaviors when applied through foliar sprays. Nitrogen, especially in the form of urea, is easily absorbed due to its non-polar nature. It can quickly penetrate the cuticle and enter leaf tissues. Iron is absorbed as positively charged ions, attracted by the negatively charged leaf surface. Phosphorus absorption occurs after the electrical balance is maintained inside the tissue. Zinc requires chelating agents like nicotianamine for effective transport within the plant. The mobility of nutrients varies depending on their chemical properties. Some nutrients move easily through phloem, while others have limited mobility. Environmental factors also influence nutrient behavior. Proper formulation enhances nutrient uptake.

Factors Affecting Foliar Nutrition

Several factors influence the effectiveness of foliar nutrition in plants. Environmental conditions such as temperature and humidity play a major role in nutrient absorption. High humidity generally enhances nutrient uptake. The pH of the spray solution affects nutrient availability and stability. Leaf characteristics such as wax content and surface structure also influence absorption. The timing

of application is critical for achieving maximum efficiency. Nutrient concentration should be carefully maintained to avoid leaf damage. Wind and rainfall can affect spray retention on leaves. The stage of plant growth determines nutrient requirements. Proper spraying techniques ensure uniform distribution. Therefore, understanding these factors is essential for successful foliar feeding.

Pathways of Nutrient Entry Through Leaves

Pathway	Structure & Location	Mechanism of Entry	Type of Nutrients	Key Features	Limitations
Cuticle	Waxy outer covering of leaf (composed of cutin and wax layers)	Diffusion through lipophilic (non-polar) and hydrophilic pathways when hydrated	Urea, small neutral molecules, some ions	Acts as the main barrier but becomes permeable when moist; contains polar and non-polar regions	Thick cuticle reduces absorption; dry conditions limit penetration
Stomata	Small pores mainly on lower (abaxial) leaf surface controlled by guard cells	Entry through openings via mass flow or diffusion of solution	Dissolved nutrients, ions (Fe^{2+} , K^+ , NO_3^-)	Large pore size (3–12 μm) allows easy entry; important under high humidity	Opening and closing regulate entry; less effective in dry or hot conditions
Aqueous Pores	Tiny nano-sized pores in cuticular layer, often near trichomes and guard cells	Passive diffusion of water-soluble (hydrophilic) substances	Fe, P, micronutrients in ionic form	Allow rapid movement of small ions; size range ~0.45–1.18 nm	Only small molecules can pass; limited capacity
Ectodesmata	Microscopic channels in outer epidermal cell walls connecting external surface to protoplast	Polar transport pathway facilitating direct movement into cells	Polar nutrients, ions, metabolites	Provide direct pathway into living cells; important for selective transport	Less understood; limited number and distribution
Lenticels (in some plants)	Openings in woody stems and some leaves	Diffusion through loosely packed cells	Gases and some dissolved nutrients	Supplementary pathway in certain species	Minor role in foliar nutrition
Cuticular Cracks	Small breaks or imperfections in cuticle	Direct entry of solution into inner tissues	All types depending on size	Can enhance rapid absorption	Uncontrolled entry may cause toxicity or damage

Transport Inside the Plant

After absorption, nutrients are transported to different parts of the plant. The phloem plays a key role in transporting nutrients to growing regions, known as sinks. This process requires energy and is called symplastic movement. The xylem transports nutrients along with water through apoplastic movement. Transpiration and root pressure drive the movement in xylem. Nutrient mobility varies depending on their chemical nature. Some nutrients are easily redistributed, while others remain localized. Proper transport ensures balanced nutrient distribution in the plant. This process supports growth and development. Environmental conditions also affect nutrient transport. Efficient transport is essential for optimal plant performance.

Practical Applications

Foliar nutrition has wide applications in modern agriculture. It is commonly used to correct micronutrient deficiencies in crops. Farmers apply foliar sprays during critical growth stages to enhance productivity. It is also used in horticultural crops to improve quality and yield. Foliar feeding is effective in stress conditions such as drought or poor soil fertility. Advanced fertilizers like nano-fertilizers are applied through foliar methods. This technique reduces fertilizer wastage and improves efficiency. It is widely adopted in crops like wheat, maize, and vegetables. Proper management practices increase its effectiveness. Thus, foliar nutrition is an important tool in crop production.

Conclusion

Foliar nutrition is an efficient and practical method of supplying nutrients directly to plants. It ensures rapid absorption and quick response to nutrient deficiencies. This method improves nutrient use efficiency and supports plant growth. Although it cannot replace soil fertilization, it acts as an important supplement. Foliar feeding is especially useful under adverse soil conditions. It enhances crop yield and quality significantly. Proper understanding of mechanisms and factors improves its effectiveness. Farmers can use this method for sustainable agriculture. It also reduces environmental impact by minimizing nutrient losses. Therefore, foliar nutrition is a valuable approach in modern farming systems.

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FORENSIC ENTOMOLOGY: HOW INSECTS HELP TO SOLVE CRIMES

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Abstract

Forensic entomology is a specialized branch of forensic science that studies insects and other arthropods associated with decomposing remains to assist in legal investigations. Insects are often the earliest organisms to colonize a dead body, and their predictable life cycles provide valuable biological evidence for estimating the post-mortem interval (PMI), or the time since death. By identifying insect species and examining their developmental stages, forensic entomologists can reconstruct the timeline of decomposition and support criminal investigations. Key forensic insects include blowflies, flesh flies, carrion beetles, and houseflies, each of which arrives at different stages of decomposition and contributes unique information about the condition and environment of the body. Their life cycles from egg or larval stages to adult emergence are strongly influenced by environmental factors such as temperature, making them reliable indicators when combined with climatic data. Beyond estimating time of death, insect evidence can also help determine whether a body has been moved, detect the presence of drugs or toxins, and provide clues in cases of neglect or abuse. Historical and modern criminal cases demonstrate the practical value of forensic entomology in solving crimes and supporting court proceedings. Overall, the study of insects in forensic contexts highlights how these small organisms act as crucial biological witnesses, providing scientific evidence that aids investigators in uncovering the truth behind suspicious deaths.

Keywords: Forensic entomology, Post-mortem interval (PMI), Decomposition, Insect succession

Introduction

When most people think of crime investigations, they imagine fingerprints, DNA evidence, or surveillance footage. However, there is another powerful and often surprising source of evidence called insects. The scientific field that studies insects in relation to legal investigations is called Forensic entomology, and it plays a crucial role in helping investigators uncover the truth about suspicious deaths. Forensic entomology is the study of insects and other arthropods that are associated with decomposing remains in order to answer questions in legal cases. By analyzing the types of insects present on a body and their stages of development, scientists can estimate how long a person has been dead. This estimate is known as the post-mortem interval (PMI). Insects are often the first organisms to arrive at a dead body. Because their life cycles follow predictable patterns, they provide valuable biological clues that can help investigators reconstruct the timeline of a death.

1. Blowfly: *Lucilia sericata* Meigen (F: Calliphoridae, O:Diptera)

One of the most important insect groups in forensic investigations is the Blowfly (family *Calliphoridae*). Blowflies are usually the first insects to detect and colonize a dead body, sometimes within minutes. They lay eggs in natural openings such as the mouth, nose, eyes, or wounds. These eggs soon hatch into larvae, commonly known as Maggot. The larvae feed on the decomposing tissues and grow rapidly through several developmental stages.

Life cycle

1. Egg stage: Female lays about 150–250 eggs in wounds or body openings and eggs hatch within 12–24 hours.
2. Larval stage (Maggots): Pass through three instar stages and feed on decomposing tissue for 4–10 days.
3. Pupal stage: Larvae leave the body and form a hard brown pupa.
4. Adult stage: Adult fly emerges and starts a new cycle.
5. Total life cycle: about 2–3 weeks depending on temperature.

2. Flesh fly: *Sarcophaga carnaria* Meigen (F: Calliphoridae, O:Diptera)

Importance

- Often arrive soon after blowflies.
- They are attracted to decaying organic matter and corpses.
- Used to estimate time since death and environmental conditions.

Life cycle

1. Larvae deposited: Unlike blowflies, flesh flies usually deposit live larvae instead of eggs.
2. Larval stage: Maggots feed on decomposing tissue.
3. Pupal stage: Larvae migrate to soil or dry areas to pupate.
4. Adult fly: Adult emerges and continues reproduction.
5. Life cycle duration: 10–20 days depending on temperature.

3. Carrion beetle: *Necrophorus vespilloides* Herbst (F: Staphylinidae, O:Coleoptera)

Importance

- Appear during later stages of decomposition.
- Feed on decaying flesh and maggots.
- Useful in determining advanced decomposition stages.

Life cycle

1. Egg stage: Eggs laid in soil near carcass.
2. Larval stage: Larvae feed on carrion.
3. Pupal stage: Pupation occurs in soil.
4. Adult beetle: Adults emerge and continue feeding on carcasses.
5. Life cycle: 2–4 weeks depending on environmental conditions.

4. Housefly: *Musca domestica* Linnaeus (F: Muscidae, O:Diptera)

Importance

- Found in indoor death investigations.
- Lay eggs on decomposing organic matter and corpses.

Life cycle

1. Egg stage: Eggs laid on decaying material and hatch within 8–24 hours.
2. Larval stage: Maggots feed and grow through three larval stages.
3. Pupal stage: Larvae form a pupal case (puparium).
4. Adult stage: Adult fly emerges and begins reproduction.
5. Complete cycle: 7–10 days under warm conditions.

Summary of Forensic Insects and Their Role

Insect	Arrival Time	Role in Investigation
Blowfly	Minutes after death	Estimate early PMI
Flesh fly	Early stage	Confirms time since death
Carrion beetle	Later decomposition	Indicates advanced decay
Housefly	Indoor or later stages	Helps estimate PMI indoors

Importance in forensic investigations

- Usually the first insects to reach a dead body.
- They can arrive within minutes after death.
- Their larvae (maggots) feed on decomposing tissue and help determine time of death.

Each species arrives at different stages of decomposition, forming what scientists call an insect succession pattern.

Estimating Time of Death

Forensic entomologists carefully collect insect samples from a body and the surrounding environment. By identifying the species and measuring the developmental stage of the larvae, they can estimate the age of the insects.

For example:

1. Egg stage – just laid, indicating death occurred very recently.
2. Larval stages – growing maggots suggest a death that occurred hours or days earlier.
3. Pupal stage – indicates a longer period since death.

Temperature also plays a key role because insect development speeds up in warmer conditions. Scientists therefore consider weather records when estimating the post-mortem interval.

More Than Just Time of Death

Insects can reveal much more than the time of death. Forensic entomology may also help to determine:

- Whether a body has been **moved** from one location to another
- If **drugs or toxins** were present in the body (through analysis of insect tissues)
- Whether **neglect or abuse** occurred in cases involving living victims or animals

Thus, insects can serve as silent witnesses in criminal investigations.

Real-World Applications

Forensic entomology has been used in numerous criminal cases around the world. Courts often rely on expert testimony from forensic entomologists to support timelines of death. Their findings can confirm or challenge alibis, making this field an important part of modern forensic science. In addition, forensic entomology is used in wildlife crimes, food contamination cases, and even stored-product investigations.

Success Stories of Forensic Entomology in Criminal Investigations

1. Ancient China Case (First Recorded Use of Insect Evidence)

One of the earliest documented uses of forensic entomology was described in the book called “The Washing Away of Wrongs” by Chinese forensic scientist Song Ci in the 13th century. A farmer was murdered with a sickle in a Chinese village. Investigators asked all farmers to place their sickles on the ground. Although the weapon looked clean, flies gathered on one sickle because they were attracted to microscopic traces of blood. The owner of that sickle confessed to the crime. This case is considered the first recorded use of insects in forensic investigation.

2. The Jeffrey MacDonald Murder Case (USA, 1970): Famous International Cases

This case involved the murder of a woman and her two daughters. Forensic entomologist John D. Byrd analyzed blowfly larvae found at the crime scene. The developmental stage of the larvae helped determine the exact timeline of death. The insect evidence contradicted the suspect's story and supported the prosecution's timeline, contributing to the conviction.

3. "Eyeball Killer" Case (USA, 1992)

Serial killer Charles Albright murdered women in Texas. Forensic entomologist Neal Haskell studied insect activity on the victim's body. The analysis revealed when the body had been exposed and how long it had been decomposing. Entomological evidence helped reconstruct the timeline and contributed to Albright's conviction.

4. Hawaii Child Death Case (USA)

In another investigation studied by forensic entomologist Lee Goff, beetle larvae found on a buried child's body were examined. The development stage of beetle larvae showed that the child had died about 53 days before discovery. This contradicted the father's alibi and helped to obtain a confession.

Conclusion

Although they are small and often overlooked, insects provide critical clues in legal investigations. Through the study of insect life cycles and behaviour, Forensic entomology transforms these tiny organisms into valuable tools for justice. By carefully analysing insects found at crime scenes, scientists can help reconstruct events, estimate time of death, and ultimately assist in solving crimes. In the world of forensic science, insects are not just pests - they are key witnesses that never lie.

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FUNCTIONAL BEVERAGES: TYPES, HEALTH BENEFITS AND MARKET TRENDS

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Abstract

Functional beverages are gaining significant attention due to their ability to provide health benefits beyond basic nutrition. These beverages are formulated by incorporating bioactive compounds, vitamins, minerals, probiotics and other health-promoting ingredients aimed at improving overall well-being. The increasing consumer awareness of health, fitness and preventive nutrition has driven the rapid growth of the functional beverage market. Functional beverages can be broadly categorized into energy drinks, hydration or sports drinks and relaxation beverages, each designed to address specific physiological needs such as energy enhancement, electrolyte replenishment, stress reduction, and improved mental focus. In addition to performance benefits, many functional beverages contribute to cardiovascular health, digestive health and immune support through the inclusion of antioxidants, probiotics, prebiotics and plant-derived bioactive compounds. Probiotic and fiber-enriched beverages play an important role in maintaining gut microbiota balance, while vitamin and antioxidant-rich drinks help strengthen immune function and reduce the risk of chronic diseases. Recent market trends highlight a growing preference for beverages formulated with natural ingredients, clean-label formulations and personalized nutrition solutions tailored to individual health needs. However, concerns related to excessive sugar and caffeine content in certain products, particularly energy drinks, emphasize the importance of balanced formulation and responsible consumption. Despite these challenges, continuous innovation, increasing health consciousness and advancements in functional ingredient research are expected to further expand the functional beverage sector. Functional beverages therefore represent a promising segment of the modern food industry, offering convenient and health-oriented alternatives that support preventive healthcare and improved quality of life.

Keywords: Functional beverages, bioactive compounds, probiotics, health-promoting drinks, immune support, digestive health, sports and energy drinks, clean-label beverages.

Introduction

Functional beverages are drinks that offer additional health benefits beyond basic nutrition, such as energy-boosting, hydration, or relaxation. These beverages are formulated by incorporating bioactive compounds, vitamins, minerals and other health-promoting ingredients to address specific health needs. The market for functional beverages is rapidly expanding as consumers increasingly seek products that contribute to their overall well-being. This article will explore the various types of functional beverages, their health benefits and the trends driving their popularity.

Types of Functional Beverages

Energy Drinks

These beverages are designed to provide an energy boost, often containing caffeine, taurine and other stimulants. They are popular among athletes and individuals needing increased alertness and physical performance. However, the high sugar and caffeine content in many energy drinks necessitates careful formulation to avoid adverse effects (Swaroop *et al.*, 2017). Moreover, the potential health risks associated with energy drinks, particularly concerning cardiovascular and neurological effects, highlight the importance of responsible consumption and regulation (Higgins & Bhatti, 2017) (Costantino *et al.*, 2023).

Hydration and Sports Drinks

These drinks are formulated to replenish electrolytes and fluids lost during physical activity. They often contain minerals like sodium and potassium, which are essential for maintaining hydration and muscle function. Incorporating these essential minerals helps enhance performance and recovery, making hydration drinks vital for athletes and active individuals.

Relaxation Drink

These beverages aim to promote relaxation and reduce stress, often containing ingredients like chamomile, valerian root, or L-theanine, which are known for their calming effects. Incorporating these ingredients into relaxation drinks can enhance their effectiveness, making them popular choices for individuals seeking natural ways to manage stress and improve overall well-being.

Health Benefits

Cardiovascular Health

Functional beverages can contribute to heart health by incorporating ingredients with antihypertensive and hypolipidemic properties. For instance, fruit-based functional beverages often contain bioactive compounds that support cardiovascular health (Sahar *et al.*, 2019) (Puiggros *et al.*, n.d.). Additionally, the growing interest in functional beverages reflects a broader trend towards health and wellness, as consumers prioritize products that align with their lifestyle choices and health goals (Yıldırım *et al.*, 2024).

Digestive Health

Probiotic and prebiotic beverages are designed to improve gut health by promoting beneficial bacteria in the digestive system. These drinks can help prevent intestinal diseases and improve overall digestive function (Aron, 2019). Furthermore, the integration of dietary fiber in functional beverages can enhance their digestive health benefits by promoting regularity and supporting a healthy gut microbiota.

Immune Support

Many functional beverages include vitamins and antioxidants that enhance immune function, helping to protect against infections and diseases (Yilmaz-Akyuz *et al.*, 2019). The incorporation of bioactive ingredients in these beverages can significantly bolster immune response and overall health, making them a critical component of modern nutrition strategies (Gasmi *et al.*, 2023).

Market Trends and Consumer Preferences

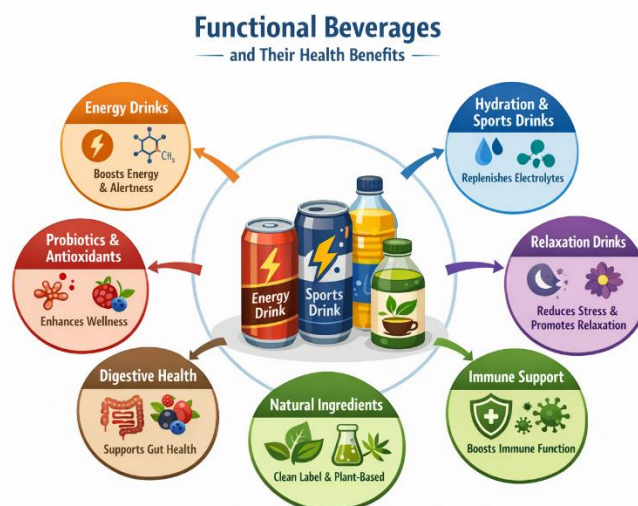


Figure 1: Health Benefits of Functional Beverages

Natural Ingredients

There is a growing consumer preference for beverages made with natural and local ingredients, free from artificial additives. This trend is driving the development of functional beverages that emphasize clean labels and natural health benefits (Musarra *et al.*, 2019). This shift reflects a broader movement towards transparency in food sourcing and a desire for products that promote health without compromising quality.

Customization and Personalization

Consumers are increasingly interested in beverages tailored to their specific health needs, such as energy enhancement, weight management, or mental focus. This demand is leading to more personalized functional beverage options (Yilmaz-Akyuz *et al.*, 2019). This demand for transparency is influencing manufacturers to innovate and create products that align with consumer values, ultimately shaping the future of the functional beverage market.

Regulatory Considerations

The development of functional beverages is subject to global regulations that ensure safety and efficacy. Manufacturers must navigate these regulations to successfully market their products (Sahar *et al.*, 2019). These regulations often focus on labeling, ingredient safety, and health claims, ensuring that consumers receive accurate information about the functional benefits of these beverages.

Conclusion

Functional beverages offer numerous health benefits, it is important to consider potential drawbacks. For instance, the high caffeine and sugar content in some energy drinks can lead to negative health effects if consumed excessively. Additionally, the efficacy of certain bioactive compounds in functional beverages may vary among individuals, necessitating further research to optimize formulations for diverse consumer needs. Despite these challenges, the functional beverage market continues to grow, driven by consumer demand for health-promoting products.

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GENOTYPE ENVIRONMENT INTERACTION ($G \times E$) IN CROP IMPROVEMENT

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Abstract

Crop performance is dictated by the complex interplay between genetics and environmental factors, represented by the equation $P = G + E + (G \times E)$. This interaction ($G \times E$) occurs when genotypes respond inconsistently across different locations or seasons, complicating the selection of high-yielding, stable varieties. Environments are categorized into predictable (soil, day length) and unpredictable (rainfall, temperature) factors. To evaluate stability and adaptability, breeders utilize biometrical models like Eberhart and Russell, which measures mean yield and regression coefficients, and advanced tools like AMMI and GGE biplots. Ultimately, understanding these interactions is essential for developing resilient crops that maintain productivity across diverse agricultural landscapes.

Introduction

The success of modern agriculture relies heavily on the ability of plant breeders to develop crop varieties that not only produce high yields but do so consistently across various locations and seasons. However, the performance of a crop is rarely a result of its genetics alone. It is the complex interplay between a plant's genetic blueprint and the world it grows in; known as Genotype $\times$ Environment Interaction ($G \times E$) that ultimately determines the final harvest.

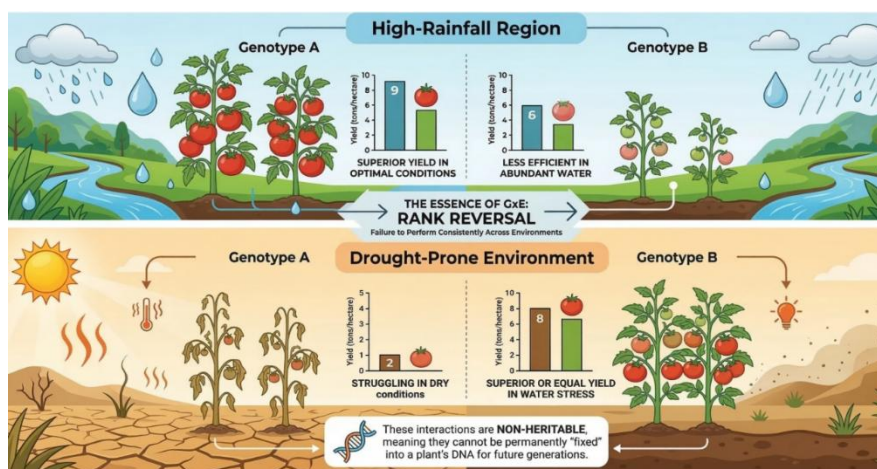
Genotype (G): This refers to the specific genetic makeup of an individual organism. It is the internal "instruction manual" inherited from parent plants.

Environment (E): This is the sum total of all physical, chemical, and biological factors surrounding an individual, excluding its own genotype. It encompasses everything from the soil pH to the daily temperature and rainfall.

Phenotype (P): The phenotype is the set of observable physical traits of a plant, such as its height, leaf shape, or grain yield. The relationship between these components is often expressed by the fundamental equation: $P = G + E + (G \times E)$. This indicates that a plant's observable performance (P) is the result of its genetics, the environment it grows in, and the specific way that genotype reacts to that environment.

Defining genotype $\times$ environment interaction

$G \times E$ interaction occurs when genotypes respond differently across a range of environments. In simpler terms, the relative ranking of varieties changes depending on where they are grown.



Classification of environmental factors

The environment is not a single static entity but a collection of variables that can be classified based on their predictability and scale:

1. Predictable vs. unpredictable factors

Predictable factors: These are more or less permanent features, such as soil type, day length (photoperiod), and general climate determined by latitude and longitude. They also include controllable management practices like fertilizer doses, planting dates, and irrigation schedules.

Unpredictable factors: these are fluctuating variables that are not under human control, such as annual rainfall, sudden temperature spikes, and variations in relative humidity.

2. Macro vs. micro environments

Macro environment: Refers to variables with large, easily recognizable effects on a crop, often spanning entire regions or seasons. These are largely influenced by predictable factors and human management.

Micro environment: This is the specific environment of a single plant or genotype compared to another growing in the same field at the same time. These effects are subtle, governed by unpredictable factors, and are not easily recognizable.

Adaptability and stability in plant breeding

In crop improvement, breeders select plants based on their phenotype. However, the effectiveness of this selection depends on how much of that phenotype is actually due to the genotype rather than temporary environmental boosts. This leads to two critical goals:

Adaptation: The fitness of a genotype in a specific environment, favoring traits necessary for survival.

Adaptability: The ability of a genotype to perform stably over a wide range of environments, favoring traits that drive high productivity.

Stability: A stable genotype maintains constant performance regardless of changes in environmental conditions.

Biometrical models for stability analysis

To accurately rank varieties for stability, breeders use various mathematical models. If initial analysis of variance (ANOVA) shows that the $G \times E$ interaction is significant, one of the following models is typically employed:

1. Finlay and Wilkinson Model (1963)

This model was the first systematic approach to analyze phenotypic stability over different locations. It measures mean performance and a regression coefficient (b):

b = 1: Average stability.

b > 1: Below average stability (variety is sensitive to environmental changes).

b < 1: Above average stability (variety is resistant to environmental changes).

b = 0: Absolute stability.

2. Eberhart and Russell Model (1966)

This is the most popular model because it is relatively simple and inexpensive. It adds a third parameter: the deviation from regression (s^2_d). According to this model, an ideal stable variety should have a high mean yield, a regression coefficient of unity ($b=1$), and minimal deviation from the regression line ($s^2_d=0$).

3. Perkins and Jinks Model (1968)

This approach is more complex, as it tries to analyze $G \times E$ in terms of specific gene actions like additive, dominance, and epistatic effects. While it provides independent estimations of mean performance and environmental index, it is more difficult and expensive to implement.

4. Freeman and Perkins Model (1971)

Similar to the Eberhart and Russell model, it divides total variance into genotypes, environments, and $G \times E$. However, it is considered more expensive and requires more experimental area.

Advanced tools: AMMI and GGE biplots

Modern breeders often use the Additive Main Effects and Multiplicative Interaction (AMMI) model. This model combines standard ANOVA with Principal Component Analysis (PCA) to extract patterns of $G \times E$ that would otherwise be missed.

Conclusion

As climate change continues to impact agriculture through shifting temperatures and erratic rainfall, understanding $G \times E$ interaction has never been more vital. By using stability analysis and biometrical models, scientists can reduce the risk of yield loss and select the best possible cultivars for specific target regions, ensuring food security in an unpredictable world.

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GLUTATHIONE: THE HIDDEN SHIELD HELPING PLANTS SURVIVE STRESS

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Abstract

Glutathione is a vital antioxidant molecule that plays a central role in protecting plants against various abiotic stresses such as drought, salinity, extreme temperatures, and toxic metals. It is a low molecular weight thiol compound that maintains cellular redox balance and detoxifies reactive oxygen species generated under stress conditions. Glutathione exists in reduced (GSH) and oxidized (GSSG) forms, and their balance is crucial for normal cellular functioning. It participates in important processes such as signal transduction, enzyme activation, and stress response regulation. Under stress conditions, increased glutathione levels enhance plant tolerance by stabilizing membranes, improving water relations, and supporting antioxidant defense systems. Additionally, it contributes to metal detoxification through phytochelatin synthesis. Thus, glutathione is an essential component in improving plant resilience and productivity under adverse environmental conditions.

Keywords: Glutathione, abiotic stress, antioxidant, ROS detoxification, plant tolerance

Introduction

Plants are constantly exposed to various environmental stresses such as drought, salinity, extreme temperatures, and toxic metals. These stresses negatively affect plant growth, development, and productivity. To survive under such conditions, plants have developed complex defense mechanisms. One of the most important components of this defense system is glutathione, a small but powerful antioxidant molecule. Glutathione plays a central role in maintaining cellular balance and protecting plant cells from oxidative damage. It helps in detoxifying harmful reactive oxygen species produced during stress conditions. The importance of glutathione in plant physiology has gained significant attention in recent years. It is considered a key molecule in stress tolerance. Understanding its function can help improve crop resilience. Thus, glutathione is essential for plant survival under adverse conditions.

Biochemical Nature of Glutathione

Glutathione is a low molecular weight, water-soluble thiol compound composed of three amino acids: glutamate, cysteine, and glycine. It is commonly represented as GSH in its reduced form and GSSG in its oxidized form. The presence of a sulfhydryl (–SH) group makes it highly reactive and functionally important. Glutathione is widely distributed in various plant tissues and cellular compartments. It plays a crucial role in maintaining the redox balance within cells. The conversion between GSH and GSSG is a key indicator of cellular stress status. Enzymes like glutathione reductase and glutathione peroxidase regulate this balance. Its water-soluble nature allows easy movement within the plant system. Glutathione also interacts with other biomolecules. This unique biochemical nature makes it a vital antioxidant in plants.

Biosynthesis of Glutathione

Glutathione is synthesized in plants through a two-step enzymatic process. The first step involves the formation of γ -glutamylcysteine from glutamate and cysteine, catalyzed by the enzyme γ -glutamylcysteine synthetase. In the second step, glycine is added to form glutathione, catalyzed by glutathione synthetase. This biosynthesis occurs mainly in chloroplasts and cytosol. The availability of cysteine is a limiting factor in glutathione production. Environmental stresses often trigger an increase in glutathione synthesis. The regulation of biosynthesis is controlled at both genetic and enzymatic levels. Proper synthesis is essential for maintaining cellular redox homeostasis. Increased glutathione levels enhance plant tolerance to stress. Thus, biosynthesis plays a key role in plant defense mechanisms.

Compartmentation of Glutathione

Glutathione is distributed across different cellular compartments such as chloroplasts, mitochondria, cytosol, and nucleus. Each compartment maintains its own pool of glutathione to regulate local redox balance. The chloroplast contains a high concentration of glutathione due to its role in photosynthesis and ROS production. In mitochondria, glutathione helps protect respiratory processes from oxidative damage. The cytosol acts as a central hub for glutathione metabolism and transport. Glutathione is also transported through the phloem to different plant parts. This compartmentalization ensures efficient functioning under stress. It allows localized defense responses in cells. Proper distribution is essential for plant survival. Thus, compartmentation plays a key role in glutathione function.

Role of Glutathione in Plants

Glutathione performs multiple functions in plant systems beyond stress tolerance. It acts as a major antioxidant, protecting cells from oxidative damage. It is involved in detoxification of harmful substances and xenobiotics. Glutathione also plays a role in cell division and growth regulation. It participates in signal transduction pathways under stress conditions. It helps maintain cellular redox balance, which is essential for normal metabolic processes. Glutathione is involved in sulfur metabolism and transport. It also supports enzyme activation and protein synthesis. Its presence is crucial for proper functioning of cellular processes. Overall, glutathione is a multifunctional molecule in plant physiology.

Glutathione under Drought Stress

Drought stress leads to water deficiency, causing physiological and biochemical changes in plants. Under such conditions, glutathione levels increase to protect cells from oxidative damage. It helps maintain leaf water content and reduces dehydration effects. Glutathione is involved in regulating stomatal closure through interaction with plant hormones like abscisic acid. It enhances root growth and cell division, helping plants access deeper water sources. It also activates antioxidant enzymes that neutralize reactive oxygen species. Increased glutathione levels improve osmotic balance in plants. Studies have shown higher glutathione content in drought-tolerant plants. It plays a key role in stress signaling pathways. Therefore, glutathione is crucial for drought stress adaptation.

Glutathione under Salinity Stress

Salinity stress causes ionic imbalance and toxicity in plant cells. Glutathione helps in reducing the harmful effects of excess sodium ions. It stabilizes cell membranes and maintains their integrity. Glutathione reduces passive sodium influx into cells, improving salt tolerance. It also protects photosynthetic machinery from damage. The molecule enhances the activity of antioxidant

enzymes that combat oxidative stress. Glutathione improves water relations and nutrient uptake under saline conditions. It also regulates hormone signaling pathways involved in stress responses. Increased glutathione levels are associated with better plant growth under salinity. Thus, it plays a significant role in salt stress tolerance.

Glutathione under Temperature Stress

Extreme temperatures, both high and low, can cause severe damage to plant cells. High temperatures increase the production of reactive oxygen species, leading to oxidative stress. Glutathione helps in scavenging these harmful molecules and protecting cellular components. It maintains membrane stability and prevents lipid peroxidation. Under cold stress, glutathione enhances enzyme activities and metabolic processes. It also supports the synthesis of protective proteins. Increased glutathione levels improve plant tolerance to temperature fluctuations. It works in coordination with other antioxidants in the AsA-GSH cycle. This cycle plays a vital role in stress defense. Therefore, glutathione is essential for temperature stress management.

Glutathione under Toxic Metal Stress

Toxic metals such as cadmium, lead, and mercury pose serious threats to plant health. Glutathione plays a key role in detoxifying these metals. It binds with metal ions through its sulfhydryl group, forming stable complexes. These complexes are further converted into phytochelatins, which help in sequestration of metals. This process prevents metal toxicity in plant cells. Glutathione also reduces oxidative damage caused by metal stress. It enhances the activity of detoxifying enzymes. Plants with higher glutathione levels show better tolerance to heavy metals. It also protects cellular structures from damage. Thus, glutathione is vital for metal stress resistance.

Stress Type	Effect on Plants	Role of Glutathione (GSH)	Outcome in Plants
Drought Stress	Water deficit, leaf rolling, reduced growth	Maintains leaf water content, regulates stomatal closure, enhances antioxidant activity	Improved drought tolerance and growth
Salinity Stress	Ion toxicity (Na ⁺ , Cl ⁻), osmotic imbalance	Stabilizes membranes, reduces Na ⁺ influx, enhances antioxidant defense	Better salt tolerance and cell protection
High Temperature	Oxidative damage, protein denaturation	Scavenges ROS, protects membranes, increases GSH/GSSG ratio	Reduced heat damage and improved survival
Low Temperature	Reduced metabolism, membrane damage	Enhances enzyme activity, supports protective protein synthesis	Improved cold tolerance
Toxic Metal Stress	Heavy metal toxicity (Cd, Pb, Hg)	Binds metals via -SH group, forms phytochelatins, detoxifies harmful ions	Reduced toxicity and improved plant health
Oxidative Stress	Excess reactive oxygen species (ROS)	Acts as major antioxidant, participates in AsA-GSH cycle	Protection from cellular damage

Conclusion

Glutathione is a central molecule in plant defense against various abiotic stresses. It plays a crucial role in maintaining redox balance and protecting cells from oxidative damage. Its involvement in

detoxification, signaling, and metabolic regulation highlights its importance. Glutathione enhances plant tolerance to drought, salinity, temperature, and toxic metal stresses. It also supports growth and development under adverse conditions. Despite its importance, the exact mechanisms of its regulation are not fully understood. Further research is needed to explore its genetic and molecular aspects. Advances in biotechnology can help utilize glutathione for improving crop resilience. Overall, glutathione is a key component in sustainable agriculture.

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GUARDING THE BLUE ECONOMY: ROLE OF NSPAAD IN AQUATIC DISEASE CONTROL

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Introduction

Fish is one of the most affordable and nutritious sources of high-quality protein, essential fatty acids, and minerals. In a country like India, where food security and livelihoods are closely linked to natural resources, fisheries play a vital role. India ranks third globally in fish and aquaculture production, with an estimated output of 17.54 million tonnes (2022–23) and exports worth nearly ₹63,969 crore. Fish production in India has shown an impressive average annual growth of about 8% during the last four decades. The country is the third-largest fish-producing country and one of the largest exporters of shrimps. However, a recent study indicates huge economic losses due to shrimp diseases. This highlights the significant threat of diseases to the growth of aquaculture. Early detection is considered crucial for controlling the spread of diseases. Disease surveillance in aquaculture involves systematically watching, collecting, testing, and analyzing data on fish and shrimp health to spot diseases early, track outbreaks, and guide control measures using farmer reports (passive) for quick alerts and regular pond sampling/lab tests (active) for hidden threats. It's essential because early detection stops small problems from wiping out ponds (like Haryana's 54% bacterial hits), cuts massive losses (10-15% production costs), prevents export bans from viruses like WSSV/TiLV, supports clean certification, and builds data for smarter biosecurity in crowded carp/shrimp farms keeping your operation profitable and sustainable.

What is NSPAAD?

The National Surveillance Programme for Aquatic Animal Diseases (NSPAAD) is a nationwide initiative launched by the Government of India to monitor, detect, and control diseases affecting aquatic animals such as fish and shrimp. It involves a network of laboratories, research institutes, and fisheries departments that collect and analyze disease-related data, provide early warning of outbreaks, and offer scientific advice to farmers. The programme focuses on strengthening both passive (farmer-based) and active (expert-led) surveillance systems to reduce economic losses, prevent the spread of pathogens, and ensure sustainable growth of the aquaculture sector in India. The Department of Animal Husbandry, Dairying and Fisheries, Ministry of Agriculture, Government of India, took a visionary step in the year 2013 by approving a National Surveillance Programme for Aquatic Animal Diseases (NSPAAD) with funding through the National Fisheries Development Board, Hyderabad. This programme was initiated in 14 states and later expanded to cover 19 states and 3 Union Territories. The programme involved 31 NSPAAD Collaborating Centres and was coordinated by ICAR-National Bureau of Fish Genetic Resources. Since 2022, Phase 2 of NSPAAD has been implemented pan-India with the involvement of 32 collaborating centres, including the ICAR Fisheries Research Institutes and the Colleges of Fisheries. Besides, State Fisheries Departments and Marine Products Export Development Authority have been included to strengthen the programme, and it is funded under Pradhan Mantri Matsya Sampada Yojana by the Department of Fisheries, Government of India.

Purposes of Disease Surveillance

The primary objectives of disease surveillance are to assess disease prevalence, identify active cases, prove disease-free status, and enable early detection of emerging or novel diseases. The first two goals focus on monitoring diseases already present within a country, while the latter two target surveillance for diseases not yet reported there. Further details on these surveillance purposes are outlined below.

Measuring Level of Disease

The most common indicators of disease levels are prevalence and incidence. A single measurement reveals the disease burden in a population at a specific moment. Integrating surveillance data with economic impact assessments allows ranking diseases by severity, helping prioritize control efforts for those causing the greatest losses. Multiple measurements over time and space further reveal patterns in disease distribution—spatial analysis across regions identifies key risk factors driving outbreaks.

Early Detection of Disease Incursions

Every country needs strong surveillance to spot new disease outbreaks fast. Quick detection of incoming diseases is vital for successful control, as early action dramatically cuts costs and boosts eradication success the longer the delay, the harder and pricier it gets to contain the spread.

Demonstrating Freedom from Disease

Absence of disease in a country offers key advantages, such as unrestricted animal exports, but authorities must have solid proof of true disease freedom to claim these benefits. Disease-free status also justifies halting control measures, while allowing importing nations to block shipments from infected regions. Detecting even one infected animal confirms disease presence, whereas proving freedom relies on probabilistic evidence—assessing the likelihood that infection is genuinely absent.

Types of Surveillance System

Surveillance systems are often divided into two primary categories: passive and active surveillance.

A. Passive Surveillance

Passive surveillance occurs when farmers conduct initial observations and report suspected disease outbreaks, often seeking expert advice for on-farm diagnosis and treatment—the farmer being the first data collector. Their primary motivation is resolving immediate health issues, with surveillance serving as a secondary benefit. Farmer-based reporting represents the most widespread and vital surveillance method globally, offering broad population coverage and enabling early detection of novel diseases through recognition of any clinical signs.

B. Active Surveillance

Active surveillance occurs when an aquatic animal health expert conducts the initial examination without prior farmer notification of a disease issue, with surveillance as the primary objective. This typically involves structured surveys designed to gather targeted data for specific questions, including sampling plans, appropriate sample sizes, and bias-free analysis. Unlike passive systems, active surveillance detects subclinical infections, delivers high-quality focused information, and meets precise survey requirements. Active surveillance, also called representative survey, accurately measures disease levels and supports planning/monitoring of control programs. These surveys provide unbiased disease prevalence data, enabling comparisons across regions and time

periods. However, they prove less effective for early detection of new outbreaks or case-finding in control efforts, being costly, logistically complex, limited to small population samples, time-bound rather than continuous. Recent adoption of risk assessment in active surveillance has spawned efficient risk-based surveillance approaches.

Salient Achievements of NSPAAD

The programme has been successful in strengthening the passive surveillance system in the country. Till 2024, about 850 awareness programmes involving over forty thousand fish farmers have been organized. Besides, to strengthen the diagnostic capability of officers of State Fisheries Departments, about 125 training programmes involving three thousand officers have been organized whereby the officers are sensitized about major diseases and their diagnosis as well as management measures to minimize the losses. Under the passive disease surveillance, over 4000 disease cases have been investigated, and scientific advice is being provided to the farmers to manage the diseases in order to minimize the losses due to aquatic animal diseases. Over the years, there has been an increase in the disease reporting by the farmers following the implementation of the NSPAAD project.

Table 1 New aquatic animal diseases reported for the first time in India under NSPAAD till 2024

Sl. No.	Disease Name	Pathogen	Host
1	Goldfish haematopoietic necrosis disease	Cyprinid herpesvirus 2 (CyHV-2)	Goldfish
2	Koi sleepy disease	Carp edema virus (CEV)	Koi carp
3	Tilapia lake virus disease	Tilapia lake virus (TiLV)	Tilapia
4	Infection with Red Sea bream iridovirus	Red Sea bream iridovirus (RSIV)	Sea bass
5	Epitheliocystis	<i>Candidatus Actinochlamydia pangasiae</i>	Striped catfish
6	Infection with infectious myonecrosis virus	Infectious myonecrosis virus (IMNV)	Pacific white shrimp
7	Hepatopancreatic microsporidiosis	Enterocytozoon hepatopenaei (EHP)	Pacific white shrimp
8	Infection with rhabdovirus	Rhabdovirus	Snakehead
9	Infection with mud crab reovirus	Mud crab reovirus (MCRV)	Mud crab
10	Infection with tilapia parvovirus	Tilapia parvovirus (TiPV)	Tilapia
11	Infection with Wenzhou shrimp virus 8	Wenzhou shrimp virus 8 (WzSV8)	Pacific white shrimp
12	Infection with <i>Macrobrachium rosenbergii</i> Golda virus	Mr. Golda virus (MrGV)	Freshwater prawn
13	Bacillary necrosis of pangasius	<i>Edwardsiella ictaluri</i>	Pangas (Pangasius)

Importantly, NSPAAD has helped to dispel rumours of acute hepatopancreatic necrosis disease (AHPND), a WOA-listed disease, from the country. The disease was first reported in China in 2009. Subsequently, the disease had spread to Thailand by 2012, at a time when the country was at the top position as the major exporter of shrimp. The disease had a devastating effect on the shrimp industry in Thailand where it resulted in a 65% decrease in shrimp production within a year. There were speculations about the occurrence of AHPND in India in 2013. Hence, an emergency response team was constituted under NSPAAD, which carried out targeted surveillance to determine the status of the disease. AHPND was not detected in any of the samples. Subsequently in 2017, following reports of AHPND in three bordering districts of a neighbouring country, targeted active surveillance was undertaken in bordering districts of West Bengal, and all the screened samples were found to be negative for *Vibrio parahaemolyticus* AHPND strain. Now, India has the evidence to be considered free of AHPND.

Conclusion

The rapid growth of aquaculture in India has brought immense opportunities for food security, employment, and export earnings, but it has also increased the vulnerability of the sector to disease outbreaks. In this context, the National Surveillance Programme for Aquatic Animal Diseases has emerged as a crucial safeguard for the country's blue economy. By strengthening both passive and active surveillance systems, enhancing diagnostic capacity, promoting farmer awareness, and enabling early detection of emerging pathogens, NSPAAD has significantly reduced the risks associated with aquatic diseases. Its achievements—ranging from the identification of new diseases to establishing disease-free status for major pathogens—demonstrate its effectiveness as a national disease monitoring framework. Ultimately, NSPAAD not only protects farmers from economic losses but also ensures sustainable aquaculture development, strengthens export credibility, and secures the future of India's fisheries sector.

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HARVEST OF GLORY, SEEDS OF CONCERN: REVISITING AGRICULTURAL RESEARCH IN INDIA

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The Architect of Survival

The story of modern India is inseparable from the story of its soil. In the mid-1960s, India stood at a precarious crossroads, described by international observers as a "ship-to-mouth" economy, tethered to the whims of foreign food aid. The subsequent metamorphosis; the Green Revolution was not merely a policy success; it was a scientific triumph. Led by the visionary synergy of scientists, policymakers, and farmers, the nation achieved what many thought impossible: absolute food-grain self-sufficiency. For decades, the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs) were the crown jewels of national development. They were the "Glorious" architects of a transformation that saved millions from hunger. However, as we approach the second quarter of the 21st century, that luster is fading. Today, the institutional framework that once led the world is navigating "Challenging Times," marked by fiscal stagnation, a dangerous obsession with short-term "management" over fundamental science, and a burgeoning dependency on imports for essential nutrition.

The Cereal Bias and the "Yellow" Neglect

The "Glorious Period" was primarily a "Cereal Revolution." By focusing on high-yielding varieties of wheat and rice, India secured its caloric base. However, this success created a structural imbalance that haunts us today. While wheat and rice received the lion's share of irrigation, minimum support prices (MSP), and research funding, pulses and oilseeds were relegated to the "marginal" sidelines. Oilseeds—the source of our essential fats—and pulses—our primary protein source—are predominantly grown in rainfed, semi-arid regions. Because these crops were not the focus of the initial technological leap, their productivity has been stagnated. India is now the world's largest importer of edible oils, a vulnerability that mirrors our energy dependence. We have achieved "food security" in terms of calories, but we have failed to achieve "nutritional security"—the visionary agricultural scientist, Prof. Chittaranjan Kole has been embarking upon since 2013 on various national and international platforms!

The Fiscal Retreat: Science on a Shoestring

The most immediate cause of the current "Challenging Times" is a palpable retreat in public funding. Science cannot thrive in an environment of fiscal uncertainty.

- **Stagnant Allocations:** In real terms, the budget for the Department of Agricultural Research and Education (DARE) has failed to keep pace with inflation or the growing complexity of climate-driven challenges. When research budgets are tight, the first casualty is "Long-Term Research" the 10 to 15 years breeding cycles required to develop truly resilient crop varieties.

- **The GDP Gap:** While global leaders in agriculture invest 2% to 3% of their agricultural GDP into R&D, India lingers below 0.7%. This underinvestment forces our premier institutions into "maintenance mode," where the majority of funds are consumed by establishment costs and salaries, leaving a pittance for actual laboratory innovation or field trials.
- **The Human Capital Crisis:** An aging scientific cadre and a shift toward short-term contractual hiring (Young Professionals and SRFs) have disrupted the mentorship and continuity essential for scientific breakthroughs. A scientist on a one-year contract cannot be expected to commit to a decade-long project to decode drought-resistance genes.

The Management Trap: Why AI is Not a Substitute for Science

In the search for "quick fixes," policy has increasingly pivoted toward "Digital Agriculture." This is what we call the "Management Trap." There is a growing, dangerous assumption that Artificial Intelligence (AI), drones, and big data can replace the fundamental biological sciences of the farm.

AI is an exceptional tool for optimization. It can tell a farmer precisely when to apply fertilizer or predict a pest outbreak with high accuracy. However, AI is a "messenger," not the "message." AI cannot biologically engineer a mustard seed that yields 30% more oil, nor can it create a chickpea variety that fixes more nitrogen in degraded soils. These are biological problems that require biological solutions.

By prioritizing the "dashboard" (management tools) over the "engine" (basic research), we are effectively managing a decline rather than fueling a resurgence. If the underlying genetic potential of our seeds remains stagnant, no amount of digital precision can force them to yield more. We must use AI to assist the scientist, not to excuse the lack of investment in the scientist.

The Export Paradox and Strategic Vulnerability

A major policy shift in recent years has been the push for "High-Value Exports"—Basmati rice, grapes, mangoes, and spices. While this brings in foreign exchange, it creates a "Strategic Paradox." We are exporting water-intensive, high-value crops while simultaneously spending billions of dollars to import basic necessities like palm and soybean oil.

This dependence on other countries for 60% of our edible oil is a ticking time bomb. Recent global disruptions in the energy sector—specifically the volatility in cooking gas (LPG) prices—serve as a grim preview of what could happen to our food plates. When global supply chains tighten due to conflict or climate catastrophes, the "import-led security" model collapses. A nation that cannot produce its own cooking oil or protein is not truly sovereign; it is merely a customer of global volatility.

Structural Decay and the "Lab-to-Land" Gap

Even when our scientists do achieve breakthroughs, the "Lab-to-Land" bridge is crumbling. The extension services, once the pride of the State Agricultural Universities, have weakened.

- **Fragmented Holdings:** As farm sizes shrink, technology that works on a 100-acre research station often fails on a half-acre marginal plot.
- **Weak Linkages:** There is a growing disconnect between the researcher in the lab and the farmer in the field. Without a robust, publicly-funded extension system, even the best seeds remain locked in the breeder's cupboard.
- **Private Sector Bias:** Private investment naturally flows toward high-margin hybrid seeds for cash crops, leaving "public good" crops like pulses and minor millets—the crops of the poor—in a state of technological neglect.

The Way Forward: Reclaiming the Glory

To move from these challenging times back to a period of glory, we must reimagine the role of the agricultural scientist in the national narrative.

- **Financial Atmanirbharta:** We must commit to a "National Agricultural Research Fund" that is insulated from annual budget fluctuations, aiming for a minimum of 1% of agricultural GDP.
- **Mission-Mode Focus on Oilseeds:** We need a "Yellow Revolution 2.0." This must be a science-led mission, focusing on the genetic improvement of mustard, groundnut, and soybean, specifically tailored for the rainfed frontiers of Central and Western India.
- **Empowering the Scientist:** We must reduce the administrative burden on our researchers. A scientist's value is measured in the field and the lab, not in the number of files they process. We must restore the prestige of the agricultural profession to attract the brightest young minds back to the soil.

Call to Action: A Manifesto for National Resilience

The time for incremental changes has passed. If India is to reach the milestone of Viksit Bharat by 2047, it cannot do so on the back of imported oil and stagnant yields. We call upon the government, the scientific community, and the private sector to unite under a singular National Agricultural Sovereignty Protocol with **Policy-Calibrated Reform Propositions:**

Positioning Agricultural Research as a Strategic National Security Priority

- Recognize agricultural research and food systems as **critical components of national security**, on par with defense.
- Ensure **enhanced and protected budgetary allocations** for DARE and allied institutions through long-term financial commitments.
- Integrate agricultural research into the broader framework of **Viksit Bharat 2047** with clear national targets for self-sufficiency and resilience.

Rebuilding the Last-Mile Knowledge Delivery System

- Strengthen extension systems by creating a dedicated cadre of **"Science Communicators"** to bridge the gap between laboratory innovation and farm-level adoption.
- Promote **human-centric, field-based advisory services** complemented by digital tools.
- Enhance institutional linkages between **ICAR, SAUs, and state departments** for effective technology dissemination.

Mission-Mode Focus on Dryland and Climate-Resilient Agriculture

- Launch a national mission targeting **dryland and rainfed regions** as the next growth frontier.
- Prioritize R&D in **pulses, oilseeds, and climate-resilient crops** to reduce import dependency and enhance nutritional security.
- Promote **integrated use of AI, biotechnology, and traditional sciences** as complementary tools for sustainable productivity enhancement.

Enhancing Institutional Autonomy with Accountability

- Grant **greater academic, administrative, and financial autonomy** to State Agricultural Universities (SAUs).
- Establish **transparent and merit-based mechanisms** for the selection of Vice-Chancellors at the state level.
- Redefine ICAR's role toward **broad coordination, standard-setting, and strategic guidance**, rather than direct institutional control over curricula, appointments, and routine monitoring.

- Introduce **independent accreditation frameworks** to ensure quality without over-centralization.

Strategic Prioritization of Domestic Research Investments

- Prioritize **public funding for national institutions (ICAR, SAUs, public universities)** to strengthen domestic research capacity.
- Rationalize external collaborations to ensure they are **need-based, outcome-driven, and aligned with national priorities**.
- Encourage **self-reliance in agricultural innovation ecosystems**, reducing excessive dependence on externally funded agendas.

8.6 Functional Clarity Between Research, Education and Extension

- Clearly delineate institutional roles:
 - **ICAR:** Strategic and advanced research
 - **SAUs:** Education and field-level extension
- Minimize duplication of efforts by promoting **complementarity rather than overlap**.
- Strengthen SAUs as the **primary interface between science and farmers**, revitalizing the “Lab-to-Land” pathway highlighted in your document.

Rationalization and Consolidation of Research Infrastructure

- Undertake a **comprehensive review of ICAR institutes** to identify overlapping mandates.
- Consolidate or restructure institutions with **duplicated research domains** to improve efficiency and resource utilization.
- Promote **inter-institutional collaboration platforms** instead of parallel, fragmented efforts.

Equitable and Need-Based Resource Allocation

- Develop a **transparent funding allocation model** based on:
 - Cropping area
 - Agro-climatic relevance
 - Contribution to national food and nutritional security
- Ensure that **resource distribution reflects ground realities**, particularly in agriculturally intensive states.
- Reduce disproportionate concentration of funds in **administrative or low-agriculture regions**.

Financial Prudence and Outcome-Oriented Expenditure

- Introduce **strict expenditure prioritization frameworks** focusing on research outputs and field impact.
- Rationalize spending on:
 - Conferences and events
 - Awards and ceremonial activities
 - Non-essential travel and large-scale exhibitions
- Redirect savings toward **core research, infrastructure, and farmer-centric innovations**.

Strengthening Financial Accountability Mechanisms

- Establish **performance-linked funding systems** for institutions and programs.
- Encourage **periodic independent audits** focusing on outcomes rather than procedural compliance.

- Limit routine funding to non-essential societies and organizations unless **directly contributing to measurable agricultural outcomes.**

Promoting Efficiency Through Institutional Discipline

- Encourage a culture of **resource optimization and scientific responsibility** across institutions.
- Align all funding and programmatic decisions with **national priorities of food, nutritional, and economic security.**
- Foster **result-oriented governance frameworks** across ICAR and SAUs.

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HATCHERY MANAGEMENT OF INDIAN MAJOR CARPS (IMC)

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Abstract

Indian Major Carps (IMCs), comprising *Catla catla*, *Labeo rohita*, and *Cirrhinus mrigala*, form the backbone of freshwater aquaculture production in India. The sustainable growth and intensification of carp farming largely depend on the continuous availability of high-quality fish seed, which is achieved through efficient and scientifically management hatchery operations. This review highlights the key components of IMC hatchery management, including broodstock selection and maintenance, induced breeding techniques, hatchery design and systems, egg incubation, larval rearing practices. It also discusses the major challenges affecting seed quality, such as poor broodstock management, environmental fluctuations, disease outbreaks, and technical limitations in hatchery operations. Emphasis is placed on practical management strategies supported by research findings and institutional recommendations to improve seed survival, growth and overall production efficiency. The review aims to provide a comprehensive understanding of hatchery management practices essential for ensuring sustainable and profitable IMC seed production.

Keywords: Indian Major Carps, Hatchery management, Induced breeding, Carp seed production, Aquaculture sustainability.

Introduction

Indian Major Carps (IMCs), consisting of *Catla catla*, *Labeo rohita*, and *Cirrhinus mrigala*, constitute the cornerstone of inland aquaculture in India, contributing a substantial proportion of fish production. These species are widely preferred due to their fast growth rate, consumer acceptance, and adaptability to diverse aquaculture systems. Traditionally, natural breeding of IMCs occurs in riverine environments during the monsoon season, where flooding provides suitable environmental cues for spawning. However, reliance on natural seed collection has proven unreliable due to seasonal variability, declining riverine ecosystems, and increasing demand for quality seed in aquaculture. The advancement of induced breeding and hatchery technologies has revolutionized carp seed production by enabling controlled and large-scale breeding under artificial conditions. These technological interventions have ensured the timely availability of quality seed, thereby supporting the rapid expansion and intensification of carp culture practices across the country.

Hatchery management of IMCs is a multidisciplinary process involving aspects of reproductive biology, broodstock nutrition, water quality management, and hatchery system engineering. Effective integration and management of these components play a crucial role in determining fertilization efficiency, hatchability rate, larval survival, and overall quality of fish seed produced. Therefore, scientific hatchery management is essential for sustaining productivity and ensuring the long-term growth of carp aquaculture in India. (FAO, 2011; ICAR-CIFA, 2018).

Broodstock Management

Selection and Maintenance of Broodstock

Broodstock quality is one of the most critical factor influencing hatchery performance and seed quality in Indian Major Carps (IMCs). The reproductive efficiency, fertilization success, and survival

of larvae largely depend on the health, genetic quality, and physiological condition of brood fish. Under normal pond rearing conditions, IMC brooders generally attain sexual maturity within 2–3 years, although maturation may vary depending on species, nutrition, and environmental conditions.

Selection of broodstock is carried out based on several biological and physical characteristics. Healthy fish exhibiting normal body morphology, uniform growth, active swimming behaviour, and absence of external deformities or disease symptoms are preferred. Additionally, brooders should possess well-developed gonads and appropriate body weight corresponding to their age to ensure successful spawning and production of viable eggs and milt.

Selected brood fish are usually maintained in separate ponds for males and females to facilitate controlled breeding and prevent premature spawning. Broodstock ponds are managed with proper water quality, adequate natural food availability, and supplementary feeding using nutritionally balanced diets to promote gonadal development. The recommended stocking density for broodstock rearing typically ranges from 1,000 to 1,500 kg ha⁻¹, depending on pond productivity and management practices. Maintaining optimal stocking density helps reduce stress, ensures adequate feeding, and supports proper growth and reproductive maturation of brood fish. (CIFRI, 2016).

Broodstock Nutrition

Nutrition plays a crucial role in broodstock development, directly influencing gonadal maturation, spawning success, fecundity, and egg quality in Indian Major Carps (IMCs). Proper nutritional management ensures the production of healthy gametes, which ultimately determines larval survival and growth performance. Inadequate or imbalanced nutrition can result in poor reproductive performance, reduced fertilization rates, and weak progeny. Broodstock diets for IMCs generally contain 30–35% crude protein along with balanced lipid levels to meet the high energy requirements associated with reproductive development. Proteins provide essential amino acids required for gonadal growth and gamete formation, while lipids serve as an important energy source and support hormone synthesis during maturation. In addition to macronutrients, adequate inclusion of essential micronutrients is vital for maintaining physiological and reproductive health. Supplementation with vitamins, particularly vitamin E and vitamin C, has been widely reported to enhance reproductive performance. Vitamin E functions as an antioxidant that protects developing gonadal tissues and improves egg quality, while vitamin C supports immune function, stress resistance, and overall broodstock health. Furthermore, essential fatty acids, especially omega-3 and omega-6 fatty acids, play a significant role in embryonic development, larval viability, and successful hatching. Proper formulation and regular feeding of nutritionally balanced broodstock diets are therefore essential for achieving high seed production and maintaining hatchery efficiency (ICAR, 2020).

Breeding Behaviour and Induced Breeding

Indian Major Carps (IMCs) are seasonal breeders that naturally spawn during the monsoon season in riverine environments. Their breeding activity is stimulated by specific environmental cues such as rainfall, increased water current, fluctuations in temperature, rise in water level, and changes in water conductivity. These natural stimuli create favourable physiological and behavioural responses in brood fish, leading to gonadal maturation and spawning. However, dependence on natural breeding conditions is often unreliable and insufficient to meet the increasing demand for quality

carp seed. Under hatchery conditions, these environmental stimuli are simulated through the application of induced breeding techniques, primarily involving hormonal administration. Induced breeding enables hatchery operators to control and synchronize spawning, thereby ensuring timely and large-scale production of fertilized eggs. This technique has become a standard and widely adopted practice in carp hatcheries across India due to its reliability, efficiency, and ability to produce uniform and high-quality seed. Induced breeding in IMCs is commonly carried out using pituitary gland extract obtained from donor fish or synthetic hormone preparations such as Ovaprim and similar commercial formulations. These hormonal agents stimulate final maturation and ovulation in females, as well as spermiation in males, facilitating controlled spawning under artificial conditions. The successful implementation of induced breeding techniques has significantly contributed to the expansion and sustainability of carp aquaculture in India (FAO, 2011).

Hormones Used and Breeding Protocol

Hormonal Preparations

Induced breeding of Indian Major Carps (IMCs) primarily relies on the administration of hormonal preparations to stimulate final gonadal maturation, ovulation in females, and spermiation in males. The selection of appropriate hormonal agents plays a vital role in determining spawning success, fertilization rate, and seed quality. The commonly used hormonal preparations in carp hatcheries include pituitary gland (PG) extract and synthetic hormone formulations such as Ovaprim, Ovatide, and Wova-FH. Pituitary gland extract is prepared from the pituitary glands of mature donor fish and contains gonadotropic hormones that stimulate reproductive processes. Although PG extract has been widely used traditionally, its preparation requires technical skill, proper preservation, and careful dosage standardization. In recent years, synthetic hormone formulations have gained greater acceptance among hatchery operators due to their consistent potency, ease of administration, longer shelf life, and reduced variability in breeding performance. These formulations typically contain analogues of Gonadotropin-Releasing Hormone (GnRH) combined with dopamine antagonists, which enhance the release of endogenous gonadotropins responsible for spawning. The recommended hormone dosages vary slightly among IMC species and depend on broodstock maturity and environmental conditions. Standard dosage ranges commonly adopted in hatchery practices are presented in Table 1.

Table 1. Recommended hormones dosage for Induced Breeding of IMCs

Species	Female Dose (ml kg ⁻¹)	Male Dose (ml kg ⁻¹)
<i>Catla catla</i>	0.4–0.6	0.2–0.3
<i>Labeo rohita</i>	0.3–0.5	0.2–0.3
<i>Cirrhinus mrigala</i>	0.3–0.5	0.2–0.3

(Source: ICAR-CIFA, 2018).

Proper selection of hormone type and accurate dosage administration are essential to ensure successful spawning, high fertilization rates, and production of healthy larvae.

Hatchery Systems for IMC Seed Production

Various hatchery designs have been developed and adopted for Indian Major Carp (IMC) seed production to facilitate efficient breeding, egg incubation, and larval rearing under controlled conditions. The commonly used hatchery systems include Chinese circular hatcheries, Fibre Reinforced Plastic (FRP) carp hatcheries, and eco-hatcheries. Although these systems differ in

design, construction materials, and operational scale, they share similar functional components necessary for successful seed production. A standard IMC hatchery system typically consists of spawning tanks, incubation units, and water circulation and aeration mechanisms. Spawning tanks provide a controlled environment for hormone-induced breeding and egg fertilization. Incubation units are specifically designed to maintain fertilized eggs in a suspended state, which prevents egg clumping, ensures uniform oxygen supply, and reduces mortality. Efficient water circulation systems help simulate natural riverine conditions that stimulate embryonic development and improve hatching success. Among the available designs, Chinese circular hatcheries are widely used due to their efficient water flow pattern, higher hatching capacity, and operational reliability. Similarly, FRP hatcheries have gained popularity because of their durability, ease of installation, portability, and suitability for small- and medium-scale hatchery operations. Eco-hatcheries, which utilize locally available materials and energy-efficient designs, are increasingly being adopted as cost-effective alternatives in certain regions. Regardless of hatchery type, maintaining continuous water circulation and adequate aeration is essential for successful incubation and larval survival. Proper hatchery design and management play a crucial role in improving fertilization efficiency, hatching rate, and overall seed quality (CIFRI, 2016).

Egg Incubation and Hatching

Egg incubation is a critical stage in Indian Major Carp (IMC) seed production, as it directly influences hatching success and larval survival. IMC eggs are non-adhesive and semi-buoyant in nature, which allows them to remain suspended in water when adequate circulation is maintained. Following induced spawning, fertilized eggs are carefully collected and transferred to hatching jars or specialized incubation chambers designed to maintain optimal environmental conditions for embryonic development. Successful incubation requires maintaining suitable water quality parameters. The optimal temperature range for IMC egg development is generally between 26°C and 30°C, while dissolved oxygen levels should be maintained above 5 mg L⁻¹ to support normal embryogenesis. Continuous water flow and gentle aeration are essential to keep the eggs in suspension, prevent clumping, and ensure uniform oxygen distribution. Under favorable conditions, hatching usually occurs within 14–18 hours, although the duration may vary depending on species, temperature, and water quality conditions. Improper handling, fluctuations in environmental parameters, and poor water quality can increase the risk of fungal infections, which significantly reduce hatchability and larval survival. After hatching, the larvae initially rely on their yolk sac as the primary source of nutrition. As the yolk sac is gradually absorbed, the larvae begin feeding on natural plankton available in the rearing environment. Therefore, proper management of incubation conditions and early larval nutrition is essential for producing healthy and robust spawn.

Larval Rearing and Early Feeding

Larval rearing is a crucial phase in Indian Major Carp (IMC) seed production, as survival and growth during this stage largely determine the overall success of hatchery operations. Newly hatched larvae are delicate and physiologically immature, making them highly sensitive to environmental stress and nutritional deficiencies. During the initial 48–72 hours after hatching, the larvae depend entirely on endogenous nutrition derived from yolk sac reserves, which provide essential nutrients required for early development and organ formation. Following complete absorption of the yolk sac, larvae begin exogenous feeding, marking a critical transition period in their development. Timely initiation of external feeding is essential to prevent starvation and ensure proper growth. Traditionally, larvae are transferred to well-prepared nursery ponds enriched with natural plankton, which serve as an

ideal and nutritionally balanced food source. The presence of diverse plankton communities, particularly zooplankton such as rotifers and cladocerans, significantly improves larval survival and growth performance compared to reliance on artificial feeds alone. In hatchery-based rearing systems, supplementary feeding is often practiced to enhance larval nutrition and survival. Commonly used supplementary feeds include boiled egg yolk emulsion and finely powdered formulated feed, which provide easily digestible nutrients suitable for early larval stages. Proper feeding management, along with maintenance of suitable water quality and stocking density, plays a vital role in ensuring healthy larval development and high survival rates (ICAR, 2020).

Water Quality Management

Water quality management is a fundamental component of Indian Major Carp (IMC) hatchery operations, as embryonic development, larval survival, and seed quality are highly sensitive to changes in environmental conditions. Maintaining optimal water quality ensures proper metabolic functioning, reduces physiological stress, and minimizes the risk of disease outbreaks during breeding and rearing phases. Key water quality parameters such as temperature, dissolved oxygen, pH, and ammonia concentration must be maintained within recommended ranges to support successful breeding, incubation, and larval development. Temperature plays a crucial role in regulating metabolic rate, gonadal maturation, and embryonic growth, while dissolved oxygen is essential for respiration and overall physiological stability. Similarly, maintaining a stable pH range supports normal biochemical processes, whereas elevated ammonia levels can be toxic to eggs and larvae, leading to increased mortality and developmental abnormalities.

Table 2: Optimum Water Quality Parameters for IMC Hatcheries

Parameter	Recommended Range
Temperature	26–32 °C
Dissolved Oxygen	>5 mg L ⁻¹
pH	7.0–8.5
Ammonia	<0.02 mg L ⁻¹

(Source: FAO, 2011; ICAR-CIFA, 2018)

Regular monitoring of these parameters using standard water quality assessment methods is essential to maintain a stable hatchery environment. Periodic water exchange, proper aeration, removal of organic wastes, and maintenance of adequate water flow help prevent accumulation of toxic metabolites and maintain suitable rearing conditions. Effective water quality management reduces stress, prevents deformities, and significantly improves fertilization success, hatchability, and larval survival in IMC hatchery systems.

Common Constraints in IMC Hatcheries

Despite significant technological advancements in induced breeding and hatchery system design, several constraints continue to affect the efficiency and reliability of Indian Major Carp (IMC) seed production. These challenges often result in reduced fertilization rates, poor hatchability, and increased larval mortality, thereby affecting overall hatchery productivity. One of the major constraints is the use of immature, genetically inferior, or poorly nourished broodstock. Inadequate broodstock conditioning and improper feeding practices lead to poor gonadal development, reduced fecundity, and production of low-quality eggs and milt. Another common issue is insufficient water circulation and aeration in breeding and incubation units, which reduces oxygen availability and promotes egg clumping, ultimately lowering hatching success. Fungal infection of

eggs, particularly caused by *Saprolegnia* species, is another significant problem in carp hatcheries. Such infections usually occur due to poor water quality, accumulation of organic matter, or excessive handling of eggs during incubation. Additionally, high mortality during the transition from endogenous to exogenous feeding represents a critical bottleneck in larval rearing. Delayed or inadequate supply of suitable live feed during this stage often results in starvation and poor larval survival. Most of these constraints arise primarily from management deficiencies rather than technological limitations. Adoption of scientific broodstock management practices, maintenance of optimal water quality, timely disease prevention measures, and proper larval feeding strategies can significantly improve hatchery performance and seed quality.

Conclusion

Efficient hatchery management of Indian Major Carps (IMCs) is essential for ensuring sustainable seed production and supporting freshwater aquaculture development. Successful hatchery operations depend on proper broodstock selection, nutrition, and conditioning, which directly influence gamete quality and spawning success. The adoption of induced breeding techniques using standardized hormonal protocols has enabled reliable and large-scale production of carp seed under controlled conditions. Additionally, well-designed hatchery systems with efficient spawning, incubation, and larval rearing units play a crucial role in improving fertilization, hatching success, and larval survival. Maintenance of optimum water quality parameters and implementation of preventive health management practices help reduce stress, disease occurrence, and early-stage mortality. Integration of these scientific management practices ensures the consistent availability of high-quality IMC seed, thereby enhancing productivity, profitability, and long-term sustainability of freshwater aquaculture in India.

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HIGH PRESSURE PROCESSING (HPP): A NON-THERMAL APPROACH TO SEAFOOD SAFETY AND QUALITY

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Introduction

Fish is a significant and popular food worldwide. Still, because of its very perishable nature, rapid oxidative and microbiological deterioration that occurs right after capture, it has a limited shelf life and is therefore highly dependent on post-harvest preservation (Zhao et al. 2019). Traditional food processing techniques like thermal treatment help increase shelf life and destroy bacteria, but they can also harm food's physicochemical and sensory qualities, particularly for foods sensitive to temperature (Zhao *et al.*, 2019). Emerging non-thermal food processing technologies are being developed as an alternative to or replacement for conventional thermal techniques due to consumers' growing interest in microbiologically safe goods with superior appearance, flavour, high nutritional content, and longer shelf life (Zhao *et al.*, 2019). High-pressure treatment (HP) is defined as a non-thermal preservation method that can prolong the shelf life of fish when used alongside appropriate refrigeration and handling techniques, involving the application of high pressures (100–1200 MPa) as a kind of cold preservation (Bhat *et al.*, 2021). HPP helps in preservation, which inactivates harmful pathogens and vegetative spoilage microorganisms by using pressure rather than heat to induce a pasteurization effect (Muntean *et al.*, 2016). HP promotes structural and metabolic alterations in bacteria by impacting their cell membranes and walls, resulting in their inactivation (Chouhan *et al.*, 2015).

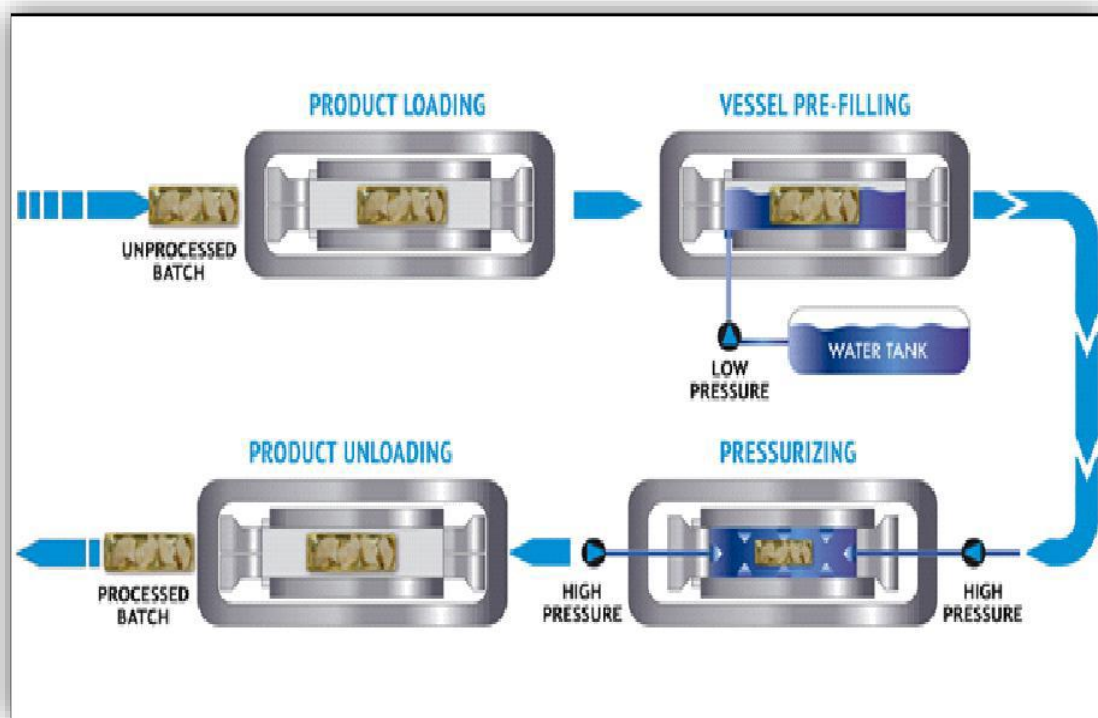
Principles: The basic principles that govern the high-pressure effect on the behaviour of foods are

- (i) **Pascal's Isostatic principle:** According to Pascal's isostatic principle, high pressure acts uniformly and instantly throughout the sample, independently of the size and shape of the food product (Smelt, 1998).
- (ii) **Le Chatelier's principle:** The Le Chatelier's principle states that when a system at equilibrium is disturbed, the system then responds in a way that tends to minimise the disturbance.

A typical processing cycle given by (Srinivas *et al.*, 2018)

1. Packaged food items are placed in the pressure vessel
2. Vessel is sealed and filled with water
3. A pump (with intensifier) forces more water into the vessel, creating hydrostatic pressure
4. The fluid medium isostatically transmits pressure.
5. A small temperature increase may occur in the product, depending on the product composition.
6. Vessel pressure is maintained for a predetermined period of time (usually between 30 seconds and 15 minutes), during which time pathogens and spoilage bacteria are inactivated.

7. When the cycle is complete, the vessel is quickly depressurised, and temperatures return to the starting temperature.
8. Vessel is opened, and product is removed.



Source: (Srinivas *et al.*, 2018)

Advantages:

1. HPP does not involve in breaking covalent bonds which prevents the development of unpleasant flavours to the product and maintains the natural freshness and quality.
2. High pressure is able to modify the palatability and functional properties by inducing denaturation and muscle protein gelation.
3. Process can be carried out at ambient temperatures that helps in reducing the thermal energy used during conventional processing.
4. High pressure processing is isostatic in nature, equally applied to all particles of food, with no particle escapes.
5. Since high pressure is not time-mass dependent, pressure acts instantaneously thereby reducing the processing time.
6. This non thermal technology is independent of size and geometry of the food.
7. The process is eco-friendly, with no waste and requires only electric energy.

Application in seafood processing:

Sr. No.	Sample	Experiment	Findings	Reference
1	Tuna	Low-intensity treatment (220 MPa for 30 min)	Help to extend the shelf-life and decreasing the proteolytic activities, texture degradation, and	Nagarajaroo, 2016

Sr. No.	Sample	Experiment	Findings	Reference
			formation of TVB-N and histamines.	
2	Barramundi (<i>Lates calcarifer</i>)	HPP for 150–200 MPa for 3 min before frozen.	Observed an increased hardness and decreased lipid oxidation and extend the shelf life for 18 weeks at –18°C.	Truong <i>et al.</i> , 2016
3	Cod (<i>Gadus morhua</i>)	200MPa/min at 25 °C for 20min	Help to reduce the protein oxidation, and Help to improve the digestibility	Zhang <i>et al.</i> , 2019
4	Grey mullet (<i>Mugil cephalus</i>)	High-pressure treatment and chilling (0, 400, 500, and 600 MPa for 10 min, 2–4°C)	HPP help to reduce the formation of metabolites such as (hypoxanthine, trimethylamine, and biogenic amines), and these reductions were positively correlated with decreases in microbial levels.	Lan <i>et al.</i> , 2024

Source: (Sarika and Bindu, 2022)

Conclusion

Food preservation technology has advanced significantly with the use of high pressure processing. High Pressure Processing (HPP) is an innovative and effective method of food preservation that ensures safety while maintaining the natural quality of food. It combines safety and freshness by removing hazardous bacteria without sacrificing quality. HPP help to in shelf-life extension and safety assurance without compromising sensory and nutritional quality of fresh and processed foods.

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HYDROPONICS IN FLORICULTURE

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Hydroponics is the practice of growing plants without traditional soil, instead delivering nutrients through a water-based mineral solution. In this system, plant roots are either suspended directly in nutrient-rich water or supported by inert media like perlite, coco coir, or rock wool that merely provide physical support without nutritional value.

Although the concept dates back centuries, hydroponics gained scientific traction in the 20th century when researchers realized that plants could thrive and often outperform soil-grown counterparts when their nutritional needs were precisely managed. In the floriculture industry, where aesthetics, quality and predictability are paramount, hydroponics has emerged as a compelling alternative to soil cultivation.



Benefits of Hydroponics

1. Space and Resource Efficiency

One of the most significant advantages of hydroponics is its ability to maximize productivity in limited space. Because flower crops do not compete for nutrients or space in soil, they can be grown more densely. This makes hydroponics especially appealing for urban and peri-urban flower production where land is expensive or scarce.

Hydroponic systems also use significantly less water than soil cultivation because nutrient solutions are recirculated and reused rather than lost to deep percolation. In regions facing water scarcity an increasingly common challenge this water-saving benefit can be transformational.

2. Controlled Environment, Year-Round Production

Floriculture is often a seasonal business. Traditional flower farming depends on climatic conditions that dictate planting and blooming cycles. Hydroponics changes that by enabling controlled

environment agriculture (CEA), within greenhouses or even indoor vertical farms, growers can manipulate light, humidity, temperature and nutrient supply to produce flowers year-round, independent of the weather outside.

This has profound implications not just for consistent supply but for international trade: imported flowers grown under stable hydroponic conditions can compete in markets that once suffered from seasonal shortages.

3. Improved Plant Health and Quality

Nutrients are delivered directly to the roots in precise ratios, the hydroponic flowers often exhibit uniform growth, stronger stems and more consistent flowering than soil-grown plants. A well-managed hydroponic system can accelerate growth rates and increase yields which is crucial for high-value ornamentals where quality directly affects market price.

Hydroponics also eliminates many soil-borne pests and diseases, reducing the need for broad-spectrum pesticides and enabling cleaner, healthier plant production.

Common Hydroponic Systems in Floriculture

Floriculturalists employ several hydroponic methods, each with unique strengths:

Nutrient Film Technique (NFT)

This method circulates a thin film of nutrient solution past the plant roots. Because roots are constantly bathed in nutrients and oxygen, plants can absorb what they need efficiently. NFT is popular for crops with smaller root systems.

Deep Water Culture (DWC)

Here, plants are suspended with their root systems submerged in a nutrient reservoir. Oxygenation is maintained with air stones or pumps. DWC systems offer excellent nutrient delivery and can suit larger ornamentals.

Kratky Method

A passive hydroponic technique requiring no pumps or electricity, the Kratky method suspends roots above a nutrient reservoir that gradually recedes as plants consume water. While simple and low-cost, it works best for smaller or slow-growing ornamentals.

Hydroponics Meets Floriculture in Practice: Examples

Hydroponics is not just a theory it is used commercially for many floriculture crops:

- **Roses:** High-value stems grown in controlled conditions consistently meet color and size expectations that soil environments cannot always achieve.
- **Gerberas and Chrysanthemums:** These cut flowers benefit from precise nutrient delivery and controlled light cycles, leading to extended vase life and market appeal.
- **Lily and Gladiolus:** Taller blooms with robust stems thrive in hydroponic systems where nutrient uptake is optimized.

Beyond these, a wide range of ornamental species including marigolds, begonias, orchids, and even exotic tropical flowers are being experimented with successfully in hydroponic conditions.

Challenges and Considerations

Despite its promise, hydroponic floriculture comes with real challenges:

Cost and Technical Skill

Setting up hydroponic infrastructure—nutrient tanks, pumps, monitoring sensors and controlled environments it requires high initial investment and technical know-how. Novice growers often struggle with balancing nutrient solutions, monitoring pH or managing lighting and climate systems.

Energy Dependency

Many hydroponic systems rely on artificial lighting and climate control, especially in indoor farms. This increases energy consumption and requires reliable power to avoid expensive crop losses during outages.

Knowledge Intensity

Understanding plant nutrition, water chemistry and disease avoidance in hydroponics demands specialized training. Unlike traditional soil farming, errors in nutrient balance or pH can quickly impact entire crops.

The Future of Hydroponic Floriculture

Hydroponics is increasingly seen as more than a niche innovation; it's regarded as a strategic approach to sustainable floriculture, especially in urban and peri-urban contexts where land and water are limited. With advances in precision agriculture such as IoT-based monitoring systems hydroponic farms are becoming smarter, more efficient and capable of predictive nutrient management that minimizes waste and maximizes quality.

In cities where floral demand is high but land is scarce, hydroponics offers a way to grow close to market, reducing transportation costs and carbon footprint while delivering fresher flowers to consumers. As sustainability becomes a selling point, hydroponic floriculture's appeal only grows.

Conclusion

Hydroponics brings excitement and innovation to floriculture, blending science and beauty in soilless cultivation. By offering efficient resource use, year-round production, and higher plant quality, hydroponics is rewriting how ornamental plants are grown. While challenges like cost and technical complexity remain, the potential rewards a greener, more consistent, and highly productive floriculture industry are driving investment and experimentation worldwide.

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IN-VITRO PROPAGATION OF APPLE FOR SUSTAINABLE PRODUCTION

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Introduction

Apple (*Malus × domestica* Borkhausen, family Rosaceae) is one of the most widespread and economically significant temperate fruit crops in the world. It is grown in North America, Europe, Asia and several other temperate regions across the world. The domesticated apple exhibits substantial genetic variability and is primarily diploid (2n =34), whereas triploid genotypes also exist. Through adequate management, this perennial fruit tree can survive and yield fruits for years.

Origin and Domestication

Apple traces its origin to the forests of Central Asia, particularly the Tien Shan mountain ranges of present-day Kazakhstan. Many scientific studies show that the wild apple species originating from this region *Malus sieversii*, is identified as main progenitor of modern-day apple. Its domestication occurred gradually through natural hybridization and selective breeding by humans. Its seeds and planting materials were transported to Europe and subsequently to other continents through early trade activities along the ancient trade routes such as Silk Road. The enormous variety of apple varieties that are currently accessible is the result of extensive method of propagation and selection.

Global and Indian Scenario of Apple Production

In 2024, apple was grown on 4,685,316 hectares of land worldwide, yielding a total production of 97,880,076.32 tons with contribution of 52%, 5.0%, 4.5%, 3.4% and 2.6% by China, United States, Turkey, Poland and India, respectively. Specifically in India, 2,625,899 tonnes of apples were produced on 304,130 hectares of land in 2024. The temperate zone cultivation is largely confined to the higher altitudes of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, and parts of the northeastern hills. Among these, Himachal Pradesh has emerged as a major apple producing state, with apple cultivation serving as the backbone of rural livelihoods and a leading cash crop among temperate fruit crops.

Apple cultivars and rootstocks

Apple tree is composite in nature as it is a union of a scion wood and a rootstock. The above ground components of the tree i.e., trunk, branches, leaves and fruits make up a scion wood. While, the lower part of the tree, that typically contains the root system is called as the rootstock. Though numerous apple cultivars are used for commercial production purpose, but few of them are enlisted as follows:

Harvesting Season	Apple Cultivar
Early Season (June-July)	Early McIntosh, Tydeman's Early, Summer Red, etc.
Mid-Season (August-September)	Gala, Golden Delicious, McIntosh, Honeycrisp, Jonathan, Empire, etc.
Late Season (October-November)	Red Delicious, Fuji, Granny Smith, Cripps Pink, Ambri, etc.

Likewise, the commercially popular rootstocks of apple are as follows:

Rootstock Series	Origin	Rootstocks
Malling (M)	East Malling Research Station, England	M.27 (Very dwarf), M.9 (Dwarf), M.26 (Semi-dwarf), M.7 (Semi-dwarf)
Malling-Merton (MM)	East Malling and John Innes Institute, England	MM.106 (Semi-vigorous), MM.111 (Vigorous)
EMLA	East Malling-Long Ashton, England	EMLA 9 (Dwarf), EMLA 26 (Semi-dwarf)
Budagovsky (Bud)	Michurin Institute, Russia	Bud.9 (Dwarf), Bud.118 (Semi-vigorous)
Cornell Geneva (G / CG)	Cornell University, USA	G.11 (Dwarf), G.41 (Dwarf), G.935 (Semi-dwarf)
Polish (P)	Research Institute of Pomology and Floriculture, Poland	P.2 (Dwarf), P.22 (Very dwarf)

Methods of Apple Propagation

Orchard establishment by seed propagation is rarely practiced for commercial orchard production due to the high genetic variation in seedlings. As seed is a new genetic combination, so there is uncertainty with respect to the fruit quality, yield, and growth habit. Moreover, plants that are propagated through seed have a long period of juvenile stage and usually take 6-8 years or more to initiate fruit bearing. These limitations make seed propagation unsuitable for commercial purposes. Thus, the following vegetative approaches are primarily used for apple propagation in order to preserve the genetic purity and uniformity:

- **Grafting**

It is the most popular way of commercial apple propagation. Whip and tongue grafting, cleft grafting are some of the techniques that are employed to combine a desirable scion and a good rootstock that produce true to type plants and early bearing.

- **Budding**

Usually, budding is preferred for apple multiplication with special focus on T-budding and chip budding. The procedure is effective, the amount of scion material is less, and the success rate is high when it is done during the active sap flow.

- **Layering**

It is predominantly applied in the production of clonal rootstocks. The most widely used technique is mound layering in which the shoots arising from the base of mother plant are allowed to form roots before separation.

- **Cuttings**

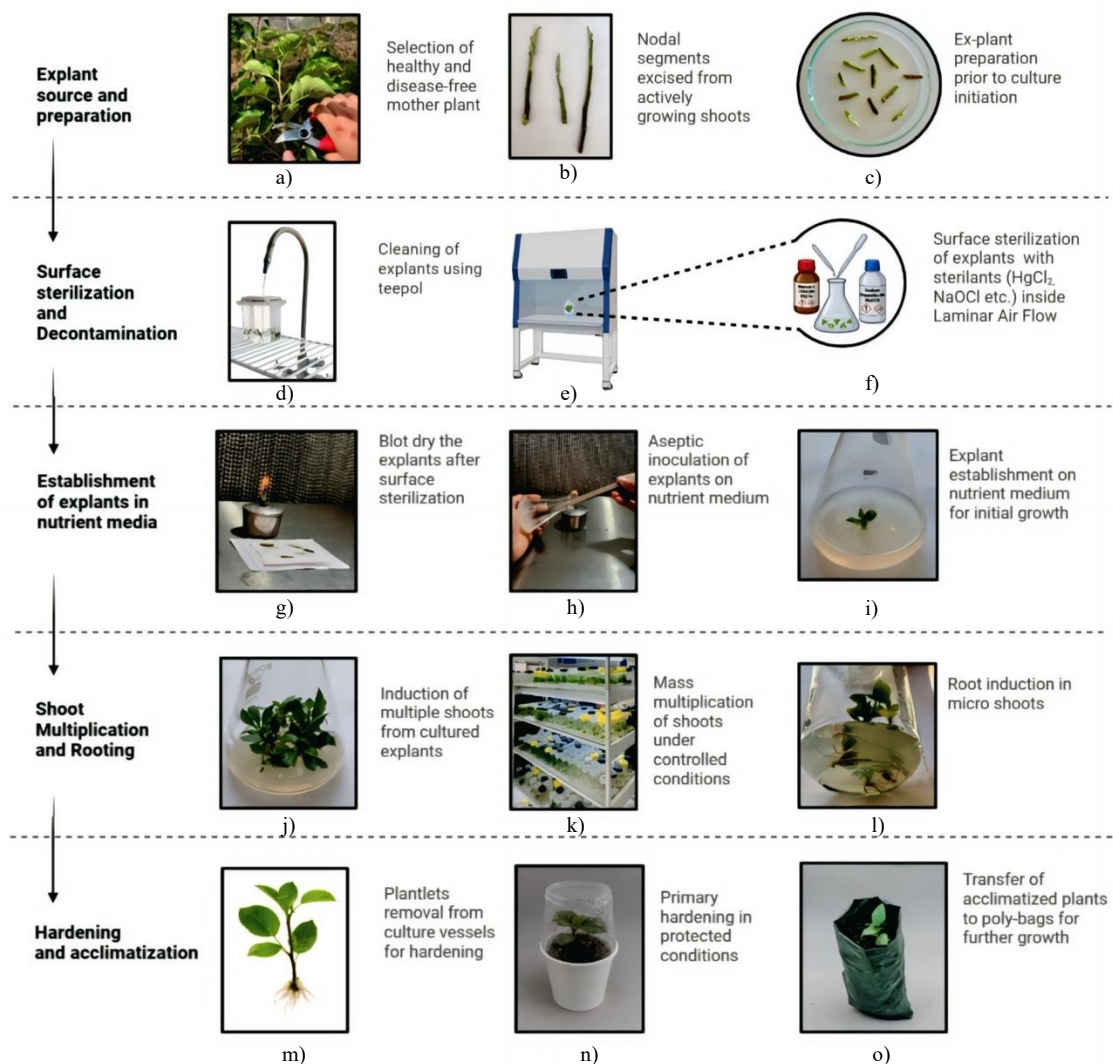
Multiplication by the use of cuttings has been found to be a challenge in apple because of low rooting capacity. Some rootstocks can be made using hardwood cuttings, although it is not very successful and may require treatment with rooting hormones.

Although traditional vegetative propagation has been very effective, but may get hampered at times due to reduced multiplication rates and the chances of spreading systemic diseases.

***In vitro* propagation: An appropriate alternative**

The development of *in vitro* propagation, commonly referred to as micropropagation, has brought a significant transformation in apple multiplication. One of the earliest successful attempts at apple tissue culture was reported by Jones in 1974 marking the beginning of organized *in vitro* propagation in apple.

It involves growing small pieces of plant parts referred to as explants like shoot tips, nodal segments and apical meristems under sterilized and controlled laboratory conditions in nutrient media. Shoot tips and nodal segments are the most commonly used among them as they are genetically stable and have a high ability to proliferate. Through repeated subculturing, a large number of uniform plantlets can be produced within a short period. The major benefit of using meristem-based cultures is that it leads to the production of disease and virus free planting material which is vital in the development of healthy and productive apple orchards.



Schematic representation of *in vitro* propagation in apple

In vitro propagation offers following advantages over conventional methods:

- **Rapid and large-scale multiplication:** It is possible to produce large numbers of plants within a short period of time by using a small explant under controlled conditions in the laboratory.
- **Production of true to type and genetically uniform plants:** The plants propagated using tissue culture are usually genetically identical to the parent plant, and ensure uniform characteristics.
- **Availability of disease-free planting material:** Pathogen free plants can be produced by culturing meristem or shoot tips, eliminating viruses and other diseases.
- **Year-round propagation independent of seasonal constraints:** Plants can be propagated all year round in laboratory settings and are no longer restricted by seasonal factors.
- **Effective multiplication of elite cultivars and clonal rootstocks:** Elite cultivars and valuable clonal rootstocks could be multiplied efficiently and still preserve the desired characteristics.

- **Reduced juvenile phase and faster orchard establishment:** Tissue cultured plants grow rapidly and can develop to the productive stage earlier than plants which are conventionally propagated.
- **Improved use of limited and valuable plant material:** It is possible to produce a large number of plants with just a small explant, which can be used to preserve rare or valuable germplasm.
- **Uniform and synchronized plant growth:** Plants cultivated by tissue culture grow consistently, resulting in organized development in orchards.
- **Conservation and safe exchange of apple germplasm:** *In vitro* cultures enable the long-term conservation and safe exchange of disease-free plant genetic resources.

Conclusion

In vitro propagation has proved to be an efficient and credible substitute, which provides a speedy multiplication, genetic homogeneity and disease-free plants. Therefore, the integration of traditional horticultural practices with modern biotechnological tools provides immense potential for strengthening the system of production of apple, as well as to guarantee the sustainability of the apple industry development in India and worldwide.

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INDUCED BREEDING IN FISHES

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Introduction

For many centuries, fish have been one of the most important food sources for humans. They are rich in protein, essential fats, vitamins, and minerals, which makes them both nutritious and affordable. As a result, fish has remained a key part of the diet for millions of people around the world. However, beneath the surface of rivers, lakes, and ponds, a serious problem has been developing. Natural fish populations are declining rapidly due to anthropogenic and environmental pressures. Pollution from industries and homes, overfishing, shrinking water areas, and more human activity have all disturbed the balance of aquatic environments.

Many communities that once relied on abundant natural fish stocks now face great uncertainty. Surprisingly, even as wild fish become less available, the need for fish is growing because of an increasing population and greater understanding of its health benefits. In this difficult situation, fish farming, also called aquaculture, has become a dependable and sustainable way to meet the demand. Among the various scientific methods that support aquaculture, induced breeding has turned out to be one of the most important advancements. In the wild, fish reproduction happens during certain seasons. They depend on environmental signals such as rising water levels, temperature changes, better water conditions, and rain. These signals tell them that their young have a good chance of surviving. However, nature does not always follow a regular pattern. For fish farmers who need a steady supply of young fish, this unpredictability can be a big challenge.

To solve this problem, scientists developed a technique called induced breeding. This is a scientific method that encourages fish to reproduce under controlled conditions. In this process, fish are given either natural or man-made hormones, or they are placed in an environment that simulates the breeding season. This enables hatcheries to ensure reliable and controlled seed production throughout the year to produce fish eggs and larvae, which are necessary for successful fish farming. Behind this process is a complex biological system the endocrine system. It acts as a communication system inside the fish's body, connecting changes in the environment with internal reproductive responses.

When environmental factors like rain or temperature change, signals are sent to the brain. These signals activate a small but powerful organ called the pituitary gland, often called the “master gland.” This gland releases hormones that control growth, development, and especially reproduction.

The pituitary gland produces gonadotropins, the key hormones involved in breeding.

Two of these hormones are particularly important:

- Follicle Stimulating Hormone (FSH) – helps the eggs and sperm to grow and mature.
- Luteinizing Hormone (LH) – causes the release of mature eggs and sperm, leading to spawning.

In induced breeding, hormones similar to these natural gonadotropins are given to the fish. This activates the same biological pathway that would naturally happen, making reproduction successful and timely. Today, induced breeding is central to modern aquaculture. Fish hatcheries can now produce healthy young fish throughout the year, ensuring a constant supply for farmers. This technology has not only boosted fish production but also improved the quality and survival rate of fish stocks.

More importantly, it has reduced the pressure on wild fish populations, allowing rivers and lakes to start healing. For thousands of fish farmers, especially in rural areas, induced breeding has created a steady source of income and better living conditions. Induced breeding represents the application of scientific knowledge to regulate natural reproductive processes under controlled conditions. By learning how environmental signals, hormones, and reproductive cycles work together, scientists have developed a method that supports both food security and the protection of the environment. As the global need for fish continues to increase, induced breeding shows how scientific knowledge can guide natural processes. It ensures steady fish production, helps improve the lives of farmers, and safeguards important natural resources for future generations.

History of Induced Breeding

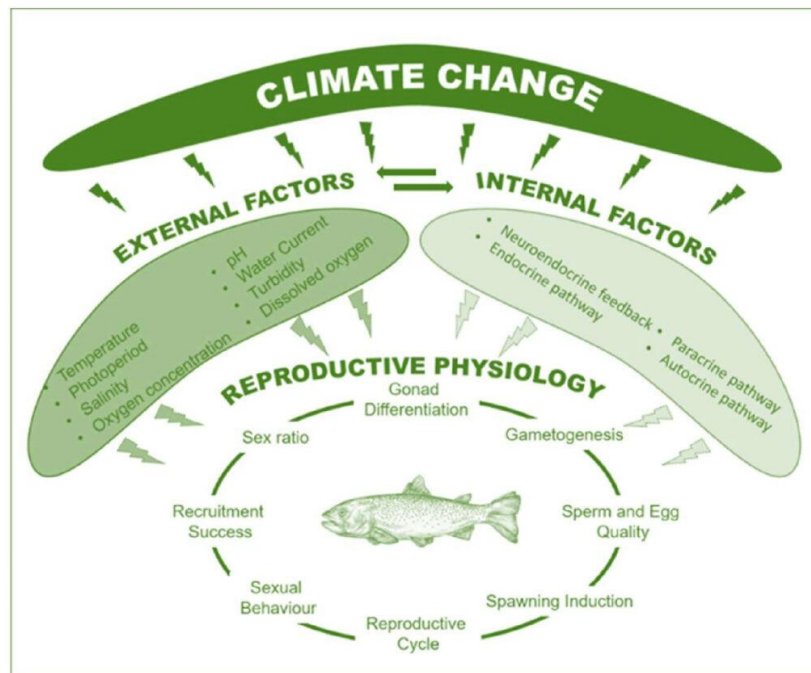
In 1930, Houssay developed the induced breeding technique in Argentina, which used pituitary extract to force viviparous fish to give birth before their time. This method represented a major breakthrough in our knowledge of and ability to control fish reproduction for aquaculture. In 1934, Brazilians successfully used pituitary extract to stimulate breeding. The practice of induced breeding spread swiftly outside of Argentina. Researchers like Merlin and Hubs adopted it in America, while Gerebilisky did the same in Russia. In 1937, Khan introduced induced breeding for the first time in India in the fish *Cirrhinus mrigala*. In 1955, Dr. Hiralal Choudhuri also applied this technique to small carps such as Indian flying barb (*Esomus danricus*) and potasi (*Pseudeotropius atherinoides*). In 1956, Ramaswamy and Sunderaraj were the very first to breed singhi (*Heteroneustes fossilis*) and magur (*Clarias batrachus*). An important turning point in the development of aquaculture was reached in 1957 when Dr. Hiralal Choudhuri successfully produced the first induced breeding of major carps using *Cirrhinus mrigala*, *C. reba*, and *Labeo rohita*. Injections of synthetic hormones or pituitary extract (gonadotropic hormones) are used to stimulate the spawning of Indian major carp (Alikunhi *et al.*, 1960). Additionally, the success of Parameswaran and Alikuni's 1963 breeding of exotic Chinese carps, *Ctenopharyngodon idella* and *Hypophthalmichthys molitrix*, showed how induced breeding methods may be used to diversify fish production.

Events of Natural Breeding

Indian major carps are among the many cultured commercial fish that often struggle to naturally generate progeny in captivity. Indian big carps are categorized as fishes that typically reproduce in submerged areas of rivers and streams during the monsoon season rather than in lakes, ponds, or other static water bodies (Baruah, 2013). The pituitary gland's hormonal activity and gonadotropin release are influenced by a number of environmental factors, including photoperiods (day length), rainfall, temperature, and water flow. These factors control the maturation of gonads and spawning in both males and females (Alikunhi *et al.*, Ibrahim *et al.*, 1968), Siddique *et al.*, (2022), Maulu *et al.*, (2021), and 1965 Fresh floods that destroy terrestrial life and encourage the formation of microflora and microfauna assist the Indian main carp spawning site by giving the fish's fingerlings and fry a food source. The survival and spread of Indian big carps are facilitated by this flood-driven cycle (Padhi and Mandal, 1994).

Any of these environmental disturbances could result in insufficient hormone secretion in captivity, which would prevent the fish from reproducing in restricted areas. In order to stimulate fish reproduction, the induced breeding technique was developed on the basis of intentionally influencing hormonal or environmental stimuli (Kumar *et al.*, 2021).

External and internal climate-dependent factors that affect fish reproductive physiology. Need of Induced Breeding



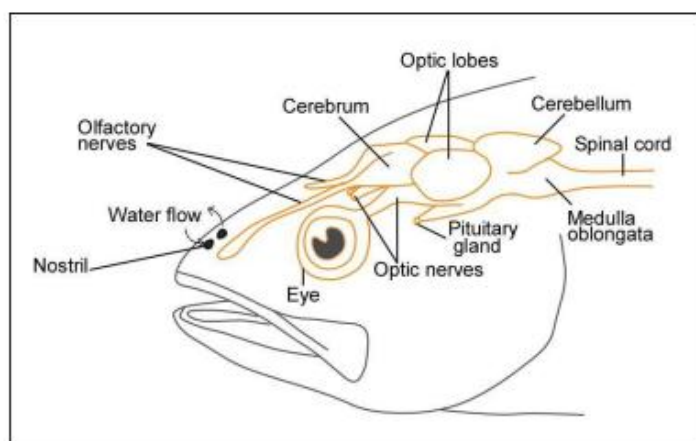
Due to the increase in demand of fish for consumption as food, amusement and decorative fishes used in aquariums, the natural fish populations are gradually declined during the past several decades, because of environmental degradation like photoperiod, rain, temperature, currents of water and overfishing, chemical composition of water and many more factors (Pankhurst and Munday 2011, Jha and Neupane 2019, Sudha, C. 2012). This raised trouble in the development of ways for hatchery products of fish. Traditional aquaculture species such as trout, catfish, common carp, golden shiner and goldfish reach sexual maturity and spawn in hatcheries or ponds, when conditions are appropriate. Indeed, some valuable fish species have proven challenging to reproduce in captivity despite their economic importance for aquaculture. Many of these fish spawning takes place in natural environments that are nearly impossible to stimulate in hatchery, hormone induced spawning is the only reliable method to induce reproduction in these fishes (Panigrahi, L. 2019, De *et al.*, 2020). The reproductive processes of fish in captivity are a crucial step towards domestication and the development of a sustainable aquaculture industry (Mylonas *et al.*, 2010, Saraiva *et al.*, 2018).

Pituitary hormone, human chorionic gonadotropin, and ovaprim (a synthetic hormone) are used in induced breeding to encourage mature or gravid fish to breed in captivity. The fish release gametes (eggs and sperm) in response to stimulation from the gonadotropin injection. The process of hypophysation involves using pituitary/hypophysis extract, which includes gonadotropins like FSH and LH that cause gametes to mature and release, to induce fish to breed.

Fish Pituitary Gland

The pituitary gland of fish is a key endocrine organ that plays a central role in regulating the neuroendocrine system, including growth, development, reproduction, and the activity of other endocrine glands. It is present in all vertebrates, from agnathans (jawless fishes) to mammals. Structurally, the gland consists of two primary components: the adenohypophysis, which originates from Rathke's pouch, and the neurohypophysis, which develops from the diencephalon (Harvey and Carolsfeld, 1993; Shanthanagouda *et al.*, 2018).

In fishes, the pituitary gland is a minute, pea-sized structure located on the ventral side of the brain within a depression known as the sella turcica. It is connected to the brain by a slender stalk. Similar to higher vertebrates, the fish pituitary coordinates various physiological functions, particularly reproduction. Among the hormones secreted by the gland, Follicle Stimulating Hormone (FSH) plays a crucial role in stimulating gonadal development and maturation, ultimately leading to the induction of spawning in fishes.



Schematic Diagram of Fish Head Showing Location of Pituitary Gland Ventral to the Brain.

Procedure of Induced Breeding Technique

The most common method of induced breeding is hormone injection in which pituitary extract or other synthetic hormone is introduced in the body of ripe breeders which may be male or female. The mechanism of induced breeding is completed in several steps.

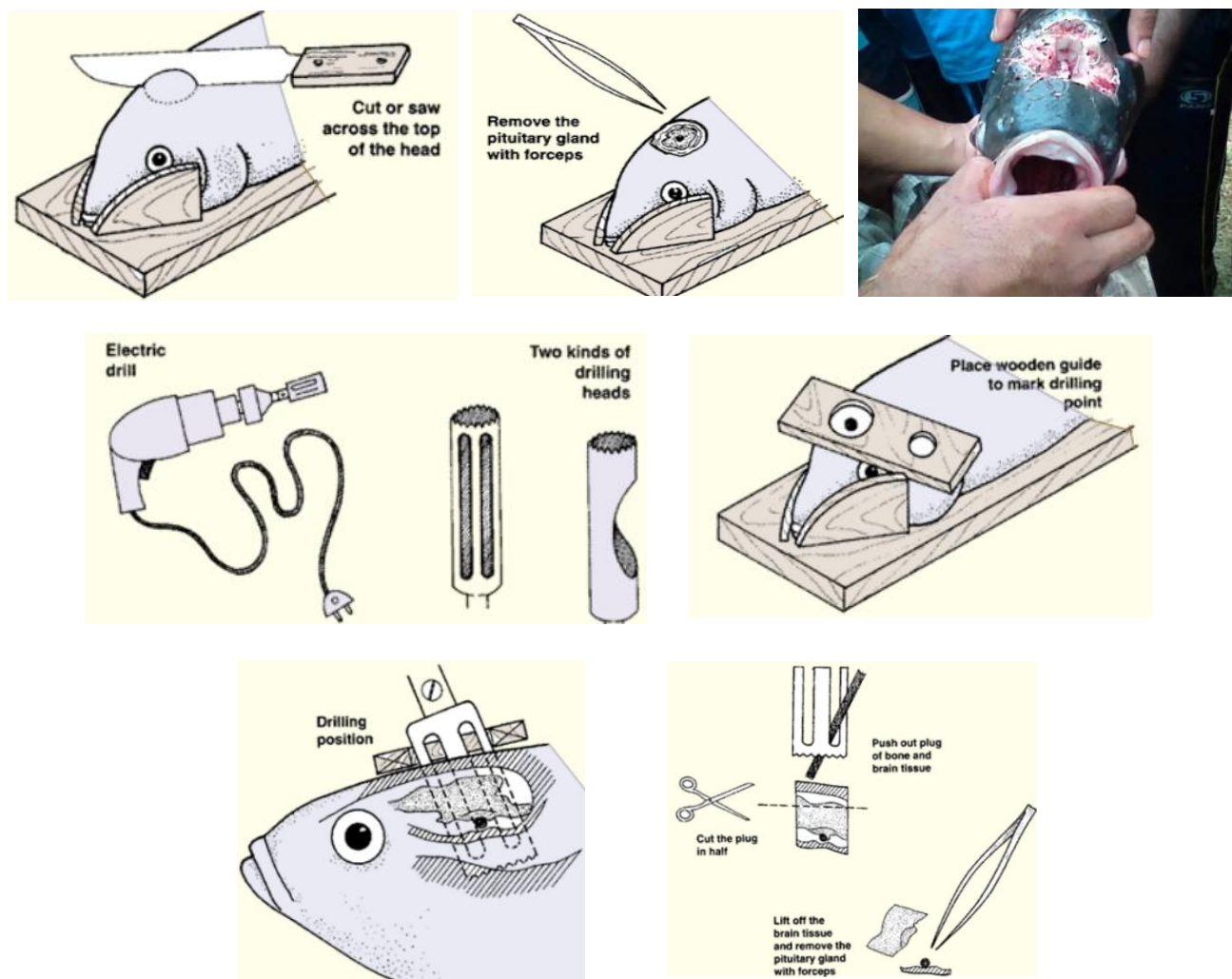
Collection of pituitary gland

The pituitary gland is collected from a fully mature donor fish. The most commonly used donor species is the common carp (*Cyprinus carpio*), as it breeds throughout the year and mature individuals are readily available year-round (Islam, 2016).

The pituitary glands can be collected using the following method:

Collection of Gland through the Foramen Magnum

First, the foramen magnum is exposed by carefully removing the vertebral portions attached to the skull. The fatty tissues are removed using forceps and cotton swabs. A pair of forceps is then gently inserted through the foramen magnum above the brain. The anterior part of the brain is carefully detached, and the remaining portion is lifted out through the opening. The pituitary gland, located at the base of the brain, is then identified and carefully removed.

Collection of Gland by Dissecting the Head

The head dissection method is comparatively less time-consuming and more economical, as the remaining head portions can later be utilized for human consumption. In this method, the fish head is first separated using a sharp butcher's knife. A portion of the scalp is removed with a single clean cut. The fatty tissues surrounding the brain are carefully cleared using cotton.

Next, the olfactory and optic nerves are severed, allowing the brain to be gently lifted and removed. The pituitary gland is then identified and located. During dissection, the gland may either come out along with the brain or remain attached to the floor of the brain cavity, often covered by a thin membrane (Das and Khan, 1962). In either case, the gland is carefully separated from the membrane or brain tissue and removed intact. Special care must be taken to avoid damaging or rupturing the gland.

Preservation of Pituitary Gland

The collected pituitary glands can be preserved for a week or longer, depending on the requirement. Immediately after collection, the glands are stored in sterile vials containing absolute alcohol to prevent degradation. The absolute alcohol preservation method is widely practiced in India, whereas the acetone-dried method is commonly used in the USSR and USA. Freezing is also employed as an alternative storage method.

The commonly used preservation methods include:

- **Absolute Ethanol Method:** Pituitary glands are preserved in absolute ethanol to maintain hormonal activity.
- **Acetone Preservation Method:** In some temperate countries, glands are preserved using acetone drying techniques.
- **Glycerine Preservation Method:** Glycerine may also be used for short-term preservation of the glands.

Preparation of Hormonal Extract from Pituitary Gland

The preserved pituitary glands collected from donor fishes are processed to prepare a hormonal extract, which is injected into mature brooders to induce spawning.

The procedure involves the following steps:

- The required quantity of pituitary glands is determined based on the total body weight and number of fish to be bred.
- The glands are first air-dried using blotting paper to remove excess preservative.
- After drying, the glands are transferred to a tissue homogenizer and crushed with a small amount of distilled water to prepare the extract.
- The grade of dilution of homogenised gland should be 2.0ml/kg of body weight of the fish.
- The pituitary extract is then centrifuged to separate the hormone and only the supernatant part of solution is utilized for injection in fishes.

The prepared extract is then used for injection into the brood fish to stimulate reproductive activity.

Selection of brood stock

Induced breeding is used to select healthy, completely ripe/gravid brood fish that weigh between 2-3 kilograms. Because they are challenging to manage, quite large brood fish are not frequently chosen. Denticulation, or the presence of tubercles, and the roughness of the dorsal side of the longer, stronger pectoral fins are two easy ways to identify ripe males. The male brood fish releases milt when the abdomen is gently pressed. The female brood fish has a large, reddish vaginal papilla in addition to a soft, protruding belly. They are removed from the main fish stocking pond and raised in a different pond as potential recipients of pituitary extract for spawning. Through liming and manuring the pond beforehand, these possible brood fish can be raised intensively. The brood stock receives synthetic feed in the form of mustard oil cake and rice bran (1:1) each day at a rate of 1% to 2% of body weight to enhance the pond's natural food supply.

Dose determination and administration of extract

The amount of pituitary extract that should be given to the brood fish in order to induce spawning varies on the recipient's body weight, sex, and gonad readiness. The dosage of each of the two injections given to female fish is based on their body weight. A first dose of 2-3 mg/kg body weight is given to Indian major carps, and a second dose of 5-12 mg/kg body weight of pituitary is given six hours later.

Male fish are also given a single dose of 2-3 mg/kg of body weight at this period. Exotic carps, such as grass carp and silver carp, only react to greater dosages, though. Male brood fish receive a single dosage of 3-4 mg of pituitary extract, whereas females of these two species receive two doses of 9-14 mg/kg body weight spaced 3-6 hours apart.

The recipient's caudal peduncle is where the pituitary extract is applied. A hypodermic syringe with a 2 ml volume that is graded to 0.1 ml is used to provide the intramuscular injection. The recipient fish is placed on its side in the hand net to administer the extract. The initial injection is typically given at noon, and the second dose is given in the evening, though there is no set time for this procedure.

Injection to the Brooders

The prepared pituitary extract is administered to sexually mature brooders to stimulate final maturation and spawning. The injection procedure varies depending on the relationship between the donor and recipient species.

Homoplastic Injection

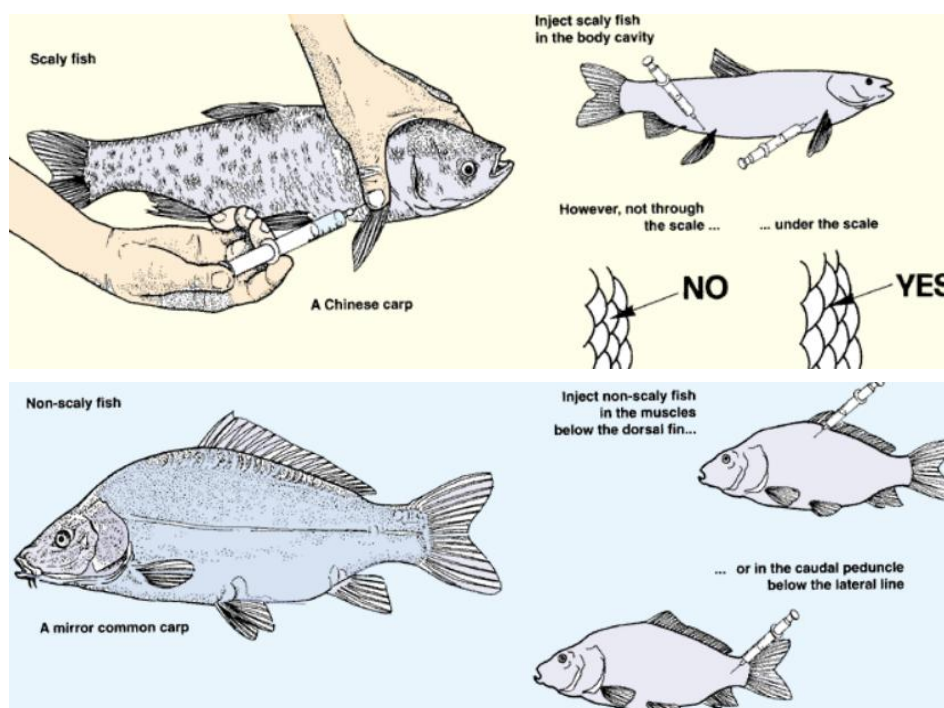
The term *homoplastic* refers to closely related species. In this method, the pituitary extract obtained from one species is injected into another closely related species belonging to the same group. For example, pituitary gland extract collected from one carp species may be used to induce breeding in another carp species.

Heteroplastic Injection

In heteroplastic injection, the pituitary gland extract from one species is administered to a distantly related species for induced breeding. For instance, pituitary extract from catfish may be used to induce spawning in carp species, or vice versa.

Spawning

After pituitary injections, the brood fish are released into the breeding hapa. This hapa, which measures roughly 3 m × 1.5 m x 1 m and is supported by four bamboo poles at four corners, is an enclosure lined with mosquito net material. In each hapa, a single set of brood fish—two females and one male—is introduced. 3 to 6 hours following the second dose of pituitary extract given to females, spawning takes place. The fish exhibit courtship behaviour prior to spawning, with the female swimming more quickly than the male. The male loses its milt as it follows the female, who continues to splash the water and release the eggs. Eggs are fertilized as a result of this coordinated spawning.



The fertilized eggs are crystalline, transparent and pearl like in appearance. Fertilized eggs remain translucent and buoyant, while unfertilized eggs appear opaque and sink. Fertilized eggs remain translucent and buoyant, while unfertilized eggs appear opaque and sink. whereas unfertilized eggs are opaque or whitish in color as shown in figure (Hossen *et al.*, 2021).



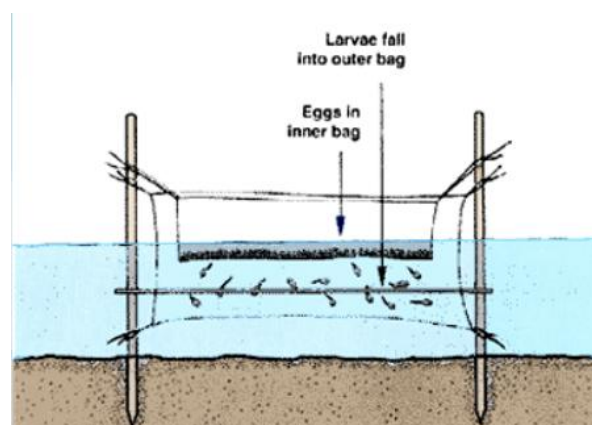
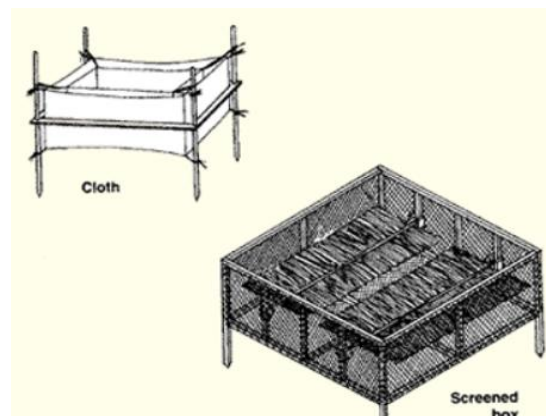
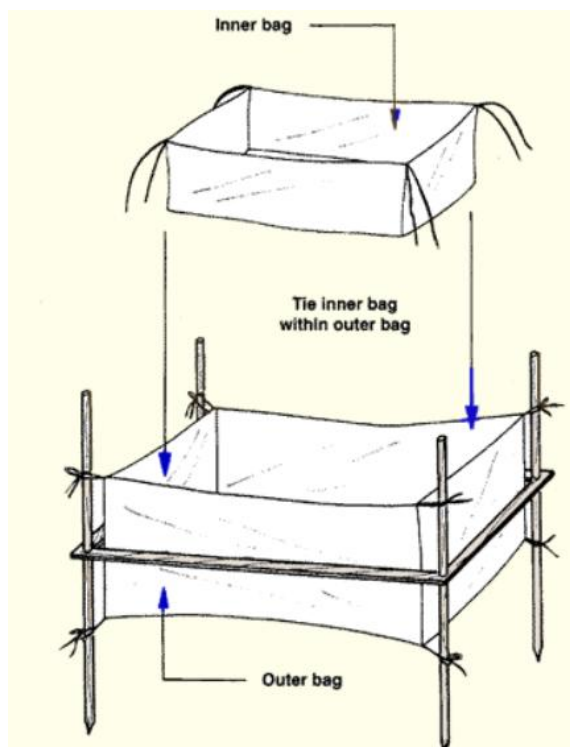
Photograph of fertilized and unfertilized eggs

Hatching

About 6 to 8 hours after fertilization, the fertilized eggs are taken away from the breeding hapa. The hatching hapa, which is really composed of two distinct hapas with one fitted inside the other, receives these fertilized eggs. The interior hapa is lined with mosquito net material, while the outer hapa is a thickly lined enclosure.

To aid in their descent to the bottom, the fertilized eggs are carefully lowered into the hapa. Each hapa contains roughly one lakh eggs. At room temperature, the eggs take between 15 to 18 hours to hatch. The hatchlings begin to move into the outer hapa via the net cloth. Hatchlings are retained in the outer hapa until yolk sac absorption is complete.

while the inner hapa—which contains the egg shells of hatched eggs and the unfertilized opaque eggs is removed. The early fry are prepared to start exogenous feeding at this point. The nursery pond is where they are moved.



Role of Other Natural And Synthetic Hormones In Induced Breeding

Hormones are essential for triggering fish reproduction. To enhance reproductive operations, dopamine antagonists are commonly used with gonadotropin-releasing hormone (GnRH) analogues. Furthermore, fish can undergo spawning and oocyte maturation in response to gonadotropin injections, such as HCG (Human Chorionic Gonadotropin) (Park *et al.*, 1992). In aquaculture and research, these hormone-based methods have been widely used to regulate and alter fish reproduction. Fish pituitary extract was originally used to promote reproduction, but because of issues with injectable preparation and preservation, synthetic hormones such as LHRH-a, HCG, WOVA-FH, Ovatile, Synahorin, and Ovaprim are now utilized for induced breeding.

LHRH-a and Domperidone

In bighead carp, *Hypophthalmichthys nobilis* (Richardson), oocyte maturation and ovulation are induced by LHRH-a (luteinizing hormone-releasing hormone agonist) and domperidone (Armandto C F, 1991).

Human Chorionic Gonadotropin or HCG

HCG is used to cause fish to ovulate. HCG provides three main benefits: HCG is a more economical option. Because of its improved stability, it has a longer shelf life. There is a purified version of it accessible.

WOVA-FH:

WOVA-FH, a synthetic analogue of gonadotropin releasing hormone (SGnRH), has demonstrated efficacy in inducing breeding in catfish, exotic carp, and Indian major carp. Fish reproductive processes are frequently manipulated by SGnRHs, and their ability to successfully induce breeding makes them an important tool for aquaculture and fisheries management.

Ovatile

Ovatile is an endemic, less expensive hormone that is used to encourage fish breeding. It works very well for major carps. Varying carp species have varying dosages. For example, silver carps and carp have 0.20-0.25 ml/kg, whereas Rohu and Mrigal have 0.20-0.40 ml/kg and Catla has 0.20-0.30 ml/kg. The hatching and fertilization rates are high, ranging from 85 to 95 percent.

Synahorin

When combined with pituitary extract, synahorin—a mixture of CG (chorionic gonadotropin) and mammalian pituitary extract—was successful in triggering spawning in both rohu and silver carp. However, rohu did not properly induce spawning when given synahorin alone.

Ovaprim

Ovaprim is a pituitary gland extract substitute and the novel fish gonadotropin hormone analog. When it comes to promoting spawning in different carp species, ovaprim is frequently thought to be superior to carp pituitary extract (Marte *et al.* 1987, Sharma and Singh 2012, Nandeesh et al. 1990). When "ovaprim" is used instead of pituitary extract, it has been found that "rohu" produces more eggs. When ovaprim was utilized, the number of eggs produced rose from 1.15 lakh to 1.41 lakh. It is a complete replacement for pituitary extract and the new inducing hormone for fish.

Conclusion

Induced breeding has become an indispensable technology in modern aquaculture. By enabling controlled reproduction through hormonal manipulation, it ensures consistent fish seed production and reduces reliance on natural spawning grounds. Continued research on hormone optimization,

broodstock nutrition, and hatchery management will further enhance its efficiency and sustainability.

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IN SITU HYBRIDIZATION: A WINDOW INTO THE HIDDEN WORLD OF GENES

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Abstract

In situ hybridization (ISH) is a powerful molecular technique used to detect and localize specific DNA or RNA sequences within cells and tissues. It is based on the principle of complementary base pairing between a labeled probe and a target sequence. Advanced forms of ISH include fluorescence in situ hybridization (FISH) and genomic in situ hybridization (GISH). FISH uses fluorescent probes to identify specific genes or chromosomal regions with high resolution, making it useful in gene mapping and medical diagnostics. GISH employs total genomic DNA as a probe to differentiate between parental genomes, especially in hybrids and polyploids. These techniques are widely used in cytogenetics, plant breeding, and genome analysis. Despite some limitations, ISH, FISH, and GISH remain essential tools for studying gene structure, function, and genome organization in modern biological research.

Keywords: In situ hybridization, FISH, GISH, DNA probe, cytogenetics

Introduction

In situ hybridization (ISH) is an important molecular biology technique used to detect specific DNA or RNA sequences within their natural location in cells and tissues. It has greatly improved our understanding of gene structure, function, and expression. Earlier methods of gene identification were time-consuming and lacked precision, but ISH made it possible to visualize genes directly on chromosomes. This technique plays a key role in cytogenetics, plant breeding, and medical diagnostics. ISH helps bridge the gap between genetic mapping and physical mapping of chromosomes. Over time, ISH has been further developed into advanced forms for better accuracy and visualization. The two major types of ISH are fluorescence in situ hybridization (FISH) and genomic in situ hybridization (GISH). These methods provide detailed insights into genome organization. Thus, ISH is a powerful tool in modern biology.

What is In Situ Hybridization (ISH)?

In situ hybridization is a technique that allows the localization of specific nucleic acid sequences within intact cells or tissues. It works on the principle of complementary base pairing between a probe and a target sequence. The probe is a labeled fragment of DNA or RNA designed to bind specifically to the sequence of interest. Once the probe binds to its target, the location can be detected using various labeling systems. ISH can be applied to chromosomes, tissues, or even whole cells. It helps in identifying gene position and studying gene expression. The technique is highly specific and sensitive. It is widely used in research and diagnostics. ISH forms the base for advanced techniques like FISH and GISH. Therefore, it is fundamental in molecular cytogenetics.

Fluorescence In Situ Hybridization (FISH)

Fluorescence in situ hybridization (FISH) is a type of ISH that uses fluorescently labeled probes to detect specific DNA sequences. When exposed to light of a particular wavelength, these probes

emit fluorescence, making it possible to visualize gene locations. FISH provides high-resolution images of chromosomes and gene positions. It is widely used for gene mapping and detecting chromosomal abnormalities such as deletions, duplications, and translocations. The technique allows simultaneous detection of multiple sequences using different colored probes. FISH can be performed on both dividing and non-dividing cells. It is faster and more sensitive compared to traditional methods. It is extensively used in medical diagnostics and plant cytogenetics. Thus, FISH is a powerful and widely applied ISH technique.

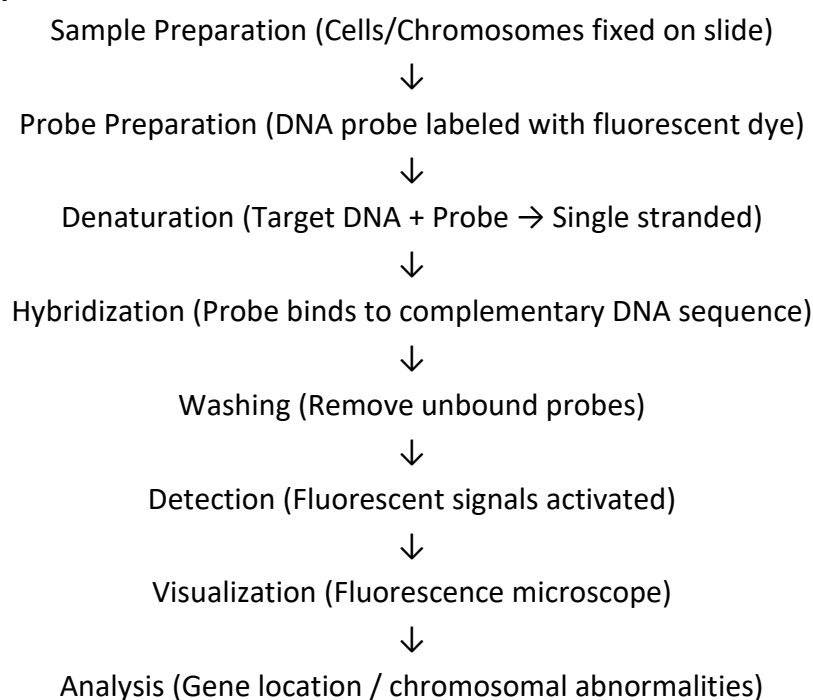
Genomic In Situ Hybridization (GISH)

Genomic in situ hybridization (GISH) is a modified form of FISH used mainly to distinguish between different genomes. It uses total genomic DNA as a probe instead of specific sequences. GISH is particularly useful in studying hybrids, polyploids, and interspecific crosses. It helps identify the origin of chromosomes from different parental species. A blocking DNA is used to prevent non-specific binding of probes. This allows clear differentiation of genomes within a single cell. GISH is widely used in plant breeding and evolutionary studies. It helps in understanding genome organization and hybridization events. The technique also aids in studying chromosome behavior during meiosis. Therefore, GISH is an essential tool in genome analysis.

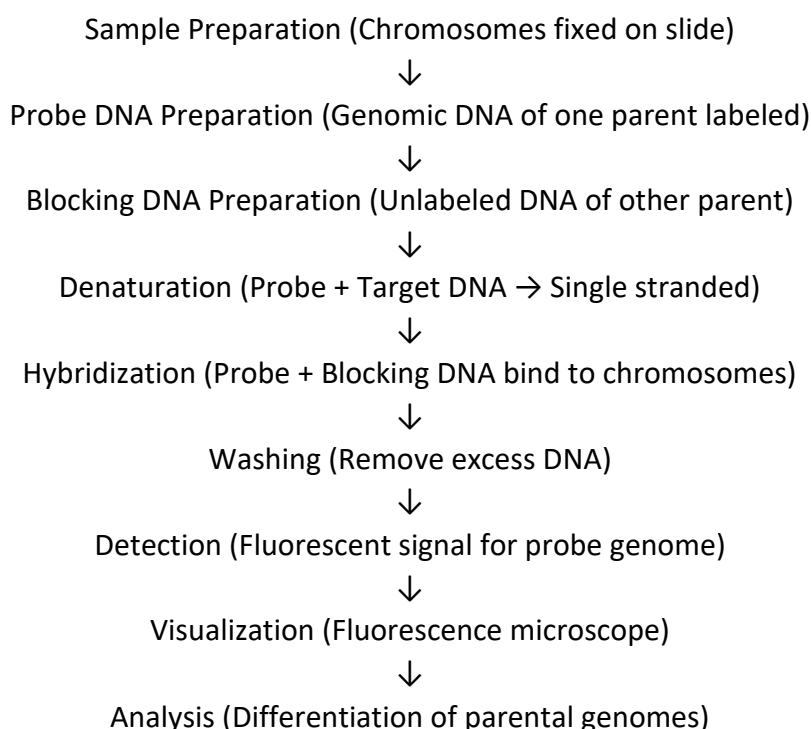
Differences Between FISH and GISH

Although both FISH and GISH are based on ISH principles, they differ in their applications and probe types. FISH uses specific DNA probes to detect particular genes or sequences. In contrast, GISH uses whole genomic DNA to differentiate between genomes. FISH is mainly used for gene mapping and detecting chromosomal abnormalities. GISH is used to study hybrid genomes and genome evolution. FISH provides very high specificity, while GISH depends on blocking DNA for accuracy. Both techniques use fluorescence for visualization. They complement each other in cytogenetic studies. Together, they provide a complete understanding of genome structure. Thus, both are important extensions of ISH.

Procedure of FISH



Procedure of GISH



Applications of ISH

ISH and its variants have wide applications in different fields of biology. FISH is used for gene mapping, detecting genetic disorders, and chromosome analysis. GISH is mainly used in plant breeding to study hybridization and genome composition. These techniques help identify the location of genes on chromosomes. They are also useful in studying gene expression patterns. In medical research, they are used for disease diagnosis. They support evolutionary studies and genome research. These methods provide accurate and reliable results. They are essential tools in modern biotechnology. Thus, ISH techniques have diverse applications.

Advantages of ISH Techniques

ISH techniques offer several advantages in genetic analysis. They provide precise localization of genes within cells. The methods are highly specific and sensitive. FISH allows simultaneous detection of multiple targets. GISH helps differentiate closely related genomes. These techniques can be used on intact cells and tissues. They reduce the need for DNA extraction and purification. ISH methods are widely applicable in research and diagnostics. They provide visual confirmation of gene presence. Continuous advancements have improved their efficiency. Therefore, ISH techniques are highly valuable in molecular biology.

Limitations of ISH Techniques

Despite their advantages, ISH techniques have certain limitations. They require careful sample preparation for accurate results. Background fluorescence can interfere with signal detection. The techniques are relatively expensive and require specialized equipment. Skilled personnel are needed to perform and interpret the results. ISH cannot detect very small mutations easily. Probe availability is limited for some sequences. Closely related genomes may be difficult to distinguish in GISH. Technical errors can affect accuracy. Continuous improvements are needed to overcome these challenges. Thus, understanding limitations is important.

Conclusion

In situ hybridization is a powerful technique that has revolutionized the study of genetics and cytogenetics. Its major forms, FISH and GISH, provide detailed insights into gene location and genome organization. FISH is widely used for detecting specific DNA sequences, while GISH is useful for studying hybrid genomes. Together, they enhance our understanding of genetic structure and function. These techniques have important applications in research, plant breeding, and medical diagnostics. Despite some limitations, they remain essential tools in modern biology. Advances in technology continue to improve their accuracy and efficiency. Thus, ISH and its variants play a crucial role in scientific research.

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AQUAPORINS: FUNCTIONAL DYNAMICS AND REGULATORY CONTROL

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Introduction

Aquaporins constitute a highly conserved superfamily of integral membrane proteins known as Major Intrinsic Proteins (MIPs), which facilitate the selective transport of water and certain small neutral solutes across biological membranes. These proteins are ubiquitously present in organisms ranging from bacteria to higher plants and animals, reflecting their fundamental role in cellular water homeostasis. Plant aquaporins typically possess molecular masses in the range of 26–34 kDa and are characterized by six transmembrane α -helices connected by five loops, with two highly conserved Asn-Pro-Ala (NPA) motifs that form the water-selective pore. In plants, aquaporins are classified into several subfamilies based on sequence homology and subcellular localization, including plasma membrane intrinsic proteins (PIPs), tonoplast intrinsic proteins (TIPs), nodulin-26-like intrinsic proteins (NIPs), small basic intrinsic proteins (SIPs), and X-intrinsic proteins (XIPs). The first plant aquaporin to be identified was Nodulin-26 from the root nodules of soybean (*Glycine max*) in 1987, where it was found to be abundantly expressed in the symbiosome membrane of nitrogen-fixing nodules. This discovery provided the earliest evidence of aquaporin involvement in plant–microbe symbiotic processes, particularly in regulating solute and water exchange between host cells and symbiotic bacteria. Subsequent functional characterization demonstrated that Nodulin-26 facilitates not only water transport but also the movement of small solutes such as glycerol and ammonia, highlighting the broader physiological roles of MIPs beyond simple water conduction.

The water transport capability of plant aquaporins was later conclusively demonstrated through heterologous expression studies, notably in oocytes and yeast systems, using aquaporin genes from *Arabidopsis thaliana*. These experiments showed dramatic increases in membrane water permeability, establishing aquaporins as the primary mediators of rapid transmembrane water flow in plant cells. Following this foundational work, aquaporins have been identified and functionally characterized in a wide range of herbaceous and woody (lignaceous) plant species, both wild and cultivated, including major crops and forest trees. Their expression is tightly regulated by developmental cues and environmental factors such as drought, salinity, flooding, temperature extremes, and nutrient availability. In roots, aquaporins control radial water movement from the soil into the vascular system; in leaves, they influence cell expansion, stomatal function, and mesophyll conductance; and in reproductive tissues, they contribute to pollen hydration and seed development. Moreover, post-translational modifications such as phosphorylation, pH-dependent gating, and interactions with membrane lipids enable rapid adjustment of channel activity in

response to changing physiological conditions. Collectively, these findings underscore that plant aquaporins are central components of plant water relations, coordinating cellular and whole-plant hydraulic conductivity and enabling plants to maintain water balance under fluctuating environmental conditions.

Classification of MIPs according to their substrate specificity and sequence similarities

Major Intrinsic Proteins (MIPs) are broadly classified into three principal subfamilies based on sequence homology and substrate specificity:

1. AQPs (aquaporins) involved in water and ion transport;
2. GLPs (glycerol-facilitators) permeable to glycerol and neutral molecules; and
3. GLAs (aquaglyceroporins) permeable to both water and glycerol

Aquaporins categorized into seven subfamilies according to their intracellular locations and sequence similarities

- a) Plasma membrane intrinsic proteins (PIPs),
- b) Tonoplast intrinsic proteins (TIPs),
- c) NOD26-like intrinsic proteins (NIPs)
- d) Small, basic intrinsic proteins (SIPs),
- e) The GlpF-like intrinsic proteins (GIPs),
- f) Hybrid intrinsic protein (HIP), and
- g) X intrinsic protein (XIP)

Each MIP subfamily is further subdivided into distinct groups based on finer differences in sequence characteristics, subcellular localization, and functional properties. For instance, plasma membrane intrinsic proteins (PIPs) are classified into two principal subgroups, namely PIP1 and PIP2. These subgroups differ in their permeability characteristics, regulatory mechanisms, and interaction patterns within the membrane. Furthermore, each subgroup comprises multiple isoforms, designated using a standardized nomenclature such as PIP1;1, PIP1;2, and so forth. Individual isoforms often exhibit tissue-specific expression, unique subcellular distribution, and specialized physiological roles, reflecting functional diversification within the family. Such hierarchical classification, from subfamily to subgroup to isoform enables precise regulation of water transport and solute movement in accordance with developmental stage, cell type, and environmental conditions.

Structure of aquaporin

Aquaporins are integral membrane proteins characterized by six membrane-spanning α -helices (H1–H6), with both the amino (N-) and carboxyl (C-) termini oriented toward the cytoplasmic side of the membrane. These helices are interconnected by five loops, designated A through E. Among them, loops B and E are structurally distinctive, as each folds into a short hydrophobic α -helix that penetrates halfway into the lipid bilayer from opposite sides of the membrane. The convergence of these two intramembrane helices, together with the surrounding transmembrane segments, creates a narrow aqueous channel across the membrane. This channel exhibits high substrate selectivity, primarily determined by two key constriction or filter regions within the pore, which regulate the passage of water molecules while excluding ions and other solutes.

Response of plant aquaporin isoforms to environmental stimuli

Plasma membrane intrinsic proteins (PIPs) and tonoplast intrinsic proteins (TIPs) are highly responsive to abiotic stresses such as drought, salinity, and low temperature, all of which disrupt cellular osmotic balance, root hydraulic conductivity, and transpiration dynamics. By modulating membrane water permeability, these aquaporins play a crucial role in maintaining cellular turgor,

regulating water uptake, and adjusting whole-plant water relations under stress conditions. In contrast, nodulin-26-like intrinsic proteins (NIPs) are more closely associated with biotic stress responses and participate in maintaining nutrient homeostasis during plant–pathogen interactions. They are thought to regulate the movement of small solutes at the host–pathogen interface, thereby influencing defense responses and metabolic balance. Furthermore, both NIPs and TIPs have been reported to physically or functionally interact with certain pathogen-derived proteins, suggesting that these aquaporins may serve as important components in the molecular dialogue between plants and invading microorganisms.

Aquaporin-Mediated Regulation of Root and Leaf Hydraulics

Plants possess a highly developed capacity to perceive environmental cues and dynamically adjust their water transport characteristics to maintain internal homeostasis. Root hydraulic conductivity (L_{pr}), which reflects the efficiency of water movement from the soil into the root vascular system, is particularly sensitive to soil-imposed abiotic stresses. Conditions such as salinity, hypoxia or oxygen deprivation (e.g., waterlogging), and nutrient deficiency commonly lead to a pronounced decline in L_{pr} across many plant species. This reduction is largely mediated through the downregulation or gating of root aquaporins, especially plasma membrane intrinsic proteins, thereby limiting water influx when soil conditions impair root function or threaten cellular integrity. Such modulation helps prevent excessive ion uptake under saline conditions and reduces metabolic demand when oxygen or nutrients are scarce.

In aerial tissues, environmental signals such as light intensity (irradiance) and endogenous chemical regulators play crucial roles in controlling water loss and internal water distribution. Irradiance strongly influences stomatal opening by stimulating photosynthetic activity, thereby increasing transpirational demand. Concurrently, the phytohormone Absciscic acid (ABA) acts as a central stress signal, particularly under drought conditions, inducing stomatal closure to minimize water loss. Beyond its effects on guard cells, ABA also modulates aquaporin expression and activity in leaf tissues, thereby regulating leaf hydraulic conductance independently of stomatal behavior. Through coordinated control of stomatal aperture and aquaporin-mediated membrane permeability, plants can finely tune both water uptake and water loss. This integrated regulation ensures the maintenance of hydraulic balance along the soil–plant–atmosphere continuum, allowing plants to survive and function under fluctuating environmental conditions.

Aquaporin-mediated plant nutrient uptake

Aquaporins play a crucial role in boron transport, particularly in facilitating the movement of boric acid across plant membranes. Evidence for this function was first reported in squash roots, where plasma membrane vesicles exhibited boric acid permeability approximately six times greater than that of microsomal vesicles. In *Arabidopsis thaliana*, AtNIP5;1 was identified as the first aquaporin significantly involved in boron uptake from the soil. Additional channels, AtNIP6;1 and AtNIP7;1, were found to be selectively expressed in leaf nodes and floral anthers, respectively, indicating tissue-specific roles in boron distribution. Furthermore, studies by Boursiac *et al* demonstrated a cooperative transport mechanism involving AtNIP5;1 and AtBOR1. In this system, AtNIP5;1 facilitates the influx of boric acid [$B(OH)_3$] into root cells, while AtBOR1 functions as a secondary active efflux transporter exporting borate [$B(OH)_4^-$] into the xylem for long-distance transport.

In rice (*Oryza sativa*), OsNIP2;1 was identified as the first aquaporin functioning as a silicon transporter, facilitating the uptake of silicic acid from the soil. This protein, along with its maize

homolog ZmNIP2;1 in maize (*Zea mays*), is localized on the distal sides of exodermal and endodermal root cells, enabling directional influx of silicic acid into root tissues. OsNIP2;1 operates in coordination with the efflux transporter Lsi2 to move silicon from root cells into the stele and vascular system for long-distance transport. Another homolog, Lsi6 (OsNIP2;2), is polarly localized in xylem transfer cells at rice nodes and is involved in unloading silicon from the xylem to support its redistribution, particularly toward developing panicles.

Ammonium/ammonia ($\text{NH}_4^+/\text{NH}_3$) represents a major nitrogen source for crops, traditionally absorbed via specific ammonium transporters, while NH_3 was long assumed to diffuse passively across membranes. However, plant–microbe symbioses have revealed an important role for aquaporins in facilitating ammonia movement. During symbiotic interactions such as mycorrhiza and biological nitrogen fixation, host plants exhibit marked changes in aquaporin expression; for example, GmNOD26 in soybean (*Glycine max*) is localized to the peribacteroid membrane of N_2 -fixing nodules. This protein functions as an NH_3 -permeable channel and interacts with cytosolic glutamine synthetase, forming a metabolite “funnel” that enhances the efficiency of ammonia assimilation. Additionally, certain fungal aquaporins expressed in ectomycorrhizal associations display high NH_3 permeability and facilitate ammonia export from fungal cells into the plant apoplast. Together, these mechanisms highlight the coordinated role of plant and microbial aquaporins in symbiotic nitrogen acquisition.

Modes of aquaporin regulation

1. Co-translational and post-translational modifications

Phosphorylation is the most widespread post-translational modification of aquaporins, regulating channel gating, trafficking, and water permeability in response to environmental and cellular signals. Glycosylation has been reported in only a few homologs, notably GmNOD26 from soybean (*Glycine max*) and a tonoplast aquaporin from *Mesembryanthemum crystallinum* (ice plant), suggesting a limited but specialized role in protein stability or membrane targeting. Evidence of methylation was first demonstrated in AtPIP2;1 of *Arabidopsis thaliana*, where Lys3 and Glu6 residues were found to be di- and mono-methylated, respectively, indicating an additional layer of biochemical regulation.

2. Gating

The gating of plant aquaporins, referring to the reversible opening and closing of the water channel pore is regulated by several physicochemical effectors that modulate membrane water permeability. Key regulators include phosphorylation, cytosolic proton concentration (H^+/pH), and divalent cations such as Ca^{2+} , which influence channel conformation and activity. Activation of aquaporins through phosphorylation was first demonstrated in PvTIP3;1 of pea (*Pisum sativum*), GmNOD26 of soybean (*Glycine max*), and SoPIP2;1 of spinach (*Spinacia oleracea*), where protein kinases and phosphatases were shown to control channel opening. Among the regulatory factors, protons and Ca^{2+} are particularly effective, especially for plasma membrane intrinsic proteins (PIPs), as changes in cytosolic pH or calcium levels can rapidly inhibit or activate water transport. Through these mechanisms, plants achieve dynamic control of cellular hydraulics in response to environmental and metabolic signals.

3. Cellular trafficking

Regulated intracellular trafficking is a crucial mechanism controlling the abundance, localization, and functional expression of plant aquaporins. Plasma membrane intrinsic proteins of the PIP1

subgroup typically exhibit little or no water transport activity when expressed alone in *Xenopus laevis* oocytes, largely due to inefficient targeting to the plasma membrane; this limitation is overcome when PIP1s are co-expressed with PIP2 isoforms, which facilitate proper membrane insertion. Stress-induced trafficking of aquaporins was first demonstrated for McTIP1;2 in *Mesembryanthemum crystallinum* (ice plant), where the protein relocates from the tonoplast to intracellular vesicles under osmotic stress. This redistribution occurs through a glycosylation-dependent mechanism, highlighting the importance of post-translational modification in controlling aquaporin localization. Such dynamic trafficking enables rapid adjustment of membrane water permeability in response to environmental changes.

Conclusion

Aquaporins (Major Intrinsic Proteins) constitute a diverse and highly regulated family of membrane channels that extend far beyond their classical role in water transport. Their structural specialization, subfamily diversification, and isoform-specific expression enable precise control of cellular permeability in response to developmental and environmental cues. In addition to regulating root and leaf hydraulics under abiotic stress, aquaporins facilitate the transport of essential nutrients and metalloids such as boron, silicon, and ammonia, thereby contributing to plant nutrition and metabolic efficiency. Their involvement in both abiotic and biotic interactions, including symbiotic associations with microorganisms, underscores their integrative role in plant adaptation.

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MECHANISMS AND MOLECULAR ADAPTATIONS OF PLANT GRAVITROPISM: FROM TERRESTRIAL ORIENTATION TO MICROGRAVITY STRESS

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Introduction

Plants have developed intricate sensory systems to navigate and exploit their immediate environment. Among these mechanisms, gravitropism is arguably the most critical for survival. It ensures that root systems penetrate the soil for water and nutrient acquisition, a process termed positive gravitropism, while shoots extend upward toward light sources for photosynthetic optimization, known as negative gravitropism. This directional growth is far more than a passive physical reaction; it is a highly regulated physiological sequence involving specialized cell populations, precise hormonal redistributions, and significant genomic plasticity. As humanity pursues long term space exploration and the establishment of extraterrestrial agriculture, understanding these molecular pathways becomes essential for ensuring food security in environments characterized by altered gravity.

The Tripartite Model of Gravitropism

Gravity Sensing: The Starch Statolith Hypothesis

The initial phase of gravitropism occurs in specialized cells known as statocytes. In the shoot system, these cells are typically located within the endodermal layer. In the root system, they are localized specifically in the columella cells of the root cap. The prevailing model for perception is the starch statolith hypothesis. This theory posits that gravity is detected through the sedimentation of amyloplasts, which are dense organelles filled with starch.

Under the gravity of Earth, these amyloplasts function as statoliths by settling toward the lower side of the cell. This physical movement provides the primary mechanical signal indicating the orientation of the plant relative to the gravitational vector. Recent research suggests that the sedimentation of these organelles exerts pressure on the actin cytoskeleton and the endoplasmic reticulum, which may initiate the subsequent signaling cascade through mechanosensitive ion channels.

Signal Transduction: The LAZY Signaling Pathway

The transition from the physical sedimentation of amyloplasts to a biochemical signal is a complex process mediated by the LAZY protein family. Upon the shifting of amyloplasts, phosphorylated LAZY proteins are observed to relocate to the lower side of the plasma membrane. This relocation often involves interactions with the TOC complex, or the translocon on the outer membrane of chloroplasts.

The repolarization of these proteins initiates a cascade of second messengers. Key molecules identified in this stage include Calcium ions, variations in cytoplasmic pH, and Inositol trisphosphate.

These messengers act to amplify the initial mechanical signal and trigger a directional chemical gradient. The goal of this transduction phase is to establish a cellular polarity that dictates the direction of hormone transport in the final stage of the response.

Curvature Response: The Cholodny Went Model and Auxin Transport

The final stage of gravitropism is the visible manifestation of differential growth, primarily driven by the phytohormone auxin, specifically Indole 3 acetic acid. According to the Cholodny Went model, the biochemical signals generated during transduction cause auxin to be transported asymmetrically. This transport is mediated by PIN formed proteins, which are specialized efflux carriers that relocate to specific sides of the cell membrane.

High concentrations of auxin on the lower side of the organ stimulate rapid cell elongation. Consequently, the lower cells grow faster than those on the upper side, forcing the shoot to curve upward. The physiological response to auxin is inverted. High concentrations of auxin on the lower side of the root actually inhibit cell elongation. Therefore, the cells on the upper side continue to grow at a normal rate, resulting in a downward curvature of the root tip toward the gravitational pull.

Physiological Impact of Microgravity

When plants are cultivated in microgravity environments, such as the International Space Station, the absence of a dominant gravitational vector leads to significant disorientation across phenotypic, cellular, and molecular levels.

Phenotypic and Cellular Disorientation

At the phenotypic level, the most striking observation is the randomization of root growth patterns. Without a gravitational guide, roots exhibit a random walk morphology rather than a direct downward trajectory. Furthermore, plants in microgravity frequently display increased branch and silique angles, delayed onset of flowering, and a measurable reduction in both seed size and nutritional quality.

At the cellular level, the lack of weight prevents amyloplast sedimentation. Amyloplasts remain dispersed throughout the cytoplasm, failing to trigger the LAZY protein relocation. This lack of mechanical stimulation correlates with changes in cell wall composition. Specifically, cell walls often become thinner and less rigid because the plant no longer requires structural reinforcement to oppose a 1g force. Interestingly, microgravity is often linked with enhanced cell proliferation, where the plant produces a higher number of cells that are smaller and less specialized than their terrestrial counterparts.

Molecular and Epigenetic Stress Responses

The molecular profile of a plant in microgravity is characterized by a state of chronic physiological stress. The disruption of normal metabolic pathways leads to the overproduction of Reactive Oxygen Species, or ROS. These unstable molecules, such as hydrogen peroxide, can cause oxidative damage to cellular membranes, proteins, and DNA. In response, the plant activates an extensive antioxidant defense network.

A critical discovery in space biology involves the role of epigenetic regulation. To adapt to the unique stress of weightlessness, plants undergo a comprehensive reprogramming of gene expression. This is facilitated through DNA methylation and histone modifications, which function as chemical tags to turn specific genes on or off without altering the underlying genetic sequence.

Studies have shown that microgravity induces specific changes in the methylation status of genes associated with cell wall remodeling, hormone signaling, and environmental stress. For example, the downregulation of genes responsible for lignin synthesis allows for thinner walls, while the upregulation of heat shock proteins and antioxidant enzymes helps the plant survive the oxidative stress. This epigenetic plasticity represents a survival mechanism, allowing the plant to rewrite its operational instructions to compensate for the missing gravitational signal.

Conclusion

Plant gravitropism is a remarkable feat of biological engineering that translates the constant pull of gravity into organized growth and development. While Earth based studies have defined the role of the starch statolith and auxin gradients, microgravity research has revealed the profound resilience and adaptive capacity of the plant genome. By utilizing epigenetic regulation and complex molecular crosstalk, plants attempt to maintain homeostasis in an environment they never encountered during their evolutionary history. Mastering these molecular nuances will be the cornerstone of developing sustainable life support systems for future lunar and Martian colonies.

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RESTORING INDIA'S SOIL CAPITAL THROUGH REGENERATIVE AGRICULTURE: POLICY PATHWAYS AND PRACTICE-BASED TRANSITION

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Abstract

India's agricultural sustainability is increasingly threatened by declining soil health, driven by intensive cultivation, imbalanced fertilization, and climate variability. Soil organic carbon depletion, nutrient imbalances, and land degradation affect nearly one-third of the country's geographical area. Regenerative agriculture (RA) offers a transformative pathway by restoring soil capital, enhancing biodiversity, and improving ecosystem resilience. This paper examines the concept of soil capital, evaluates the extent and drivers of soil degradation in India, and assesses the scientific basis and benefits of RA. It further reviews existing policy frameworks and identifies gaps that hinder large-scale adoption. A transition framework is proposed, integrating soil-centric management, diversified cropping systems, integrated nutrient management, and digital innovations. Policy recommendations include subsidy reforms, carbon farming incentives, and strengthening extension systems. The study concludes that regenerative agriculture can play a critical role in achieving sustainable intensification, climate resilience, and long-term food security in India.

Keywords : Regenerative agriculture; Soil organic carbon; Soil health; Sustainable agriculture; Climate resilience; India; Soil restoration

Introduction

Soil is the foundation of agricultural productivity and ecological stability. In India, where agriculture supports nearly half of the population, soil health is directly linked to food security, livelihoods, and economic development. However, decades of input-intensive agriculture have led to significant soil degradation, threatening long-term sustainability.

The Green Revolution marked a turning point in India's agricultural history by ensuring food self-sufficiency through high-yielding varieties, irrigation expansion, and increased fertilizer use. While these interventions enhanced productivity, they also promoted monocropping, excessive tillage, and imbalanced nutrient application. Over time, these practices have resulted in declining soil organic carbon (SOC), nutrient deficiencies, and reduced soil biodiversity.

Recent estimates indicate that approximately 36.6% of India's land is degraded, with widespread deficiencies in essential nutrients and SOC levels falling below 0.5% in many regions (ICAR, 2025). Climate change further exacerbates these issues by intensifying erosion, altering rainfall patterns, and increasing soil salinity.

In this context, regenerative agriculture (RA) has emerged as a promising approach that focuses on restoring soil health through ecological processes. Unlike conventional systems, RA emphasizes rebuilding soil organic matter, enhancing biodiversity, and improving resilience. This paper explores

the potential of RA to restore soil capital in India and outlines policy and practice-based strategies for its adoption.

Soil Capital: Concept and Significance

Soil capital refers to the cumulative value of soil's physical, chemical, and biological properties that sustain agricultural productivity and ecosystem services. It includes soil organic matter, nutrient availability, structure, and microbial diversity.

Healthy soil capital supports crop growth, enhances water retention, and facilitates nutrient cycling. It also plays a critical role in carbon sequestration, thereby contributing to climate change mitigation. Conversely, the depletion of soil capital leads to reduced productivity, increased input requirements, and environmental degradation.

In India, declining SOC is a major concern, as it directly affects soil structure, water-holding capacity, and nutrient availability. Restoring soil capital is therefore essential for achieving sustainable agricultural intensification and resilience to climate variability.

Status of Soil Degradation in India

Extent and Types: Soil degradation in India has emerged as a critical constraint to sustainable agricultural productivity and environmental stability. Current estimates indicate that nearly 36–37% of the country's total geographical area is affected by various forms of land degradation. Among these, water erosion is the most dominant, affecting over 70 million hectares, particularly in regions with undulating topography and intense monsoonal rainfall. This process leads to the loss of fertile topsoil, decline in soil organic matter, and reduced nutrient availability.

Wind erosion is another significant concern in arid and semi-arid regions, especially in western India, where sparse vegetation cover and high wind velocity accelerate soil loss. Additionally, salinity and alkalinity affect approximately 6–7 million hectares, primarily in irrigated areas with poor drainage and excessive groundwater extraction. These conditions impair soil structure, reduce permeability, and limit crop productivity.

Nutrient depletion is widespread across both rainfed and irrigated systems. Continuous cropping without adequate replenishment of nutrients has resulted in multi-nutrient deficiencies, including nitrogen, phosphorus, potassium, and micronutrients such as zinc and iron. A major concern is the decline in soil organic carbon (SOC), which has fallen below critical thresholds (<0.5%) in many intensively cultivated regions, adversely affecting soil structure, water retention, and biological activity.

Key Drivers: The degradation of soil resources in India is largely driven by unsustainable agricultural practices and resource mismanagement. One of the primary factors is the imbalanced use of fertilizers, characterized by excessive nitrogen application relative to phosphorus and potassium. This imbalance disrupts soil nutrient dynamics and reduces fertilizer-use efficiency.

Monocropping systems, particularly the rice–wheat rotation in the Indo-Gangetic Plains, have further exacerbated soil degradation by depleting specific nutrients and reducing biodiversity. Intensive tillage practices contribute to soil structure breakdown, increased erosion, and loss of soil moisture.

Crop residue burning, a common practice in several regions, leads to the loss of valuable organic matter and nutrients, while also contributing to air pollution and greenhouse gas emissions.

Groundwater depletion, driven by over-irrigation and unsustainable extraction, not only reduces water availability but also contributes to soil salinization and nutrient imbalances.

Collectively, these drivers have led to a significant decline in SOC levels, disruption of soil microbial activity, and deterioration of overall soil health.

Climate Change Linkages: Climate change acts as a multiplier of soil degradation processes, intensifying both their rate and impact. Increased rainfall intensity, a key feature of changing climate patterns, accelerates soil erosion by enhancing surface runoff and detaching soil particles. In contrast, prolonged dry spells reduce vegetation cover, making soils more susceptible to wind erosion.

Rising temperatures further exacerbate the problem by accelerating the decomposition of organic matter, leading to a decline in SOC levels. This not only reduces soil fertility but also diminishes the soil's capacity to retain moisture and nutrients.

In coastal and irrigated regions, sea-level rise and excessive irrigation contribute to salinity intrusion, adversely affecting soil quality and crop productivity. Additionally, increased frequency of extreme weather events such as floods and droughts disrupts soil structure and nutrient dynamics.

These climate-induced stresses significantly reduce soil resilience and agricultural productivity, underscoring the urgent need for adaptive and regenerative soil management strategies.

Regenerative Agriculture: Principles and Scientific Basis

Regenerative agriculture (RA) represents a paradigm shift from input-intensive, extractive farming systems toward ecological restoration and resilience-building approaches. It is a holistic, systems-based framework that seeks to regenerate soil health, enhance biodiversity, and restore ecosystem functions while maintaining agricultural productivity. Unlike conventional sustainability approaches that aim to minimize harm, RA actively improves the natural resource base, particularly soil, which serves as the foundation of agricultural systems.

Core Principles: The operational framework of regenerative agriculture is guided by a set of interrelated principles that collectively enhance soil and ecosystem health:

- **Minimal soil disturbance:** Reduced or zero tillage minimizes soil disruption, thereby preserving soil structure, preventing erosion, and protecting soil biota. It also reduces oxidation of soil organic matter, helping maintain or increase soil organic carbon (SOC) levels.
- **Continuous soil cover:** Maintaining soil cover through crop residues, mulching, or cover crops protects the soil surface from erosion, moderates soil temperature, and reduces moisture loss. It also provides a steady supply of organic matter to the soil.
- **Crop diversification:** Diverse cropping systems, including crop rotations, intercropping, and inclusion of legumes, enhance nutrient cycling, break pest and disease cycles, and improve soil biological diversity. Leguminous crops, in particular, contribute to biological nitrogen fixation.
- **Livestock integration:** Integrating livestock into cropping systems facilitates nutrient recycling through manure deposition and stimulates soil biological activity. Managed grazing systems can also enhance plant growth and carbon sequestration.

- **Use of organic inputs:** Application of compost, farmyard manure, biofertilizers, and other organic amendments improves soil fertility, enhances microbial activity, and contributes to long-term carbon accumulation.

These principles are synergistic and most effective when implemented as an integrated system rather than in isolation.

Scientific Basis: The scientific foundation of regenerative agriculture (RA) lies in restoring soil functions through biological and ecological processes. A key element is the enhancement of soil organic carbon (SOC), which improves soil aggregation, porosity, and water-holding capacity, thereby strengthening plant growth and resilience to climatic stress.

RA practices increase biomass inputs through crop residues, cover crops, and organic amendments, providing substrates for soil microorganisms. This stimulates microbial biomass and enzymatic activity, enabling efficient nutrient mineralization and cycling. Greater microbial diversity also enhances disease suppression and overall soil resilience.

Continuous soil cover reduces erosion by minimizing runoff and protecting soil from raindrop impact, while promoting stable aggregate formation and improved infiltration. Enhanced soil structure supports root development and nutrient uptake.

Regenerative systems further optimize nutrient cycling by reducing losses through leaching and volatilization. The integration of legumes and organic inputs improves nitrogen availability, while microbial processes enhance phosphorus and micronutrient accessibility.

Empirical evidence indicates that RA improves water-use efficiency, reduces reliance on synthetic inputs, and enhances yield stability over time. Overall, it represents a process-based approach that leverages natural systems to sustain productivity and restore soil health.

Benefits of Regenerative Agriculture (300–400 words)

Regenerative agriculture (RA) offers a multidimensional set of benefits that extend beyond productivity gains to encompass soil restoration, climate resilience, economic viability, and efficient resource use. These benefits are interlinked and contribute to the long-term sustainability of agricultural systems, particularly in the context of smallholder-dominated farming in India.

Soil Health Improvement: One of the most significant advantages of regenerative agriculture is the restoration and enhancement of soil health. RA practices increase soil organic carbon (SOC) through the incorporation of crop residues, cover crops, and organic amendments. Elevated SOC levels improve soil structure by promoting aggregate stability, which enhances porosity, aeration, and root penetration.

Improved soil structure also enhances water infiltration and retention, reducing the risk of runoff and erosion. Furthermore, regenerative systems foster a diverse and active soil microbial community. Microorganisms play a critical role in nutrient mineralization, organic matter decomposition, and disease suppression. Increased microbial diversity enhances soil resilience and supports sustained crop productivity. Over time, these improvements lead to a self-reinforcing system where soil fertility is maintained through natural processes rather than external inputs.

Climate Resilience and Mitigation: Regenerative agriculture contributes significantly to both climate change mitigation and adaptation. By increasing SOC levels, RA facilitates carbon sequestration, thereby removing atmospheric carbon dioxide and storing it in stable soil pools. This process helps reduce greenhouse gas concentrations and supports climate mitigation goals.

In addition, regenerative systems enhance resilience to climate variability. Improved soil structure and organic matter content increase the soil's water-holding capacity, enabling crops to withstand drought conditions. Similarly, better soil aggregation reduces vulnerability to erosion during heavy rainfall events. RA practices also lower greenhouse gas emissions by reducing reliance on synthetic fertilizers and minimizing soil disturbance, which otherwise releases stored carbon.

Economic Gains: From an economic perspective, regenerative agriculture offers substantial benefits to farmers, particularly in terms of cost reduction and long-term profitability. Reduced dependence on chemical fertilizers, pesticides, and intensive tillage lowers input costs, which is especially important for smallholder farmers with limited financial resources.

Although initial transition phases may involve slight yield fluctuations, evidence suggests that regenerative systems stabilize and often enhance yields over time. Improved soil health reduces the need for external inputs and enhances crop resilience, thereby lowering the risk of crop failure. Additionally, emerging opportunities such as carbon credit markets and premium pricing for sustainably produced crops can provide additional income streams for farmers adopting RA practices.

Resource Use Efficiency: Regenerative agriculture improves the efficiency of key agricultural resources, particularly water and nutrients. Enhanced soil organic matter increases the soil's capacity to retain moisture, reducing irrigation requirements and improving water-use efficiency. This is particularly valuable in water-scarce regions of India.

Nutrient-use efficiency is also significantly improved in regenerative systems. The integration of organic inputs and biological processes ensures a more gradual and synchronized release of nutrients, reducing losses through leaching and volatilization. This not only enhances crop uptake but also minimizes environmental pollution, such as groundwater contamination and eutrophication.

Overall, regenerative agriculture promotes a more balanced and efficient use of natural resources, contributing to sustainable intensification and environmental conservation.

Case Studies and Models

The practical relevance of regenerative agriculture (RA) in India is reflected through several successful models and field-level initiatives that demonstrate its scalability, adaptability, and socio-economic benefits across diverse agro-ecological regions.

Andhra Pradesh Natural Farming (APNF): The Andhra Pradesh Natural Farming initiative, also known as Community Managed Natural Farming (CMNF), represents one of the largest agroecological transitions globally. Implemented across millions of hectares, this model promotes chemical-free farming through the use of locally prepared bio-inputs such as microbial consortia and botanical extracts. The approach emphasizes soil biological regeneration, minimal external inputs, and farmer-to-farmer knowledge dissemination. Empirical evidence indicates improvements in soil organic carbon, enhanced microbial activity, and reduced input costs. Additionally, farmers have reported greater resilience to climatic stresses such as drought, making this model particularly relevant for smallholder systems.

Conservation Agriculture in the Indo-Gangetic Plains (IGP): Conservation agriculture (CA) has gained significant traction in the Indo-Gangetic Plains, particularly in rice–wheat cropping systems. Key practices include zero or reduced tillage, crop residue retention, and crop rotation. These

practices minimize soil disturbance, reduce erosion, and enhance soil moisture retention. Long-term studies have shown that CA improves soil structure, increases SOC levels, and enhances water-use efficiency. Moreover, it reduces labor and fuel costs associated with conventional tillage, thereby improving farm profitability. The adoption of CA has also contributed to reduced greenhouse gas emissions, aligning with climate-smart agriculture goals.

Agroforestry Systems: Agroforestry integrates trees with crops and/or livestock, offering a multifunctional approach to land use. In India's dryland and semi-arid regions, agroforestry systems such as alley cropping and silvopasture have demonstrated significant benefits. Trees contribute to carbon sequestration, improve soil fertility through leaf litter and root biomass, and enhance microclimatic conditions. They also provide additional income through timber, fruits, and fodder, thereby diversifying farmer livelihoods. Agroforestry systems have been shown to improve soil structure, reduce erosion, and increase resilience to climatic variability.

Integrated Farming Systems (IFS): Integrated Farming Systems (IFS) combine multiple agricultural enterprises—such as crops, livestock, fisheries, and horticulture—within a single farm unit. This approach promotes efficient resource use and nutrient recycling, as waste from one component serves as input for another. For instance, livestock manure is used to enrich soil fertility, while crop residues are utilized as animal feed. IFS enhances farm productivity, reduces dependency on external inputs, and improves income stability. It also strengthens ecological resilience by diversifying production systems and reducing risks associated with monoculture practices.

Collectively, these models illustrate that regenerative agriculture is not a one-size-fits-all approach but a flexible framework adaptable to India's diverse agro-climatic conditions, offering pathways for sustainable and resilient farming systems.

Policy Landscape and Gaps

India has undertaken several policy initiatives to address soil degradation and promote sustainable agriculture, creating an enabling foundation for transitioning toward regenerative agriculture (RA). However, despite these efforts, significant structural and institutional gaps continue to limit large-scale adoption.

Existing Schemes: The **Soil Health Card (SHC) Scheme** aims to promote balanced fertilization by providing soil test-based nutrient recommendations. It has improved awareness of soil health and fertilizer-use efficiency, although its effectiveness depends on farmers' ability to interpret and apply recommendations.

The **National Mission for Sustainable Agriculture (NMSA)** supports climate-resilient practices, including soil and water conservation, rainfed farming, and integrated nutrient management, aligning closely with regenerative principles.

The **Paramparagat Krishi Vikas Yojana (PKVY)** promotes organic farming through cluster-based approaches and Participatory Guarantee Systems (PGS), encouraging reduced chemical input use and eco-friendly practices that contribute to soil regeneration.

The **National Mission on Natural Farming (NMNF)** focuses on chemical-free agriculture using indigenous knowledge and biological inputs to enhance soil microbial activity and reduce dependence on synthetic fertilizers.

Key Policy Gaps: Despite these initiatives, several gaps hinder effective transition to RA. A major constraint is the fertilizer subsidy bias, where subsidies disproportionately favor chemical fertilizers,

particularly urea, making them more economically attractive and reinforcing input-intensive practices that degrade soil health.

There is also a lack of incentives for ecosystem services, as policies largely emphasize production rather than ecological outcomes such as carbon sequestration, biodiversity conservation, and soil restoration.

Weak extension and capacity-building systems further constrain adoption. Limited dissemination of regenerative practices, inadequate technical support, and fragmented training programs reduce farmer awareness and confidence in transitioning to RA.

Additionally, fragmented policy implementation across multiple schemes leads to duplication of efforts and weak coordination, preventing the development of a cohesive and integrated strategy for soil health restoration.

Addressing these challenges requires a paradigm shift from input-based support to outcome-oriented policies, along with stronger institutional convergence and farmer-centric extension systems to enable the widespread adoption of regenerative agriculture in India.

Transition Pathways

The transition toward regenerative agriculture (RA) in India requires a systematic, phased, and context-specific approach that integrates scientific knowledge with farmer-centric practices. Given the diversity of agro-climatic conditions and the predominance of smallholder systems, transition pathways must be flexible, scalable, and economically viable. Key pathways for enabling this transition are outlined below.

Soil Testing and Monitoring: A soil-centric approach is fundamental to regenerative agriculture. Regular soil testing—covering not only chemical parameters but also biological indicators such as soil organic carbon (SOC), microbial biomass, and enzymatic activity—is essential for informed decision-making. Monitoring changes in SOC and nutrient status helps assess the effectiveness of regenerative interventions over time. Strengthening soil testing infrastructure and promoting low-cost, field-level diagnostic tools can enhance farmer participation and adoption.

Crop Diversification: Diversified cropping systems are central to improving soil health and ecosystem resilience. Incorporating crop rotations, intercropping, and cover crops—particularly legumes—enhances nutrient cycling, reduces pest and disease incidence, and improves soil structure. Crop diversification also mitigates production risks by reducing dependency on single crops, thereby enhancing farm resilience under variable climatic conditions. Region-specific diversification strategies should be promoted based on agro-ecological suitability and market linkages.

Integrated Nutrient Management: Integrated nutrient management (INM) combines organic and inorganic nutrient sources to optimize soil fertility and crop productivity. The use of farmyard manure, compost, green manures, and biofertilizers improves soil organic matter and supports microbial activity, while judicious use of chemical fertilizers ensures immediate nutrient availability. This balanced approach enhances nutrient-use efficiency, reduces environmental losses, and supports long-term soil regeneration.

Water Management: Efficient water management is critical for sustaining regenerative systems, particularly in water-scarce regions. Practices such as rainwater harvesting, conservation tillage,

mulching, and micro-irrigation improve water-use efficiency and reduce dependency on groundwater. Enhancing soil organic matter also increases water retention capacity, thereby improving drought resilience. Integrated watershed management approaches can further support sustainable water use at the landscape level.

Digital Agriculture Tools: The integration of digital technologies can accelerate the adoption and scaling of regenerative agriculture. Tools such as remote sensing, geographic information systems (GIS), and mobile-based advisory platforms enable real-time monitoring of soil health, crop performance, and weather conditions. Decision-support systems powered by artificial intelligence can provide site-specific recommendations, improving resource-use efficiency and reducing risks. Digital platforms can also facilitate knowledge dissemination, farmer training, and market access.

Collectively, these transition pathways provide a comprehensive framework for shifting from conventional to regenerative systems, ensuring improved soil health, enhanced resilience, and sustainable agricultural development.

Policy Recommendations

A successful transition to regenerative agriculture (RA) in India requires a coherent policy framework that aligns economic incentives, institutional mechanisms, and scientific innovation with the goal of restoring soil capital. Strategic interventions must move beyond input-centric approaches toward outcomes that enhance soil health, ecosystem services, and farmer livelihoods.

Shift to Outcome-Based Subsidies: India's current subsidy regime is predominantly input-oriented, especially favoring chemical fertilizers such as urea, which often leads to excessive and imbalanced nutrient application. Transitioning to outcome-based subsidies is essential, wherein financial incentives are linked to measurable improvements in soil health indicators such as soil organic carbon (SOC), nutrient balance, and water-use efficiency. This approach would encourage farmers to adopt regenerative practices that enhance ecosystem functioning. Pilot initiatives can help design and validate performance-based incentive models before large-scale implementation.

Incentivize Carbon Farming: Regenerative agriculture offers substantial potential for carbon sequestration, positioning it as a key strategy for climate change mitigation. Policymakers should integrate agriculture into carbon markets by developing robust frameworks for measuring, reporting, and verifying soil carbon sequestration. Incentives such as carbon credits or payments for ecosystem services (PES) can reward farmers for adopting regenerative practices. This not only improves farm incomes but also aligns agricultural systems with national and global climate commitments.

Strengthen Research and Extension Systems: Strengthening research and extension systems is critical for scaling RA. Long-term, location-specific field trials are needed to generate empirical evidence on the performance of regenerative practices across diverse agro-climatic zones. Research efforts should focus on standardizing indicators for soil biological health and assessing economic viability.

Simultaneously, extension systems must be enhanced to improve knowledge dissemination and farmer capacity. This includes training programs, demonstration farms, and farmer-to-farmer learning models. The integration of digital advisory platforms can further improve outreach and provide site-specific recommendations.

Promote FPOs and Cluster Approaches: Farmer Producer Organizations (FPOs) and cluster-based approaches are essential for scaling regenerative agriculture among smallholders. These institutions facilitate access to inputs, credit, and markets while enabling economies of scale and

knowledge sharing. They also support value addition, certification, and branding of regenerative produce, helping farmers access premium markets. Strengthening FPOs through financial and technical support will be crucial for widespread adoption.

Collectively, these policy measures can create an enabling environment for transitioning toward resilient, sustainable, and economically viable agricultural systems in India.

Challenges and Way Forward

The transition to regenerative agriculture (RA) in India faces multiple structural and socio-economic challenges. Limited awareness and technical knowledge among farmers, coupled with inadequate access to training and demonstration models, significantly constrain adoption. Transition risks, particularly initial yield variability during the early years, further discourage smallholders lacking financial buffers or risk mitigation support.

Policy and institutional barriers also persist, as existing subsidy and procurement systems continue to favor input-intensive practices, creating disincentives for regenerative approaches. Fragmented implementation of sustainability schemes and weak institutional coordination reduce policy effectiveness.

Market constraints, including the absence of assured markets, price premiums, and standardized certification systems for regenerative produce, limit economic incentives for farmers.

Addressing these challenges requires strengthened extension services, risk-sharing mechanisms, policy realignment toward sustainable outcomes, and the development of robust market linkages to support large-scale adoption.

Way Forward

Addressing these challenges requires a coordinated and multi-stakeholder approach. Strengthening extension services and capacity-building programs is essential to improve farmer awareness and technical skills. Establishing demonstration farms and pilot projects can help showcase the benefits of RA under local conditions.

To mitigate transition risks, policymakers should introduce financial incentives, credit support, and risk-sharing mechanisms, including crop insurance tailored to regenerative systems. Reforming subsidy structures to support outcome-based approaches will further encourage adoption.

Developing robust market linkages and certification frameworks can enhance the economic viability of RA by enabling farmers to access premium markets. Finally, greater institutional convergence and integration of policies will be critical to scaling regenerative agriculture and ensuring long-term sustainability of India's farming systems.

Challenges include awareness gaps, transition risks, and policy constraints. Addressing these requires coordinated efforts across stakeholders.

Conclusion

Regenerative agriculture (RA) provides a scientifically sound and practical pathway for restoring India's soil capital while addressing food security, climate change, and environmental degradation. By prioritizing soil health, biodiversity, and ecosystem functioning, it shifts agriculture from input-intensive practices to resilient and sustainable systems. Improvements in soil organic carbon, nutrient cycling, and water retention enhance long-term productivity and stability.

In India's smallholder-dominated and diverse agro-climatic context, RA offers a flexible and scalable approach that can be tailored to local conditions. It reduces input costs, improves profitability, and strengthens climate resilience, thereby supporting farmer livelihoods.

However, large-scale adoption requires enabling policies, robust research and extension systems, and effective market linkages. Farmer-centric and risk-sensitive transition strategies, supported by institutional convergence, are essential. With coordinated efforts, regenerative agriculture can play a transformative role in achieving sustainable agricultural development and ecological balance in India.

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KARONDA: AN UNDERUTILIZED FRUIT CROP WITH GREAT POTENTIAL FOR RURAL ECONOMIES

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Introduction

India is home to a large diversity of fruit crops, many of which remain underutilized despite their nutritional and economic value. One such crop is karonda (*Carissa carandas* L.), a hardy fruit-bearing shrub belonging to the family *Apocynaceae*. It is widely distributed in tropical and subtropical regions of India and is commonly found growing in wastelands, forest margins, and dry areas. Although karonda has been traditionally used for food and medicinal purposes for centuries, its commercial cultivation and large-scale utilization remain limited.

Karonda is often referred to as a “neglected or underutilized fruit crop” because it has not received the same attention as major fruit crops like mango, apple, or banana. However, in recent years, scientists and agricultural experts have recognized its potential as an important crop for dryland agriculture and rural development. The plant is highly adaptable to harsh environmental conditions, requires minimal agricultural inputs, and can grow successfully even in poor soils where other crops fail.



The fruits of karonda are rich in essential nutrients such as vitamin C, iron, calcium, and antioxidants, making them highly beneficial for human health. Apart from its nutritional importance, karonda also plays a significant role in traditional medicine. Various parts of the plant, including fruits, leaves, roots, and bark, have been used for the treatment of several ailments. Considering its nutritional value, medicinal importance, and adaptability to marginal environments, karonda has immense potential to contribute to food security, rural livelihoods, and sustainable agriculture. Promoting the cultivation and processing of karonda can help farmers diversify their cropping systems and generate additional income (Chopra and Nayar, 1992).

Botanical Characteristics

Karonda is a small evergreen shrub that usually grows up to 2–3 meters in height. The plant has dense foliage and strong spines, which makes it suitable for use as a natural hedge or protective fence in agricultural fields. The leaves are dark green, oval-shaped, and thick, while the flowers are small, white, and fragrant. The fruits are initially green but turn pink, red, or dark purple when they ripen. One of the most important characteristics of karonda is its ability to thrive in harsh environmental conditions. The plant is well adapted to arid and semi-arid regions and can tolerate high temperatures ranging from 25°C to 45°C. It also performs well in areas with limited rainfall and poor soil fertility. Karonda can grow in a wide range of soil types, including sandy, loamy, and rocky soils. The plant is highly drought-resistant and requires very little irrigation once it becomes established. This makes it particularly suitable for cultivation in regions facing water scarcity. Another advantage of karonda cultivation is its low maintenance requirement. The plant is relatively resistant to pests and diseases, which reduces the need for chemical pesticides and fertilizers. As a result, karonda can be easily grown under organic and sustainable farming systems. Due to these characteristics, karonda is considered a promising crop for climate-resilient agriculture, especially in areas where climate change and irregular rainfall patterns are affecting crop production.

Nutritional and Culinary Value

Karonda fruits are small, round, and slightly sour in taste. Despite their small size, they are packed with a wide range of essential nutrients that are beneficial for human health. The fruit is particularly rich in vitamin C, which helps strengthen the immune system and prevents diseases such as scurvy. The approximate nutritional composition of karonda fruit per 100 grams includes:

- Iron: 10–15 mg
- Vitamin C: 20–25 mg
- Calcium: 20–30 mg
- Phosphorus: 20–25 mg
- Antioxidants such as polyphenols and flavonoids

The high iron content of karonda makes it especially valuable in regions where iron deficiency anaemia is a common health problem. Regular consumption of karonda fruits can help improve haemoglobin levels and overall health. Due to its tangy and slightly astringent taste, karonda is widely used in various culinary preparations. The fruits can be consumed fresh, but they are more commonly processed into different value-added products such as:

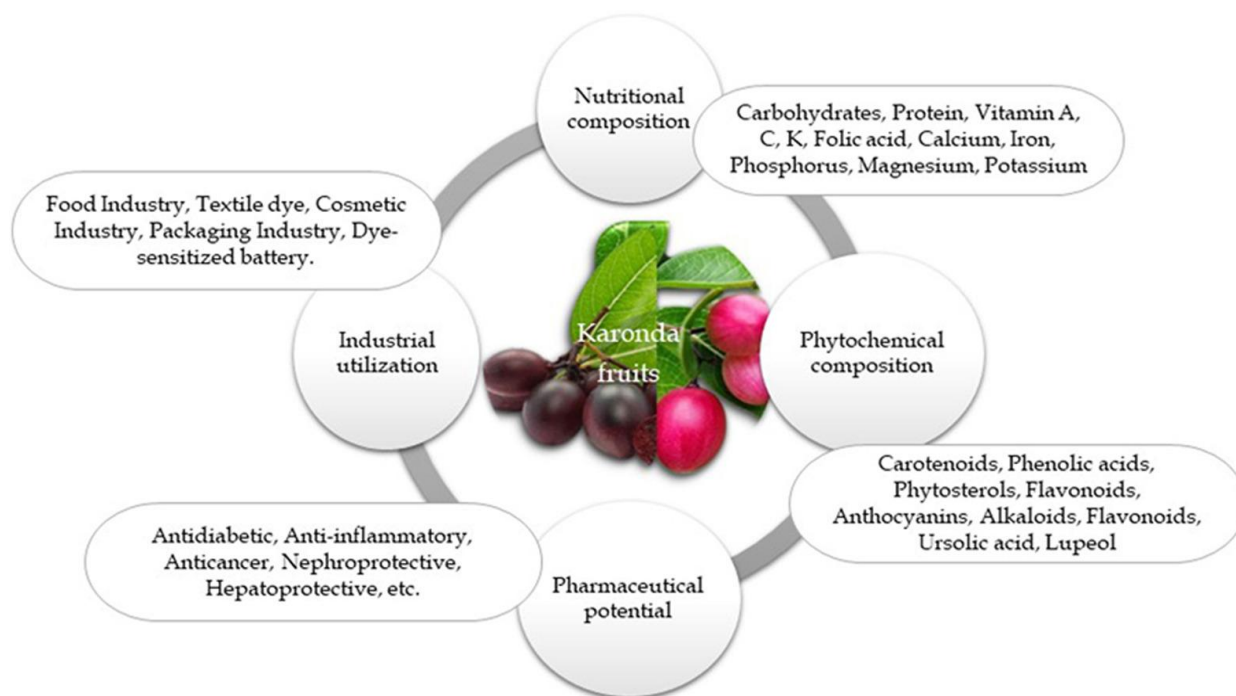
- Pickles
- Chutneys
- Jams and jellies
- Syrups and juices
- Candies and preserves

Karonda pickles are particularly popular in many parts of India because of their unique flavor and long shelf life. The fruit's natural acidity and antioxidant content also make it useful as a natural preservative in food processing. The development of value-added products from karonda can significantly increase its market demand and create new opportunities for small-scale food processing industries in rural areas (Chauhan et al 2015).

Traditional and Medicinal Uses

Karonda has been widely used in traditional medicine systems for centuries. Different parts of the plant, including fruits, leaves, roots, and bark, possess medicinal properties and have been used to

treat a variety of health problems. The fruit is known for its antiscorbutic properties, mainly due to its high vitamin C content. It has traditionally been used to prevent scurvy and improve immunity. In many rural areas, karonda fruits are consumed as a natural remedy for digestive disorders such as indigestion, diarrhoea, and constipation.



The leaves of the karonda plant possess antiseptic and anti-inflammatory properties. They are sometimes crushed and applied to wounds or skin infections to promote healing. The bark and roots are also used in herbal preparations for treating fever and certain infections. Recent scientific studies have confirmed that karonda contains several bioactive compounds such as flavonoids, alkaloids, and triterpenoids, which contribute to its medicinal properties. These compounds have shown antioxidant, antimicrobial, and cardioprotective effects. Some research also suggests that karonda may help in reducing blood cholesterol levels, controlling blood pressure, and improving heart health. In addition, the fruit has shown potential antiviral activity against certain viruses. Because of these properties, karonda is increasingly being recognized as a functional food and medicinal plant with potential applications in modern healthcare.

Role in Food Security and Nutrition

Food security and malnutrition remain major challenges in many rural areas, particularly in developing countries. Underutilized crops like karonda can play an important role in improving nutrition and food availability (Wanegaonkar et al 2021). Karonda fruits are rich in essential micronutrients such as iron and vitamin C, which are often lacking in the diets of rural populations. Including karonda in daily diets can help reduce nutritional deficiencies and improve overall health. Another advantage of karonda is that the fruits can be processed and preserved, allowing them to be consumed even during off-seasons when fresh fruits are not available. This helps ensure a steady supply of nutritious food throughout the year. Because the plant grows well in marginal lands with minimal inputs, farmers can cultivate karonda without competing with major crops for fertile land or irrigation water. This contributes to sustainable agricultural production and diversified farming systems.

Economic Importance and Contribution to Rural Development

Karonda has great potential to contribute to the economic development of rural communities. Its cultivation requires low investment, making it suitable for small and marginal farmers. Farmers can benefit economically from karonda in several ways. First, the fruit itself can be sold in local markets as fresh produce. Second, the processing of karonda into value-added products such as pickles, jams, and juices can significantly increase its market value. The cultivation and processing of karonda can also generate employment opportunities in rural areas. Activities such as harvesting, processing, packaging, and marketing create jobs for local people and support small-scale industries. In addition, karonda plants are often used as live fences or hedges around agricultural fields. This provides an additional benefit by protecting crops from grazing animals while also producing edible fruits. Government agencies, agricultural institutions, and rural development organizations can play an important role in promoting karonda cultivation by providing training, improved planting materials, and support for value-added processing.

Conclusion

Karonda (*Carissa carandas* L.) is an underutilized fruit crop with immense potential for improving rural livelihoods and promoting sustainable agriculture. Its ability to grow in harsh environmental conditions, combined with its high nutritional and medicinal value, makes it a valuable crop for dryland and marginal farming areas. The fruit's rich nutrient content, particularly its high levels of vitamin C and iron, makes it an important food source for addressing nutritional deficiencies. In addition, its wide range of culinary and medicinal uses increases its importance in both traditional and modern contexts. Promoting the cultivation, processing, and marketing of karonda can help farmers diversify their income sources, create rural employment, and strengthen local economies. With proper research, awareness, and policy support, karonda has the potential to become an important crop for food security, nutrition, and rural economic development.

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LIVE FEEDS VS. FORMULATED FEEDS IN ORNAMENTAL AQUACULTURE

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Introduction

Live feeds are essential in ornamental aquaculture for the high-survival, rapid-growth rearing of larvae and breeding of adults, providing necessary protein and fatty acids (DHA/EPA). The key organisms include *Artemia*, rotifers, copepods, *Daphnia*, and *Moina*, which are often enriched with nutrients of probiotics, or carotenoids to enhance fish colour and health status of the animal. Success of aquaculture is mainly depends on healthy cultured stock. Disease free healthy stock can be maintained by feeding live food to the cultured stock along with supplemented artificial feed. Supplemented artificial feed cannot meet all the elements required for the growth of fishes. So, fish and shellfish must be fed with live food. For getting good return from rearing of larvae of fish and shellfish they should be fed with nutrient rich diet.

Importance of live feed

Larval rearing is one of the riskiest phases of aquaculture, but it could be one of the most profitable venture. Special planning and strategies are required to overcome the risk of high mortality during this larval phase. Zooplankton is required as a initial food for many cultured fishes and for others it contributes to faster growth and higher survival. Larvae stages of fish and shellfish directly cannot feed artificial supplemented feed. They require small size live foods for their nutrition. Live foods are easily digestible protein rich diet for fish and shellfish. These live foods can be purchased from the market, which is costly and may not be available as and when required. It will also increase the production cost. But these live foods can be cultured easily and economically. Live foods include both phytoplanktonic as well as zooplanktonic organisms. Live feed (e.g., rotifers, *Artemia*, copepods) is essential for larval and juvenile ornamental fish due to limited digestive capabilities, high nutrition, and movement that stimulates hunting, significantly enhancing survival and growth rates. Live feeds are often enriched with probiotics, vitamins, and fatty acids to enhance the nutritional value, particularly for marine species. It has high digestibility, continuous movement triggers feeding response in weak larvae, and reduces mortality during early life stages. Limitations like expensive, labor-intensive to culture, and inconsistent availability.

Why Live Feeds Are Important

- High protein and essential nutrients
- Natural movement stimulates feeding response
- Easily digestible for larvae
- Improves survival rate and growth

Constrains in live feed culture

Considering several factors, live feed remains the most practical solution for larval rearing for aquaculture species. However, it is not easy to maintain a steady supply of adequate quantities of live feed at appropriate times in intensive culture systems. Among the constraints of micro algae

production the primary one is its cost of production, especially in smaller hatcheries. Difficulties in getting pure strain, lack of infrastructure facility like controlled environmental laboratory for culture maintenance etc. are some other prime areas of concern. Live feed also act as a carrier of diseases to the larvae of fish and shellfish, therefore, maintenance of hygiene is very important during live feed production. The new technology of enrichment process is a costly affair for small and medium level farmers. Similarly, the high infrastructure and labour requirement along with the variable cost for live feed production illustrates the need to develop suitable modified culture technology. Although several strains of artemia are available in India, selection and suitability of the available strains are of major concern and hence the aqua hatcheries are more dependent on imported cysts. Nutritional status of the live feed organisms needs to be summarised for feeding different larval stages of fish and shellfish. Therefore, more research thrust should be given on suitability of many of the available live food organisms.

Formulated Feeds

Formulated feeds (pellets, flakes) are used for adults and juveniles, offering balanced nutrition, ease of storage, and convenience, but are unsuitable for early, undeveloped larvae. Formulated feeds provide balanced, consistent nutrition, allowing for convenient feeding and improved growth in later life stages. Types of feeds: Flakes, pellets, nutrient-rich and disease-resistant artificial diets. Formulated feeds are artificial or prepared feeds such as:

- Micro-pellets
- Powdered starter feed.

Advantages

- Easy to store and handle.
- Nutrient composition can be controlled.

Constraints in Formulated Feeds

Poor acceptance by larvae : Fish larvae often do not recognize formulated feed as food because it does not move like live organisms such as *Artemia*, *Brachionus plicatilis* and others.

Digestibility: At the early stages, fish have an immature digestive system, so they cannot easily digest artificial feed efficiently when compare to live feeds.

Inappropriate particle size : The feed particle size is too large for the small mouth of fish larvae. Nutrient loss: Formulated feeds may dissolve quickly in water, causing loss of nutrients in the water before fish consume them.

Water quality deterioration : Uneaten feed decomposes and leads to pollute the water, increasing ammonia and reducing oxygen level in the water.

Survival rate : Compared to live feeds, formulated feeds may lead to lower survival and slower growth in early larval stages.

High Cost of feed: High-quality micro-diets and specialized larval feeds can be expensive for small-scale/ medium scale ornamental fish farmers.

Generally formulated feeds introduced during the weaning stage, often around 15 days post-hatching (dph) for certain species, allowing for transition from live feed. Formulated feeds less attractive to early larvae, may not meet all nutritional requirements of specific species, and can impair water quality if uneaten. It has limitations like larvae may not recognize it as food, Harder

to digest initially. Often results in lower survival rate if used alone. Formulated feeds requires careful storage (e.g., refrigeration or vacuum sealing) and monitoring to ensure proper intake.

Conclusion

A successful strategy often involves using live feed for early life stages, followed by a gradual weaning onto formulated feed to reduce production costs. Utilizing high-quality live feed for larvae (first 10–20 days) and transitioning to high-protein formulated feed for juveniles and adults balances survival, growth, and cost-efficiency. Live feeds are fundamental to the success of ornamental fish culture, particularly in larval and juvenile phases. Properly enriched live feeds improve growth, immunity, coloration, and reproductive performance. Strategic integration of live and formulated feeds ensures optimal development while supporting sustainability. Future focus includes low cost alternatives, technological integration, and farmer-level training to expand the benefits of live feed usage in ornamental aquaculture.

IOT-BASED SMART EAR TAG FOR LIVESTOCK HEALTH MONITORING

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Abstract

In Marathwada, livestock play a major role in farming and is a key source of livelihood for farmers. Healthy livestock ensures higher productivity (more milk, better growth, and improved reproduction). Livestock health management is a crucial factor influencing animal welfare, farm productivity, and economic sustainability. Conventional monitoring techniques rely on manual observation, which is time-consuming and often fails to identify early signs of illness or stress. This project proposes an IoT-Based Smart Health Monitoring System for Livestock that enables continuous, real-time monitoring of animal physiological and environmental conditions. The system integrates multiple sensors, including the temperature sensor (LM35) for body temperature measurement, Pulse Sensor (MAX86150) for heart rate monitoring, and an accelerometer (ADXL345) for tracking animal activity and movement patterns. Additionally, a DHT22 sensor is used to monitor ambient temperature and humidity within the livestock housing environment, while a GPS module enables location tracking. Sensor data is collected and processed using a NodeMCU (ESP8266) microcontroller, and transmitted wirelessly to a cloud platform for storage, visualization, and analysis. A mobile or web-based dashboard provides real-time data access and automated alerts when abnormal conditions are detected, facilitating timely intervention. The system supports early disease detection, stress monitoring, and improved herd management. Overall, the proposed solution enhances precision livestock farming by reducing labor dependency, lowering veterinary costs, and improving animal health and farm efficiency.

Keywords: Internet of things, Health monitoring system, Animal health, Animal husbandry, Smart sensor

Introduction

Livestock plays a vital role in the agricultural economy by providing milk, meat, and other essential products. Maintaining the health of livestock is crucial for ensuring high productivity and preventing economic loss. Traditionally, farmers relied on visual observation and periodic inspection to assess animal health, which was often inefficient and prone to errors, especially in large herds. With the advent of precision livestock farming, these systems integrate sensors, wearable devices, communication technologies, and data analytics to provide real-time insights into animal conditions. The system primarily consists of several interconnected components that work together

seamlessly. Sensors such as temperature sensors, heart rate monitors, accelerometers, and respiration sensors are either attached to animals or installed in their surroundings to collect physiological and behavioral data. These sensors are often embedded in wearable devices like smart collars, ear tags, or leg bands, which continuously record vital parameters such as body temperature, movement patterns, feeding behavior, and rumination activity. The collected data is then transmitted through communication networks such as Wi-Fi, Bluetooth, LoRaWAN, or cellular systems to a centralized data acquisition unit or cloud-based platform, where it is stored for further processing and analysis.

Objective of Smart Ear Tag for Livestock Health Monitoring system

- To monitor livestock health in real time using IoT sensors
- To measure physiological parameters such as body temperature, heart rate, movement, and chewing activity.
- To detect diseases at an early stage using sensor data analysis.
- To develop an AI-based multi-disease prediction system for accurate health monitoring.
- To predict milk production based on health parameters and breed of livestock.
- To reduce manual effort and labor in livestock monitoring.
- To provide instant alerts/notifications to farmers in case of abnormal conditions
- To improve animal health, productivity, and milk yield
- To promote smart farming and precision livestock management

Key Components

To develop an IoT-based Health Monitoring System for Livestock, several important components are required. The system mainly includes a microcontroller (Node MCU ESP8266), communication module, and a cloud platform for data storage and analysis. Sensors like a temperature sensor (LM35), heart rate sensor (MAX86150), accelerometer (MPU6050) for activity monitoring, and optionally a GPS module are attached to the animal, usually through a smart collar or ear-tag device. These sensors continuously collect physiological and behavioral data from the livestock. Various components used in the systems are discussed below in detail:

1. Microcontroller (Node MCU ESP8266)

The ESP8266 is a low-cost, highly integrated Wi-Fi microchip that enables microcontrollers to connect to wireless networks and the internet. It has become one of the most widely used modules in Internet of Things (IoT) applications due to its affordability, compact size, and built-in networking capabilities. The ESP8266 plays a crucial role in enabling smart livestock health monitoring systems by acting as a bridge between sensors and cloud-based applications.



Fig. 1: 3D View of ESP 8266 Microcontroller

2. Temperature sensor (LM35)

The LM35 temperature sensor is a widely used analog sensor that measures the body temperature of the animal with high accuracy and provides output in a linear voltage format. It is especially suitable for applications like livestock health monitoring because it can directly measure body

temperature, which is one of the most important indicators of animal health. Unlike many other temperature sensors, the LM35 is calibrated in degrees Celsius and does not require additional calibration, making it simple and reliable for practical use.

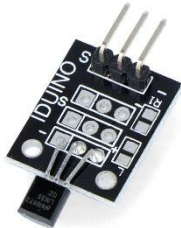


Fig. 2: 3D View of Temperature Sensor Module (LM35)

3. Heart rate sensor (MAX86150)

In a livestock health monitoring setup, the MAX86150 sensor is typically embedded in wearable devices such as collars, chest straps, or harnesses that maintain close contact with the animal's skin. The sensor continuously monitors heart rate by detecting blood volume changes using optical signals and electrical signals. These measurements help in identifying abnormalities such as elevated heart rate (tachycardia), reduced heart rate (bradycardia), or irregular rhythms, which may indicate stress, illness, pain, or environmental discomfort. It is generally placed near ear for good blood flow.



Fig. 3: 3D View of Heart Rate Sensor Module (MAX86150)

4. Accelerometer (MPU6050)

In livestock health monitoring systems, the MPU6050 plays a vital role in tracking animal activity, posture, and behavior, which are key indicators of health, well-being, and productivity. The accelerometer measures acceleration forces along the X, Y, and Z axes, which helps determine movement and tilt, while the gyroscope measures rotational motion around these axes.

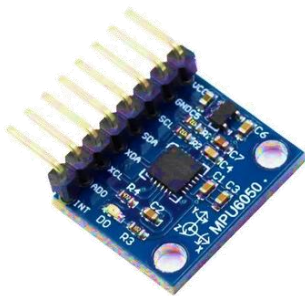


Fig. 4: 3D View of 3-axis accelerometer and a 3-axis gyroscope (MPU6050)

Working Principle

The working principle of a livestock health monitoring system involves continuous data collection, transmission, and intelligent analysis. Once the data reaches the central system, it is processed using algorithms, and in many advanced systems, artificial intelligence and machine learning techniques are applied to identify patterns and detect abnormalities. For example, a sudden increase in body temperature may indicate infection, while reduced movement or abnormal gait can signal lameness. Similarly, changes in feeding or rumination behavior may point to digestive disorders. When such deviations from normal patterns are detected, the system automatically generates alerts and notifications, which are sent to farmers or veterinarians through mobile applications or dashboards, enabling timely intervention and treatment. These systems monitor a wide range of parameters that are crucial for maintaining livestock health and productivity. These include physiological parameters like body temperature, heart rate, and respiration rate, as well as behavioral parameters such as activity level, grazing time, and rest periods. In dairy farming, additional parameters like milk yield and quality are also monitored to detect diseases such as mastitis at an early stage. Location tracking using GPS helps in managing grazing patterns and preventing animal loss, particularly in extensive farming systems.

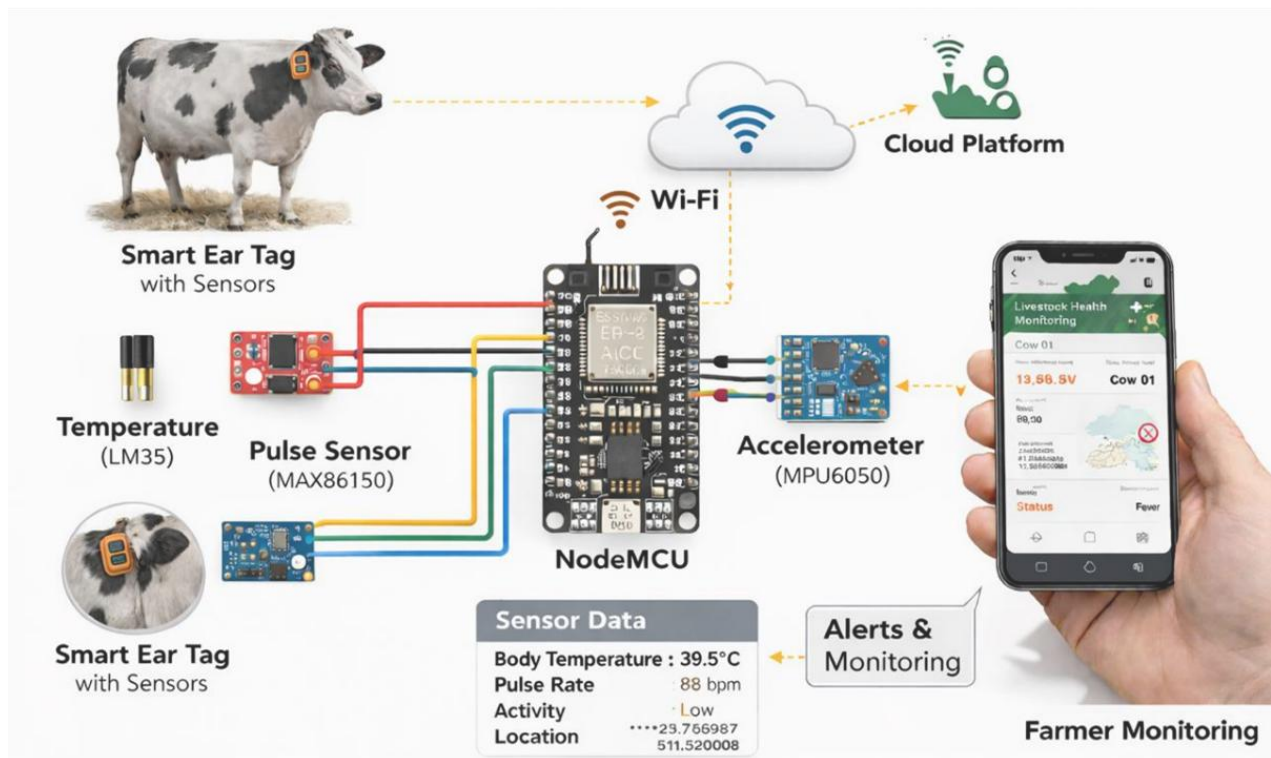


Fig. 5: System Architecture of Smart Ear Tag Livestock Health Monitoring

The adoption of livestock health monitoring systems offers numerous advantages. It significantly improves the accuracy and efficiency of disease detection, thereby reducing mortality rates and treatment costs. Early diagnosis ensures that diseases are controlled before they spread to other animals, which is particularly important in large-scale farms. Moreover, these systems enhance productivity by optimizing feeding, breeding, and overall herd management. They also reduce the need for constant human supervision, saving time and labor while enabling data-driven decision-making.

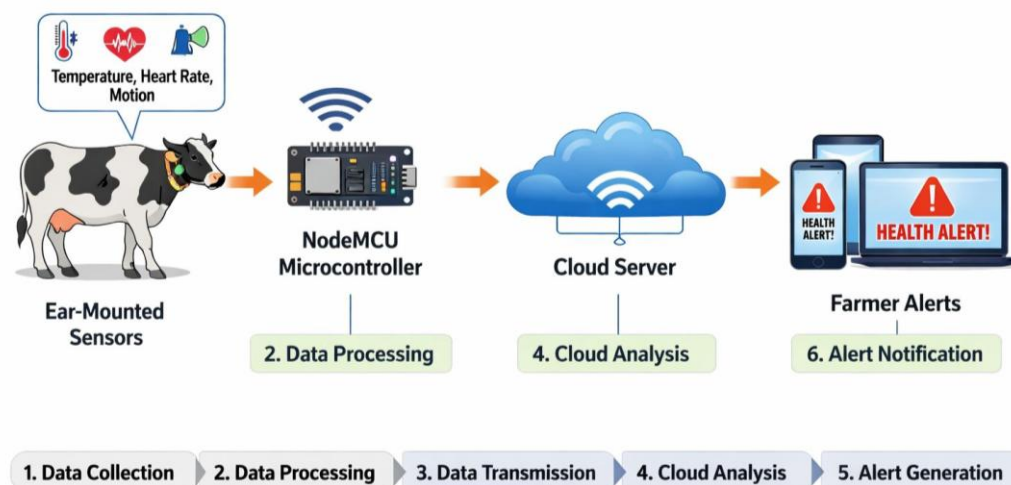


Fig. 6: Working Principle of Smart Ear Tag Livestock Health Monitoring System

Conclusion

A livestock health monitoring system is a transformative approach in modern agriculture that enables continuous and real-time assessment of animal health, behavior, and productivity. By integrating sensors, wearable devices, communication technologies, and data analytics, the system provides farmers with accurate and timely information about the condition of their livestock. This reduces dependence on traditional manual observation methods, which are often time-consuming and less reliable, especially in large-scale farming. Such systems help in the early detection of diseases, stress, and abnormal behavior by monitoring key physiological and behavioral parameters like body temperature, heart rate, movement, feeding, and rumination patterns. Early diagnosis allows for prompt medical intervention, preventing the spread of diseases and reducing mortality rates. Despite its numerous advantages, the system also faces challenges such as high initial investment, need for reliable internet connectivity, sensor maintenance, and data management complexity. However, with ongoing advancements in technologies like IoT, artificial intelligence, and smart sensors, these limitations are gradually being overcome.

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THE DEVASTATING IMPACTS OF SOIL EROSION

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Abstract

Soil degradation presents a significant environmental issue globally, influencing agricultural output, ecosystem functions, and human health. The process of soil erosion results in the depletion of nutrient-rich topsoil, a decline in the ability of soil to retain water, and a loss of soil diversity. Additionally, it heightens sediment buildup in bodies of water, which disturbs aquatic habitats and affects the quality of water. There is a noticeable decrease in agricultural yield due to lowering soil health and rising farming expenses. Moreover, soil erosion contributes to climate change by liberating stored carbon and diminishing the soil's capacity to capture carbon. Implementing effective soil preservation methods is essential to lessen these adverse effects and promote sustainable practices in land management.

Keywords: Soil erosion, agriculture, farming, sustainable land management

Introduction

The loss of topsoil, nutrients, and organic matter as a result of natural forces like wind and water or human activities like deforestation, overgrazing, and intensive farming is known as soil erosion, and it is a major environmental problem on a global scale. Food security, livelihoods, and the environment are ultimately impacted by this pervasive issue, which also has an impact on ecosystem health, water quality, and agricultural production. The Food and Agriculture Organization (FAO) estimates that 75 billion metric tonnes of fertile soil are lost globally each year, making soil erosion a serious threat to global food security (FAO, 2015).

The consequences of soil erosion are extensive and complex. An immediate consequence is the depletion of nutrient-rich topsoil, which diminishes soil productivity and impacts agricultural output. Research conducted by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) suggests that soil erosion results in a decrease of 5.3 billion tonnes of soil each year in India by itself (NBSS&LUP, 2018). Additionally, soil erosion contributes to heightened sediment levels in rivers, streams, and reservoirs, compromising water quality, harming aquatic ecosystems, and reducing water retention abilities. Moreover, soil erosion intensifies the occurrence of landslides and sudden floods, leading to fatalities, destruction of property, and the forced relocation of communities.

Soil degradation plays a role in climate change by allowing trapped carbon to escape into the air and diminishing the ability of soil to absorb carbon (Lal, 2003). This leads to a harmful cycle, where climate change further exacerbates soil erosion due to higher amounts of rainfall and more frequent storms. The enduring effects of soil degradation are significant, with possible repercussions on biodiversity, ecosystems, and the quality of life for humans. Taking action to combat soil erosion, including tree planting, measures for conserving soil, and practices for sustainable land management, is crucial to lessen these effects and promote sustainable growth.

Onsite Impacts of Soil Erosion

Loss of Top soil

- Erosion accelerates topsoil depletion. Wind blows it away, with water washing it away. Topsoil is the rich organic layer, where the organics, soil minerals and soil organisms create a rich substrate to grow plants in.
- It is being globally estimated that between 0.03-0.13 mm/year of soil loss naturally. Erosion in many agricultural regions can exceed several milli meters per year which is often faster than natural soil formation.
- Sheet, rill and gully erosion remove fine, fertile particles during heavy rains and run off, especially on bare or compacted land.
- Exposed dry soils lose fines to wind, especially in arid/semi-arid regions and after vegetation removal.
- It reduces soil fertility and productivity.

Reduced water holding capacity

- Soil's ability to retain water decreases. Water can't infiltrate, so it runs off, causing erosion and increasing flood risks. Also it leads to decreased groundwater recharge.
- Plant stress: low water holding capacity means less water available for plants during dry spells, leading to crop failure.

Decreased Crop Yields

- Erosion affects nutrient availability and root growth. It leads to lower quantity and lower quality. Yields can drop significantly, with some studies showing reductions up to 50% or more in severely affected areas and crops that grow may be smaller and less nutritious.
- It impacts food security and farmer income.
- Estimated annual losses- Rs.2-3 lakh crore in India.

Increased Soil Salinity

- High salt levels degrade soil structure, reducing its ability to form stable aggregates, making it loose and susceptible to being washed or blown away.
- Saline soils absorb water poorly, leading to increased surface run off during rains, which carries away topsoil and cause floods.

Offsite Impacts of Soil Erosion

Water Pollution

- Sedimentation: Eroded soil (soil, clay) settles in rivers, lakes and reservoirs increasing turbidity and blocking sunlight needed by aquatic plants.
- Nutrient pollution: High concentrations trigger excessive algae growth (algal blooms) through eutrophication, leading to oxygen depletion and kills fish.
- Chemical contamination: Topsoil often holds agricultural chemicals like pesticides and herbicides, as well as heavy metals. Erosion transports these pollutants, contaminating water sources and posing risks to aquatic life and humans.

Increased flood risk

- Riverbed siltation: Soil eroded from hillsides settles in rivers, raising the riverbed and reducing its capacity to hold water, causing it to overflow more easily.
- Increased runoff: Degraded soil from erosion absorbs less water, leading to faster and greater surface runoff, flooding drainage systems.

- Loss of natural barriers: Coastal erosion removes dunes, marshes and beaches, eliminating natural buffers that protect against storm surges and high tides, making flooding more severe.

Decreased water quality

- Soil erosion can lead to increased nutrients and pollutants in water bodies.
- Sediment can alter aquatic ecosystems, leading to loss of biodiversity.

Conclusion

Soil degradation has extensive effects on the environment, economy, and communities. These effects encompass the loss of productive topsoil, a decline in agricultural yield, a rise in sediment levels in water systems, and an increased likelihood of landslides and flooding. Furthermore, soil erosion plays a role in climate change and diminishes the soil's ability to store carbon. Effective approaches to prevent soil degradation include:

- Conservation agriculture
- Planting trees and restoring forests
- Techniques for soil conservation (such as terracing and contour farming)
- Practices for sustainable land use

Applying these methods can assist in lessening the negative effects of soil erosion and encourage sustainable growth.

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MONOCULTURE: THE HIDDEN WEAKNESS OF MODERN AGRICULTURE

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Introduction

Agriculture today seems great at first glance. You see big fields with just one type of crop, all lined up in neat rows. Everything looks organized, the crops grow evenly, and you can count on a good harvest. For a long time, this is what progress looked like: improved seeds, better farming methods, and bigger yields. And in many ways, it is progress. Growing huge amounts of a single crop, also known as monoculture, has helped feed millions of people, made farming easier to manage, and laid the groundwork for the modern food system we have today. But if you look closer, you might start to wonder if this is really the best way to do things. You see, just because something looks strong, doesn't mean it can last. The same thing that makes monoculture farming work well, also makes it weak. When you have a whole field, or even a whole country, growing the same type of plants, it's like putting all your eggs in one basket. If a disease or pest comes along, it can spread quickly and cause a lot of damage. What looks like a well-organized system can actually be a recipe for disaster. This is the big flaw in modern farming. In the pursuit of efficiency, it has often sacrificed diversity, which is a key part of what keeps farming systems safe.

The Promise of Uniformity

It is easy to see why monoculture became so popular. For farmers, it simplifies the process. Planting, irrigating, fertilizing, protecting, and harvesting a single crop is easier. Machines perform better in uniform fields. Inputs can be applied uniformly. Buyers and processors also prefer consistency—grains of similar size, fruits of similar shape, crops that mature at the same time and fit industrial systems.

In other words, monoculture aligns well with modern farming. It saves time, reduces management challenges, and often boosts productivity.

This is why its risks are often ignored. Because monoculture is so effective in normal conditions, it gives the impression of being stable. However, agriculture doesn't function like a controlled factory. It exists in living ecosystems, where pests change, pathogens adjust, and weather is unpredictable. A system that works well in good years can still be very vulnerable when challenges arise.

Table 1. Why Monoculture Feels Strong—And Why It Isn't

What Monoculture Offers	Why It Seems Attractive	What It Risks
Uniform crop growth	Easier management and harvest	Uniform vulnerability to disease
Standardized produce	Better fit for markets and processing	Dependence on fewer varieties
Higher short-term efficiency	Lower operational complexity	Lower resilience under stress

What Monoculture Offers	Why It Seems Attractive	What It Risks
Predictable input use	Easier fertilizer and pesticide planning	Greater damage if a single weakness is exposed
Large-scale mechanization	Faster field operations	Field-wide spread of pests and pathogens

Where the Risk Begins

The weakness of monoculture starts with something very simple: sameness.

In a diverse field, disease does not spread easily. One plant might be vulnerable, another may be resistant, and yet another could be less appealing to pests. Diversity creates friction. It slows down contagion. It breaks the chain.

Monoculture eliminates that friction. When thousands of plants have similar genetic traits, a disease that affects one plant is more likely to affect the next, and the next, and the next. For a pathogen, a uniform field isn't just a food source; it is an endless opportunity.

That is why monoculture is not just a farming choice. It is a biological risk. A fungal outbreak in a mixed system may stay limited. The same outbreak in a genetically uniform field can turn into an epidemic. A pest that adapts to one widely planted variety can suddenly find millions of identical hosts across entire districts. The threat is not just that something might go wrong. The threat is that once it does, everything can fail at once.

The Problem with Success

One of the most dangerous aspects of monoculture is that its success masks its weaknesses. As long as the weather is good and disease pressure is low, monoculture can seem like the best system. High yields build trust. Consistent harvests bring financial benefits. Over time, this creates a culture of reliance, not just among farmers, but also in seed systems, supply chains, and national agricultural planning.

Then, the shock hits. It might be a new pest. It could be a familiar disease that strikes harder in a tough season. It may be heating stress, drought, or flooding. No matter the cause, the impact is intensified because the system lacks enough internal safeguards. Instead of absorbing the shock, it quickly spreads it across the landscape.

This is the real issue with monoculture: it works wonderfully until it does not. And when it fails, it often fails all at once.

History Has Already Warned Us

Agriculture has experienced this pattern before.

The Irish Potato Famine is a well-known example. A heavy reliance on just a few types of potatoes made the crop very vulnerable to late blight. Once the disease spread, the results were disastrous. The tragedy involved politics, poverty, and colonial policy, but the biological lesson was clear: when a society relies too much on a limited genetic base, one disease can lead to a national disaster.

That warning has not been forgotten.

Today, the global banana trade relies heavily on the Cavendish variety. For years, this uniformity helped create a stable export industry. However, it also introduced a shared weakness. As *Fusarium*

wilt Tropical Race 4 spread, it revealed the dangers of depending on one genetic line. The problem went beyond just plant disease. It raised the question of whether the whole global fruit economy was built on a biological fault line.

This logic applies to more than just potatoes and bananas. In rice, wheat, maize, cotton, and even livestock systems, uniformity can turn local biological threats into widespread economic crises.

Modern Agriculture Makes The Weakness Bigger

Monoculture alone is risky. When combined with modern agriculture, it becomes even more dangerous. Today's food system is highly connected. Seed distribution is centralized. Processing is concentrated. Markets rely on steady flows of standardized produce. In many areas, farmers are encouraged, and sometimes forced, to grow the same profitable crop year after year. This means a biological problem rarely stays biological. A disease outbreak in one major producing region can lower supply, raise prices, disrupt trade, affect processors, and put pressure on household food budgets. Farmers lose income. Markets become unstable. Governments face pressure. In severe cases, one failed season can influence planting decisions for the next. That is why monoculture is not just an issue at the field level. It is a food system issue. The risk starts in the soil, but it does not stop there.

Table 2. How Genetic Uniformity Turns a Farm Problem Into a System Problem

Stage	What Happens in a Monoculture System	Wider Impact
Disease or pest enters field	Similar plants offer easy spread	Rapid field-level damage
Large area shares same crop type	Outbreak expands quickly	Regional production loss
Supply begins to fall	Markets react	Price volatility
Farmers face losses	Debt and income stress increase	Rural economic pressure
Trade or procurement is disrupted	Buyers seek alternatives	Food system instability

The Illusion of Control

A lot of people believe that modern farming can deal with risks using chemicals, improved seeds, and new technologies. And it's true, these tools are crucial. They've saved crops, boosted productivity, and helped farmers overcome many obstacles. But the thing is, they don't completely eliminate vulnerability. Sometimes, they just put it off for a while. We need to think about the long-term effects and find more sustainable solutions to really make a difference.

Diseases and pests are constantly evolving, which means they can become a bigger threat to crops over time. For example, insects can develop resistance to pesticides, making them less effective. Climate change is also playing a role, as it's altering the patterns of diseases and pests, bringing them to areas where they weren't previously a problem. This can be especially devastating for farmers who have been growing the same crop for years, only to find that it's suddenly vulnerable to a new disease or pest. If a farm is only growing one type of crop, the loss can be catastrophic.

Modern farming often gets things mixed up - it thinks being in control means being secure. But that's not always true. A farm can be run really well and still be fragile, like a house of cards. It can have all the latest technology and still be one bad event away from disaster. Just because something is precise, doesn't mean it can withstand tough times. Sometimes, it just makes it easier to spread the risk around, like a domino effect.

What Resilience Actually Looks Like

The answer is not to reject modern agriculture or romanticize the past. The world still needs productivity. Farmers still need income. Food systems still need reliability.

But productivity without resilience is a dangerous bargain.

Rebuilding diversity in the system will be essential for a more robust agricultural future, not as a barrier to efficiency but as a safeguard against failure. This may entail cultivating multiple varieties of a major crop. Crop rotation, mixed farming, local adaptation, seed diversity, and breeding initiatives that prioritize durability over yield are some examples.

Risk is not eliminated by diversity. However, it keeps one weakness from simultaneously becoming everyone's weakness. And the transition from optimizing output under ideal circumstances to preserving stability under actual circumstances may be the most significant change that agriculture currently needs to make.

Table 3. From Efficiency to Resilience

Old Priority	What It Focused On	New Priority	What It Protects
Maximum uniformity	Easy management	Managed diversity	Biological buffering
Single best variety	High short-term yield	Multiple strong varieties	Lower systemic risk
Repetition of same crop	Market convenience	Crop rotation	Soil and disease stability
Chemical-first protection	Immediate control	Integrated resilience	Long-term sustainability
Output alone	Quantity	Output + endurance	Food security

A Question the Future Will Force Us to Answer

The real issue now is not about whether a single crop can be produced on a large scale, because we know that it can. The real question is whether it can endure. In today's world, where we're dealing with climate change, new pests, plant diseases, and problems with getting food from one place to another, farming can't just focus on producing a lot of food. It also needs to make sure that food is safe. A system that works well when things are good but falls apart when things get tough isn't really strong - it's actually pretty weak. So, monoculture should be looked at for what it really is - not just a way of farming, but a flaw in the system that's hidden behind the success of modern agriculture.

Conclusion

Growing food in a modern way relies on monoculture, which is when only one type of crop is grown in a large area. This method has helped us produce a lot of food, but it has also made our food systems weaker. By planting only one type of crop, we have lost the variety of plants that our food systems depend on. This makes it easier to take care of the crops, but it also makes them more vulnerable to damage. For a long time, a major flaw in the system went unnoticed because it continued to produce results. However, the challenges facing agriculture are now changing rapidly. The risk of disease is increasing, climates are becoming more unpredictable, and food systems are more connected than ever. In this new reality, the old approach of uniformity no longer seems like a strength, but rather a vulnerability. The system is now under pressure, and its weaknesses are starting to show. The old model is no longer effective in dealing with the rising disease risks,

unpredictable climates, and interconnected food systems. As a result, a new approach is needed to address these challenges and ensure the long-term sustainability of agriculture.

The way we grow food is going to change, and it won't be the fancy, high-tech systems that win out. It'll be the ones that can handle tough times without falling apart. And the key to that is something that's been missing from a lot of modern farming: having a mix of different things.

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EFFECTS OF WEATHER PARAMETERS ON GROWTH AND PRODUCTIVITY OF KHARIF MOONGBEAN

(*Vigna radiate* (L.) R. Wilczek)

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Abstract

Moongbean is an important pulse crop grown widely in India, and its cultivation is largely influenced by weather conditions. Major weather parameters such as temperature, rainfall, humidity, and solar radiation affecting the growth, development, and yield of moongbean. Each growth stage of the crop responds differently to these factors, with the flowering stage being the most sensitive to temperature fluctuations and moisture stress. In recent years, changing climate conditions, including rising temperatures and irregular rainfall patterns, have created additional challenges for stable production. Suitable mitigation strategies, such as proper sowing time, improved varieties, and efficient water management, to reduce the negative impact of adverse weather conditions. Understanding the relationship between weather parameters and crop performance is essential for achieving sustainable and stable production of moongbean.

Key words: Weather parameters, growth stage, weather uncertainties and efficient water management.

Introduction

Vigna radiata, popularly known as moongbean, green gram or “golden gram” because of its nutritional richness. It is one of the major pulse crops grown in India during the kharif season. India is among the leading producers as well as consumers of pulses in the world. Moongbean is a drought-tolerant and low-input crop, which is also used as green manure and livestock feed. It is considered an important source of vegetable protein, containing about 20–25% protein, and is also rich in vitamins and minerals such as calcium and sodium. It has a significant role in improving soil fertility due to its nitrogen fixing ability. Due to its short duration nature, moongbean fits well into different cropping systems. However, its cultivation and productivity are largely dependent on weather conditions such as temperature and rainfall, which directly affect its growth and development. In recent years, changing climate conditions and irregular rainfall pattern have created new challenges for its cultivation. Therefore, understanding the relationship between weather factors and crop performance is essential for better productivity.

Effect of Weather Parameters on Moongbean Cultivation

Moongbean is highly sensitive to weather conditions, and its growth and productivity are greatly influenced by various meteorological parameters such as temperature, rainfall, humidity, and solar radiation.

Temperature- Its plays an important role during the entire crop growth period.

❖ **Optimum range:** 25–35°C

- ❖ Promotes rapid germination, vegetative growth, and flowering
- ❖ **Low temperature (<15°C):** Delays germination and reduces plant vigor
- ❖ **High temperature (>40°C):** Causes flower drop, poor pod setting, and reduced yield
- ❖ High temperature during maturity accelerates drying but may reduce grain quality

Effect: Proper temperature ensures better physiological processes like photosynthesis and enzyme activity.

Rainfall: Excessive rainfall can result in waterlogging conditions, which damage the root system and increase the chances of diseases. In contrast, insufficient rainfall can lead to moisture stress, negatively affecting plant development and yield. Humidity also influences the crop, as high humidity levels can promote the incidence of fungal diseases.

- ❖ Requires **moderate rainfall (50–90 cm)**
- ❖ **Well-distributed rainfall** supports uniform growth
- **Excess rainfall:** Causes water logging, Reduces root respiration, Leads to diseases like root rot
- **Rain during flowering:** Affects pollination, Leads to flower shedding and poor pod formation

Effect: Both deficit and excess rainfall negatively impact yield.

Solar Radiation : Solar radiation and sunshine hours play a vital role in photosynthesis and biomass production. Adequate sunlight ensures better growth and higher yield, whereas prolonged cloudy conditions may reduce photosynthetic activity and ultimately affect productivity. Wind also has a minor but noticeable impact, as strong winds during flowering or pod formation stages can lead to physical damage and loss of flowers.

- ❖ Requires **bright sunshine** for optimum growth
- ❖ Enhances **photosynthesis and dry matter accumulation**
- ❖ **Cloudy weather:** Reduces photosynthesis, Leads to weak plants and lower yield

Effect: Adequate sunlight is crucial for biomass production and seed filling.

Growth Stages of Moongbean and Influence of Weather

The initial stage is germination, which requires adequate soil moisture and a moderate temperature for proper seed emergence. If the temperature is too low or soil moisture is insufficient, germination may be delayed or uneven. At vegetative stage, proper sunlight and favorable temperature conditions are essential for healthy plant growth and leaf development. Any stress during this stage can reduce plant vigor and affect the overall development of the crop. During flowering stage, the crop becomes very sensitive to temperature fluctuations and rainfall variability. High temperatures or dry conditions can lead to flower drop, while excessive rainfall may disturb pollination and increase the chances of disease incidence. As a result, both situations can significantly reduce pod formation and yield. Following this, during the pod formation and grain filling stage, the crop requires relatively stable weather conditions. Excess moisture or cloudy weather during this period may reduce seed quality and grain development.

Finally, at the maturity stage, dry and warm weather conditions are considered most suitable, as rainfall during this period can damage the mature pods and affect harvesting.

Climate Change Impact on Moongbean Cultivation

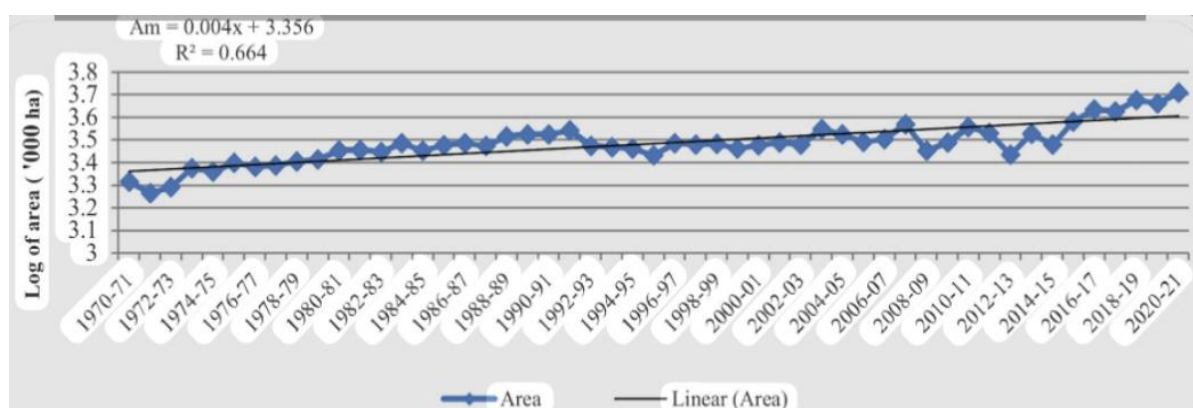
In recent times, climate change become an important factor affecting moongbean cultivation. Changes in temperature patterns, irregular rainfall, and the increasing frequency of extreme

weather events have created new challenges for farmers. Rising temperatures, particularly during the flowering stage, can lead to flower drop and poor pod formation, ultimately reducing yield. At the same time, erratic rainfall patterns may cause either drought conditions or waterlogging, both of which are harmful to the crop. Delayed onset of monsoon or uneven distribution of rainfall further affects timely sowing and crop growth. Additionally, sudden heat waves and heavy rains during critical growth stages can negatively impact both the quantity and quality of produce. As a result, even though the overall production of pulses has improved, the stability of moongbean yield remains uncertain.

Production Scenario of Moongbean in India

Over the years, moongbean cultivation in India has undergone significant changes in terms of area and production. Total area under moongbean in India is **5.5 million hectares** and production is **3.17 million tonnes** in 2025 with **570 kg/ha** average productivity. Moongbean contributes about **10% of total pulse production** in India. Leading states in area & production are **Rajasthan** contribute 45% then **Madhya Pradesh, Maharashtra etc.** In earlier decades, the production of moongbean was relatively low as it was mostly grown under rainfed conditions with traditional farming practices and limited use of improved varieties. Farmers largely depended on monsoon rainfall, which often led to unstable yields. However, in recent years, there has been a gradual rise in the moongbean production has been observed due to the introduction of high yielding varieties, better crop management practices, and increased awareness among farmers. Government initiatives promoting pulse production have also contributed to this growth.

The trend of moongbean production over the years is shown below



Source: Agricultural Statistics at a Glance (2021-22)

Mitigation Strategies for Moongbean under changing weather conditions

To reduce the adverse effects of changing weather conditions on moongbean cultivation, several mitigation strategies can be adopted at the farm level...

1. One of the most important approaches is the selection of suitable varieties that are tolerant to drought and high temperature stress.
2. Adjusting the sowing time according to weather conditions also plays a key role, as timely sowing helps the crop escape extreme weather events during sensitive stages like flowering.
3. Proper water management practices, including efficient irrigation scheduling and drainage facilities, are essential to avoid both moisture stress and waterlogging conditions. In addition, the use of mulching can help conserve soil moisture and regulate soil temperature, thereby supporting better plant growth.

4. Crop diversification and intercropping systems may also reduce the risk associated with weather variability.
5. Farmers can further benefit from weather forecasting and agro-advisory services, which provide timely information for decision-making related to irrigation, sowing, and crop protection.

Conclusion

Moongbean cultivation is highly dependent on weather conditions, and its growth and productivity are strongly influenced by parameters such as temperature, rainfall, humidity, and solar radiation. Each growth stage of the crop has specific weather requirements, and any deviation from these conditions can lead to significant yield losses. In recent years, climate change has further increased the uncertainty in weather patterns, resulting in challenges like irregular rainfall, rising temperatures, and frequent extreme events. It is essential to adopt climate-resilient strategies to ensure sustainable production of moongbean in the future. In addition, the use of weather forecasting and agro-advisory services can support farmers in making better crop management decisions.

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NEED AND ROLE OF NANOTECHNOLOGY IN FERTILIZER, DEVELOPMENT OF NANO DAP IN INDIA BY IFFCO AND ITS SUPERIORITY OVER THE GRANULAR DAP

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Abstract

Nano DAP fertilizers are pioneering a new era of sustainable crop production. With their ability to enhance nutrient absorption, reduce environmental impact, and fortify crops against adversity, Nano DAP fertilizers hold the promise of a brighter future for agriculture. As we continue to innovate in this field, these tiny particles may indeed be the key to simultaneously nourishing our global population and preserving our planet for generations to come. Collaboration among farmers, researchers, and policymakers is essential to unlock the full potential of Nano DAP fertilizers and usher in a new era of agricultural sustainability.

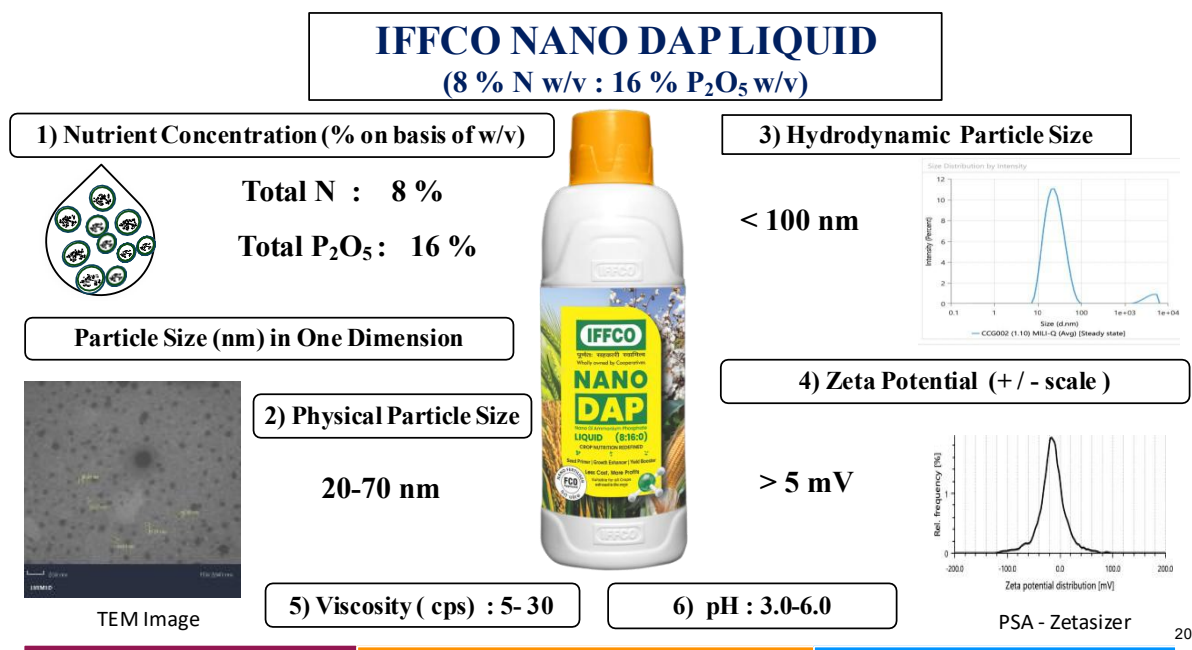
Keywords: Role of Nano DAP, alternate source of DAP, Foliar Fertilisation, Seed Primer, Growth Enhancer, Yield Booster

Introduction

In India, cereals, pulses and oil seeds are grown in marginal soils and also Indian soils contain low levels of phosphorous, that low level of soil phosphorus is a great obstruction to the growth and development of crops. However pulses are being phosphorus-sensitive, thus phosphorous plays a crucial role in promoting the growth of a strong root system, ensuring optimal nutrient absorption and water uptake. Emerging soil health degradation threats pose serious concerns. Abysmally low soil organic carbon (<0.5%), emerging multi-nutrient deficiencies (N, P, K, S, Zn, B and Fe), low nutrient use efficiencies (30-50% Nitrogen, 15-25% Phosphorus, 50-60% Potash, 8-12% Sulphur and 2-5% micronutrients) and declining fertiliser responses (<5 kg /kg NPK) are major issues threatening growth in agriculture production on sustainable basis. Absolutely low phosphorus use efficiency in India resulting in low biomass or yield relative to the amount of P applied. This occurs because P is highly immobile, often binding with soil minerals (Ca, Al, Fe), limiting uptake to only 10-25% of applied fertilizer, leading to wasted nutrients and environmental loss, etc. Foliar application of nano phosphorous has been found to increase the growth, dry matter production and yield of crops. Nano DAP as a seed treatment can enhance root growth resulting in robust seedling establishment and also it increases as the root nodulation, helps in the efficient use of nutrients and nitrogen fixation, later stages foliar spray of nano DAP at the early vegetative stage favoured better crop growth by absorbing phosphorus through stomata leading to increased urease activity in leaves which converts nitrogen and phosphorus into protein, amino acids and growth hormone, this encourages cell growth and nano Phosphorus absorbed through leaves helps in efficient partitioning of photosynthates from vegetative part to reproductive parts, Perhaps the fact that excess assimilate stored in

the leaves and later translocated into seeds at the time of senescence, ultimately led to higher yield. So, the nano DAP may act as an alternate source of nitrogen and phosphorus.

IFFCO Nano DAP



IFFCO Nano DAP is a liquid fertilizer containing 8% Nitrogen and 16% Phosphorus (16%), designed as a highly efficient, sustainable alternative to conventional DAP. By using particles smaller than 100 nm, it improves nutrient absorption via foliage and seeds, boosting root development, chlorophyll, and overall yield, while reducing chemical runoff.

1. Key Roles and Advantages of Nano DAP

- **High Nutrient Efficiency:** Its small particle size enables easy entry into plants through stomata and plant openings, leading to higher efficiency, faster uptake, and reduced nutrient loss compared to conventional granules.
- **Targeted Nutrition:** It serves as an effective foliar application to correct nitrogen and phosphorus deficiencies during standing crops, aiding seed vigor and root development.
- **Enhanced Crop Performance:** Increased application efficiency leads to higher chlorophyll content, enhanced photosynthesis, and improved crop yields.
- **Sustainable Agriculture:** It reduces reliance on traditional chemical fertilizers and lowers the carbon footprint by offering a more concentrated, easily transported, and environmentally friendly alternative.
- **Cost-Effective:** It is more economical than traditional fertilizers and reduces the import burden for the country.

2. Mechanism of Action

A. Absorption: The nanoparticles are applied through spraying, allowing for easy absorption via the leaf surface.

B. Entry: Particles penetrate plant tissues directly.

C. Assimilation: Once inside, they provide nitrogen and phosphorus to fuel ATP synthesis, promoting photosynthesis and metabolism.

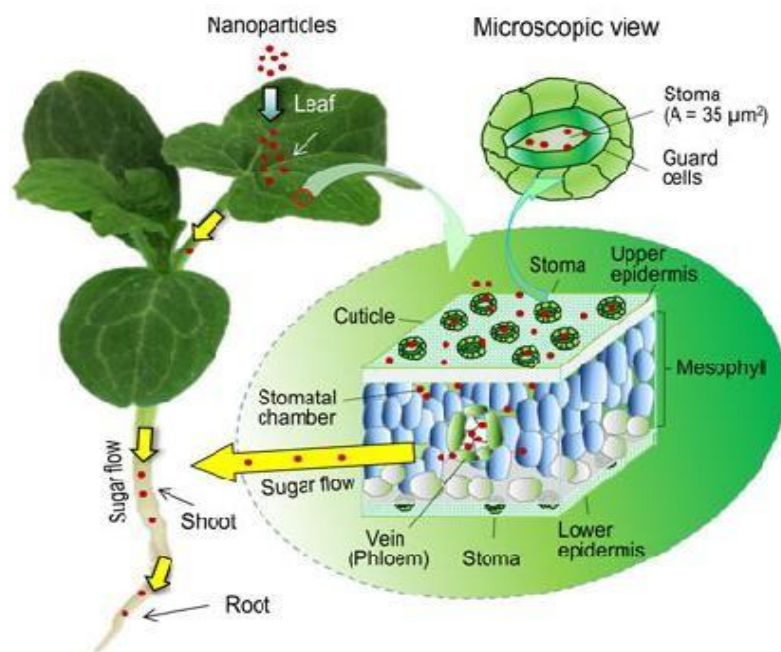


Diagram 1. Source: Wang *et al.*, 2013

3. How to efficient use of Nano DAP for

- Seed Treatment:** This could be used at 3-5 ml per Kg of seeds by dissolving in the required quantity of water to form a thin film on the seed surface. Leave for 20-30 minutes; Shade dry it and sow it.
- Seedling/Tuber/Sett treatment:** Could be applied at 3-5 ml per liter of water. Dry it in the shade and then transplant it.
- Foliar Spray:** This could be used at 2-4 ml per liter of water at a good foliage stage. An additional spray at the pre-flowering stage can be applied in long during and high phosphorus-requiring crops. Apply 2nd Foliar spray at the Pre-Flowering / Late Tillering stage for better response in high phosphorus-requiring crops.

Compared to traditional soil-applied fertilizers, foliar-applied nano-fertilizers offer significant advantages, including faster nutrient absorption, improved cost-effectiveness and minimal impact on soil health. Additionally, foliar application supplies vitamins and essential elements that may be deficient in the soil. The foliar application of nano DAP fertilizer in combination with conventional phosphatic fertilizer showed potential in reducing the soil application of phosphorus. It was observed that application of 100% RDF of N and P was superior. However, using 75% RDF N and P + foliar spray with nano DAP @ 4 ml/L at 25 DAS and 50% RDF N and P + Seed treatment with nano DAP @ 5 ml/kg seed + First foliar spray with nano DAP @ 4 ml/L at 25 DAS seems to be more effective for achieving higher growth and yield attributing characters of wheat (Parmar et al,2024).

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NEXT-GEN AGRICULTURE: TRANSFORMING INDIAN FARMING WITH SMART TECHNOLOGIES AND SUSTAINABLE INNOVATIONS

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Abstract

The rapid advancement of digital technologies is transforming agriculture into a data-driven, precision-oriented sector often referred to as Next-Generation Agriculture. The role of emerging tools such as 5G connectivity, Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), the Internet of Things (IoT), aerial imagery, and big data analytics in addressing contemporary agricultural challenges while promoting sustainability. Studies show that these technologies enhance crop monitoring, soil and water management, and market forecasting, even in remote or marginal farming regions. Sensor-based IoT systems enable real-time tracking of critical parameters such as soil moisture, nutrient content, and temperature, supporting informed decision-making for irrigation, fertilization, and crop selection. AI and ML models, including Convolutional Neural Networks (CNNs), Random Forests (RF), and Support Vector Machines (SVM), have been increasingly applied to optimize farm productivity, resource efficiency, and risk management. Overall, these digital technologies can guide agriculture towards a more sustainable, inclusive, and efficient future, aiming to modernize farming systems in India and globally.

Keywords: Next-Generation Agriculture; Smart Farming; Artificial Intelligence; Machine Learning; IoT; Precision Agriculture; Sustainable Agriculture; Crop Management

Introduction

Agriculture remains a foundational pillar of India's economy, supporting the livelihoods of millions and contributing significantly to national GDP (Ahmad *et al.*, 2021). However, the sector faces mounting challenges from climate change, unpredictable weather patterns, soil degradation, dwindling water resources, and rising food demand (Liakos *et al.*, 2020). Traditional cultivation practices, while valuable, struggle to meet these pressures effectively and sustainably.

Next-Generation Agriculture, also referred to as Agriculture 6.0, integrates advanced digital technologies into farming systems to improve productivity, sustainability, and resilience. By leveraging 5G connectivity, AI, ML, IoT, aerial imaging, and big data analytics, modern agriculture enables precise real-time monitoring, targeted management of inputs, and informed decision-making (Singh *et al.*, 2024). These technologies are transforming conventional agricultural practices into smart, efficient, and data-driven systems.

Digital Technologies Reshaping Agriculture

5G Connectivity

The deployment of high-speed 5G networks is pivotal in enabling real-time data exchange across farming operations. With low latency and high bandwidth, 5G supports seamless communication among IoT sensors, drones, autonomous machinery, and decision-support systems (Singh *et al.*,

2024). This connectivity is particularly valuable for remote and topographically challenging farm areas where traditional networks are unreliable.

Artificial Intelligence and Machine Learning

AI and ML applications have advanced rapidly in agriculture. AI-driven models such as CNNs are utilized for high-accuracy detection of plant diseases and assessment of crop health through image analysis (Liakos *et al.*, 2020). Traditional ML algorithms like Random Forests and Support Vector Machines enable trend prediction, yield forecasting, and risk assessment (Saini *et al.*, 2022). These models extract meaningful insights from complex datasets, transforming raw data into actionable recommendations for farm management. Machine learning also supports predictive analytics for climate risk forecasting, enabling farmers to prepare for extreme weather events or seasonal shifts (Ahmad *et al.*, 2021). By harnessing large datasets, ML improves precision in decisions related to sowing, harvesting, and input management.

Internet of Things (IoT) and Sensor Networks

IoT systems collect continuous, real-time field data through soil moisture probes, weather stations, nutrient sensors, and actuators (Bhattacharya *et al.*, 2023). These systems enable precision irrigation by optimizing water application based on soil moisture levels and climatic conditions. IoT-enabled automation can significantly reduce resource wastage, enhance crop performance, and decrease operational costs. In addition to irrigation, IoT tools support smart fertilization practices by deploying nutrients only where required a key advantage for sustainable production (Kumar *et al.*, 2021). By pairing sensor data with predictive modeling, farmers can better understand field variations and respond accordingly.

Aerial Imaging and Drones

Unmanned Aerial Vehicles (UAVs), commonly known as drones, equipped with multispectral and hyperspectral cameras provide rich crop health data (Ma *et al.*, 2025). When paired with AI analytics, drone imagery allows early detection of stress, pest infestations, and nutrient deficiencies, enabling corrective actions before yield losses occur. Moreover, drones support variable rate application (VRA) strategies, applying inputs such as water or pesticides only to zones that need them, thus enhancing efficiency (Ma *et al.*, 2025). This spatial precision reduces environmental impact and input costs.

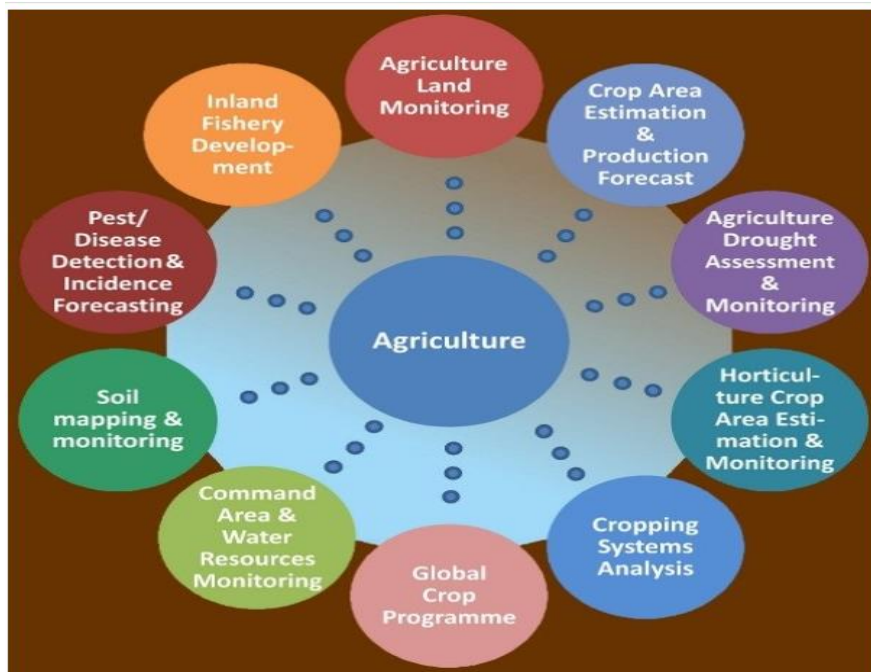
Big Data Analytics

Big data platforms compile and process extensive datasets from IoT networks, weather stations, soil surveys, and satellite imagery. This data supports predictive analytics that can forecast climate patterns, market demand, and potential yield outcomes (Ramesh & Sharma, 2023). By integrating data streams across scales from farm plots to regional production systems stakeholders can model scenarios and prioritize adaptive strategies.

Applications in Indian Agriculture

Next-Gen Agriculture integrates technologies like remote sensing, GIS, AI, IoT, and data analytics to improve decision-making across agriculture (Ahmad *et al.*, 2021; Liakos *et al.*, 2020). It enables land monitoring, crop area estimation, yield forecasting, and drought assessment for sustainable planning (Bhattacharya *et al.*, 2023; Ramesh and Sharma, 2023). Horticultural monitoring supports high-value crop management, while cropping system analysis optimizes rotations and soil health (Ma *et al.*, 2025). Water resources and soil mapping enhance irrigation and precision farming, and predictive pest/disease detection reduces losses and chemical use (Kumar *et al.*, 2021; Singh *et al.*,

2024). These integrated applications make Next-Gen Agriculture a comprehensive approach to boosting productivity, sustainability, and resilience in modern agriculture (Saini *et al.*, 2022).



Conclusion

Next-Generation Agriculture combines digital technologies like AI, ML, IoT, drones, and 5G to make farming more efficient, precise, and sustainable. These innovations help optimize resources, improve productivity, and support climate-resilient practices while empowering farmers with data-driven decisions. Despite challenges such as cost and infrastructure, strategic adoption of smart technologies can transform Indian agriculture into a resilient, inclusive, and sustainable sector capable of meeting future food demands.

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NITROGEN MANAGEMENT AND ITS EFFECT ON CURD QUALITY IN CAULIFLOWER

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Abstract

Cauliflower is a major vegetable crop valued for its compact, white, attractive curds, which largely determine its market price and consumer appeal. Among the nutrients that influence its growth, nitrogen plays a central role in building strong foliage and supporting the development of high-quality curds. However, both insufficient and excessive nitrogen can upset this delicate balance deficiency limits leaf growth and produces small, loose curds. At the same time, over-application promotes excessive vegetative growth and delays curd formation. The article highlights the importance of balanced, timely nitrogen management as the key to achieving optimal curd size, firmness, and colour. It also discusses practical, field-based strategies that maintain nutrient balance, enhance curd quality, and ensure profitable, environmentally responsible cauliflower production.

Keywords: Nitrogen management, cauliflower, curd quality, nutrient balance, sustainable production

Introduction

Cauliflower is a key cole crop grown widely in both kitchen gardens and commercial fields. For growers, success is judged not just by yield but by the quality of the curd. In competitive markets, buyers prefer curds that are large, compact, bright white, and free from looseness or discolouration. These visible traits strongly influence consumer acceptance and ultimately determine the price farmers receive. Among the nutrients affecting curd development, nitrogen plays a central role. It drives vegetative growth by promoting leaf area and canopy development, which are essential for photosynthesis and curd formation. However, nitrogen management requires precision. Inadequate nitrogen restricts growth and limits curd size, while excessive application often promotes excessive vegetative growth, resulting in loose, less compact, or discoloured curds and reduced market quality (Giri *et al.*, 2023; Giri, 2021). This article examines how balanced nitrogen management influences curd quality in cauliflower. It is intended to help students and growers understand how appropriate nitrogen practices can improve productivity while maintaining the visual and structural qualities required for better market acceptance and higher economic returns.

Nitrogen and Cauliflower Growth: A Simple Overview

Nitrogen strongly influences cauliflower growth from early leaf development to curd formation. It is the nutrient most closely associated with deep green foliage, plant vigour, and overall canopy development. Adequate nitrogen promotes the production of broad, healthy leaves that efficiently intercept light and sustain high photosynthetic activity, providing the energy required for continuous tissue growth. In cauliflower, leaf development has direct implications for curd

formation. The curd, a modified shoot, depends mainly on assimilates produced by the leaves. Plants with well-developed, healthy foliage are therefore more likely to initiate curding at the appropriate stage and produce firm, compact heads. Conversely, nitrogen deficiency leads to pale, stunted plants with limited leaf area and small curds, while excessive nitrogen favours luxuriant vegetative growth, often delaying curd initiation and resulting in loose or poorly compacted curds (Sahito *et al.*, 2018; Pandey *et al.*, 2019). Balanced nitrogen nutrition allows the crop to grow vigorously while ensuring a timely shift from vegetative growth to curd development. This balance is readily visible in the field: nitrogen-deficient plants rarely produce marketable curds, whereas overly vigorous plants may appear healthy but fail to deliver acceptable curd quality. The ideal cauliflower plant lies between these extremes, combining healthy green foliage with efficient assimilate partitioning toward compact, bright, and market-preferred curds. Such visual differences under varying nitrogen levels are commonly observed in cauliflower fields and are illustrated in Figure 1.

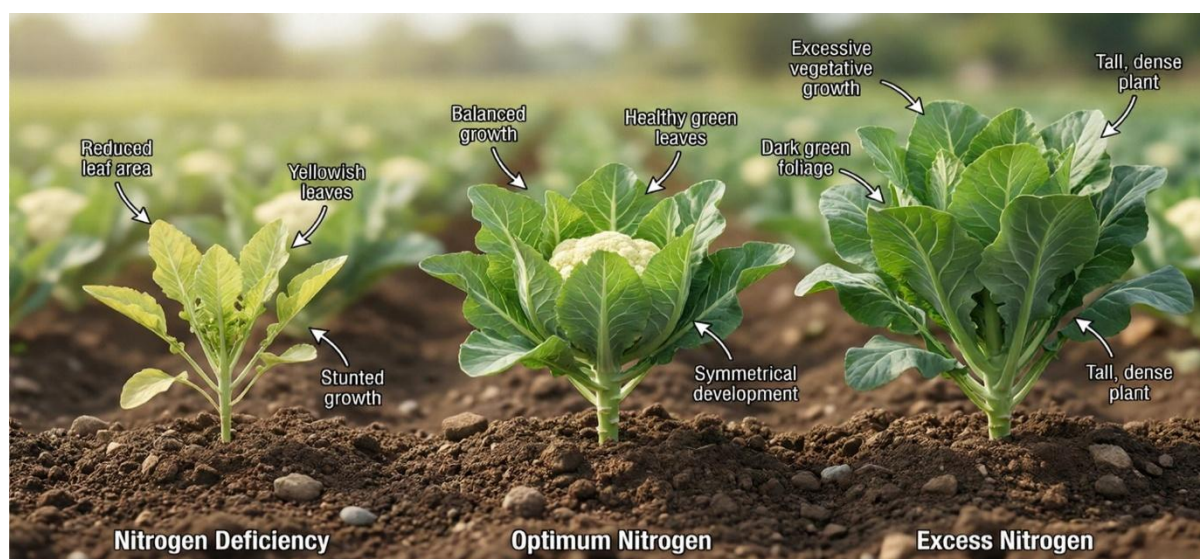


Figure 1. Influence of nitrogen nutrition on vegetative growth and plant morphology of cauliflower.

Nitrogen Requirement in Cauliflower

Cauliflower is a nutrient-demanding crop, requiring relatively higher amounts of nitrogen than many other vegetables. This high demand is closely linked to its rapid early growth and the development of a large leaf canopy. During the initial stages, cauliflower produces broad green leaves that serve as the plant's primary photosynthetic surface, supplying the energy needed for stem development and subsequent curd formation. As canopy size increases, nitrogen demand rises accordingly to sustain active growth. Nitrogen requirement, however, is not uniform throughout the crop cycle. During the early vegetative stage, adequate nitrogen is essential for establishing a strong plant frame and sufficient leaf area. As the crop approaches curd initiation, nitrogen demand becomes particularly critical, as the plant must maintain growth while shifting from vegetative to curd-forming development. During curd development, a continuous but balanced nitrogen supply supports curd enlargement, firmness, and colour, whereas imbalances at this stage can adversely affect market quality (Pandey *et al.*, 2019; Sony *et al.*, 2020). Actual nitrogen needs vary with cultivar maturity group, soil fertility, and prevailing climatic conditions. Early-maturing varieties require timely nitrogen availability due to their short growth period, while late-maturing types

respond better to a more sustained supply. Across varieties and environments, mismatches between nitrogen supply and crop demand often result in poor performance. Nitrogen deficiency restricts growth and curd size, while excessive application delays maturity and produces soft or loose curds (Giri *et al.*, 2023; Katuwal *et al.*, 2023). Balanced, stage-specific nitrogen management, therefore, remains central to achieving healthy plant growth and high-quality, market-ready curds. The stage-wise role of nitrogen in cauliflower growth and its influence on curd quality is summarised in Table 1.

Table 1: Growth Stage-wise Role of Nitrogen in Cauliflower and Its Impact on Curd Quality

Crop growth stage	Role of nitrogen at this stage	Effect on final curd quality
Early vegetative stage	Promotes leaf initiation and leaf area development	Strong leaf framework supports better curd formation later
Active vegetative growth	Maintains photosynthetic capacity and plant vigour	Adequate assimilation supply for curd initiation
Curd initiation stage	Supports smooth transition from vegetative to reproductive phase	Timely curd initiation and uniform curd development
Curd development stage	Helps maintain curd growth without excessive foliage	Compact, well-formed curds with better market quality

How Nitrogen Affects Curd Quality

Role of Nitrogen in Curd Formation

Nitrogen plays a decisive role in determining the final appearance and market quality of cauliflower curds. For growers, success is not measured solely by curd size but also by compactness, whiteness, and uniformity, which strongly influence consumer preference and price. The timing and amount of nitrogen supplied during crop growth directly affect these quality attributes, making nitrogen management one of the most critical factors governing both yield value and market acceptance (Giri *et al.*, 2023).

Building the Foundation through Healthy Foliage

Adequate nitrogen supports the development of a strong and efficient leaf canopy that captures sunlight and produces assimilates required for curd growth. Well-nourished foliage continuously supplies carbohydrates to the developing curd, resulting in larger, denser, and more uniform heads. In contrast, nitrogen deficiency restricts leaf development, resulting in pale, stunted plants with reduced photosynthetic capacity. Such plants often form small, open, and uneven curds that lack visual appeal and market value (Pandey *et al.*, 2019).

When Too Much Nitrogen Becomes a Problem

Excessive nitrogen application can be equally detrimental to curd quality. Over-supplied plants exhibit excessive vegetative growth, delaying curd initiation and disrupting normal curd development. The resulting curds are often loose, leafy, or poorly compacted and may show uneven structure. Although such plants appear vigorous in the field, the harvested curds frequently fail to meet market standards due to softness and poor form (Sahito *et al.*, 2018; Katuwal *et al.*, 2023). Maintaining moderation rather than maximizing nitrogen input is therefore essential.

Influence on Curd Colour and Market Value

Nitrogen also indirectly affects curd colour, a key determinant of market price. Adequate nitrogen promotes sufficient leaf cover, which shades the curd and helps maintain its bright white colour.

Nitrogen-deficient plants often develop sparse foliage, exposing the curd to sunlight and leading to yellowing or a creamy discolouration. Although edible, such curds are perceived as inferior by consumers and are typically sold at lower prices (Giri, 2021). Visual differences in curd size, compactness, and colour under varying nitrogen levels are illustrated in Figure 2.

Balancing Growth for Best Returns

In practice, optimal nitrogen management ensures vigorous plant growth without compromising curd development. Farmers who synchronize nitrogen supply with crop demand consistently produce curds that are compact, white, and uniformly shaped. This balance between vegetative growth and curd formation directly translates into improved marketability and higher economic returns, underscoring nitrogen's importance not just as a growth nutrient but also as a key driver of curd quality.

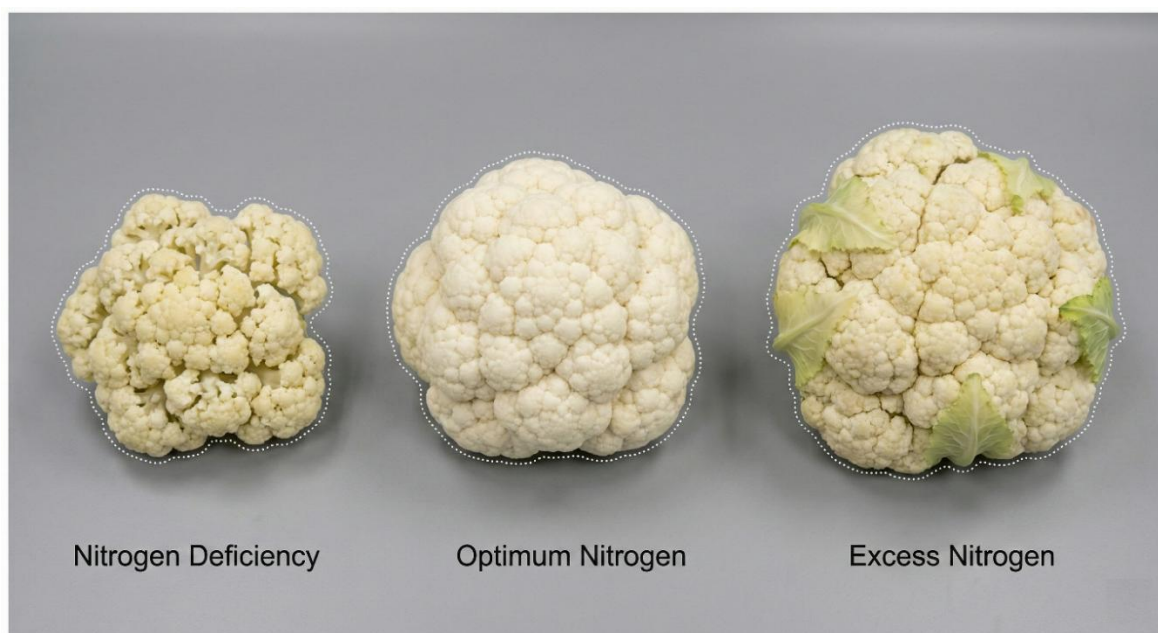


Figure 2. Influence of different nitrogen levels on curd size, compactness, and appearance of cauliflower.

When Nitrogen Goes Wrong

When Nitrogen Balance Goes Off Track

Nitrogen is essential for healthy cauliflower growth, but improper management quickly translates into poor crop performance and reduced curd quality. In practice, nitrogen imbalance appears in two contrasting forms: deficiency and excess. Although opposite in nature, both disrupt normal plant growth and reduce the market value of the harvested curds.

Effects of Nitrogen Deficiency

Nitrogen deficiency is usually first reflected in the foliage. Plants appear weak, growth slows down, and leaves turn pale green to yellowish. Reduced leaf number and size limit light interception and photosynthetic activity, restricting the supply of assimilates required for curd development. As a result, curds remain small, loose, and often irregular in shape. Their lack of compactness and brightness makes them less attractive in the market. Under severe deficiency, curd initiation may be delayed or incomplete, leading to uneven maturity within the field (Pandey *et al.*, 2019; Katuwal *et al.*, 2023).

Consequences of Excess Nitrogen

Excess nitrogen often gives a misleading impression of crop health. Plants become tall, lush, and dark green, indicating vigorous vegetative growth. However, this excessive leafiness often delays curd initiation and disrupts normal curd development. The resulting curds are commonly loose, leafy, or poorly compacted and may show uneven structure and discolouration. Despite high biomass production, these curds rarely meet market-quality standards. Studies have consistently shown that excessive nitrogen reduces curd compactness and overall quality, even when yield appears satisfactory (Sahito *et al.*, 2018; Giri *et al.*, 2023).

The Cost of Imbalance

Both nitrogen deficiency and excess ultimately lead to economic losses. Deficiency limits curd size and yield, while excess nitrogen compromises quality, uniformity, and market acceptance. In over-fertilized crops, high vegetative growth does not necessarily translate into better returns, as poorly formed curds fetch lower prices. Balanced nitrogen management, therefore, remains central to producing healthy plants, high-quality curds, and profitable cauliflower crops.

Practical Nitrogen Management in Cauliflower

Importance of Basal Nitrogen Application

Successful cauliflower production begins with strong early establishment, which depends heavily on timely nitrogen availability. Basal nitrogen application at transplanting or shortly thereafter supports rapid recovery from transplant shock and promotes early leaf and stem development. Adequate nitrogen at this stage encourages uniform plant establishment, faster canopy development, and active photosynthesis, creating a solid foundation for later curd formation. Fields lacking early nitrogen supply often show uneven growth, weak plants, and delayed crop development, which ultimately affects curd size and uniformity (Pandey *et al.*, 2019; Giri *et al.*, 2023).

Benefits of Split Application

Cauliflower requires nitrogen throughout its growth cycle, but its demand varies with crop stage. Applying the entire nitrogen dose at once is inefficient and may lead to nutrient losses or excessive vegetative growth early in the season. Splitting nitrogen into two or three applications is a more effective strategy, ensuring availability during critical stages such as vegetative growth and curd initiation. Split application improves nitrogen use efficiency, maintains steady plant growth, and supports the development of compact, well-formed curds without delaying maturity (Sahito *et al.*, 2018; Sony *et al.*, 2020).

Integrated Use of Nitrogen Sources

Combining inorganic nitrogen fertilizers with organic sources, such as compost or well-decomposed farmyard manure, can further improve crop performance. Organic inputs enhance soil structure, moisture-holding capacity, and microbial activity, while inorganic fertilizers provide readily available nitrogen for immediate crop uptake. This integrated approach supports sustained nutrient release, promotes balanced plant growth, and contributes to consistent curd quality, particularly under intensive production systems.

Minimizing Nitrogen Losses

Efficient nitrogen management also depends on reducing nutrient losses in the field. Applying nitrogen near the root zone, preferably after irrigation or rainfall, helps minimise volatilisation and leaching losses. Avoiding excessive doses and adjusting nitrogen supply to crop stage and soil

fertility improves nutrient use efficiency and prevents imbalanced growth. By synchronizing nitrogen application with actual crop demand, growers can achieve high yields, superior curd quality, and better economic returns while maintaining soil and environmental health (Manisha *et al.*, 2023).

Conclusion

Nitrogen remains one of the most important nutrients in cauliflower production, but its actual value lies in how wisely it is managed. Balanced, timely nitrogen application helps maintain the proper balance between leafy growth and curd development, leading to compact, white, market-preferred curds. Both deficiency and excess interfere with this balance—either restricting growth or promoting unwanted leafiness that reduces curd quality and uniformity. By focusing on careful scheduling and moderate supply, farmers can enhance yield, quality, and profitability together. For future vegetable scientists and growers, adopting responsible nitrogen management is key to sustaining productivity while protecting soil and environmental health for generations ahead.

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NUTRI-SENSITIVE AGRICULTURE: GROWING FOOD THAT NOURISHES LIVES

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Abstract

Nutri-Sensitive Agriculture (NSA) is an emerging approach that connects agriculture with improved nutrition and health outcomes. Unlike conventional agricultural systems that mainly emphasize higher production and yield, NSA focuses on producing diverse, nutrient-rich foods and promoting healthy dietary practices. It highlights the need to integrate nutrition goals into agricultural production to address persistent problems of malnutrition and micronutrient deficiencies. Despite increased food production, a large section of the population—especially women, children, and low-income households—still struggles to access affordable and nutritious food. The approach also points out the limitations of current agricultural practices such as monocropping, low dietary diversity, and weak policy integration. NSA recognizes the important role of women and smallholder farmers in promoting diversified farming systems and improving household nutrition. In India, initiatives like Mission POSHAN 2.0, Integrated Child Development Services (ICDS), and PM POSHAN Abhiyaan support nutritional improvement. Strengthening nutrition education, empowering women, and promoting diversified agriculture are key to building sustainable food systems and improving overall health and well-being.

Keywords : Nutri-Sensitive Agriculture, Women Empowerment, Smallholder Farmers, Food Security, Malnutrition

Introduction

Nutri-Sensitive Agriculture (NSA) is a food-based approach to agricultural development that aims to improve nutrition and health by increasing the availability, accessibility and consumption of nutritious foods. Unlike conventional agriculture that mainly focuses on increasing food production, NSA emphasizes the cultivation of diverse, nutrient-rich and safe foods that support healthy diets (Baral & Das, 2024). Good nutrition is not determined only by what people eat but also by their ability to access healthy and affordable foods. Nutri-Sensitive Agriculture therefore promotes farming systems, agricultural extension services and community practices that improve the availability of nutritious foods while also enhancing nutrition knowledge, food preparation skills and safe food handling. Despite significant improvements in agricultural production, malnutrition remains a serious challenge. According to the Global Hunger Index 2025, India ranks 102nd out of 123 countries with a score of 25.8, indicating a serious level of hunger. Reports from the International Panel of Experts on Sustainable Food Systems (IPES-Food, 2023) highlight that certain groups such as women, children, indigenous communities and low-income households often face greater barriers in accessing affordable nutritious food.

Why Current Agriculture is Not Enough

Modern agricultural systems largely prioritize calorie-rich staple crops such as rice and wheat rather than nutrient-dense foods like pulses, fruits, vegetables and millets. The focus on yield and income

has encouraged monocropping systems that reduce dietary diversity. As a result, even when food production increases, many households still suffer from hidden hunger, which refers to deficiencies in essential vitamins and minerals. Factors such as soil degradation, post-harvest losses, poverty and limited integration of nutrition goals in agricultural policies further restrict access to healthy diets. This situation highlights the urgent need to promote diversified and nutrition-sensitive farming systems.

Key Elements of Nutri-Sensitive Agriculture

Several factors influence the effectiveness of Nutri-Sensitive Agriculture:

- **Dietary diversity:** Encouraging the cultivation and consumption of cereals, pulses, fruits, vegetables and animal-source foods helps ensure balanced nutrient intake.
- **Household food security:** Year-round availability and access to safe and nutritious foods help reduce hunger and undernutrition.
- **Women's empowerment:** Women's control over income, resources and household decisions significantly improves child feeding practices and family nutrition.
- **Nutrition education:** Awareness about balanced diets, food preparation and hygiene practices promotes better food utilization.
- **Improved farm income:** Higher incomes enhance the ability of households to purchase nutritious foods.
- **Post-harvest management and food safety:** Proper storage and handling reduce food losses and ensure safe consumption.

Role of Women and Small Farmers

Women and smallholder farmers play a crucial role in promoting nutrition-sensitive agriculture. In many rural households, women are responsible for food production, processing and preparation. Their participation in agricultural decision making such as crop selection, marketing and household food purchases has been shown to improve dietary diversity and nutritional outcomes. Studies also indicate that households with diversified farm production tend to have more diverse diets. When women have greater decision-making power, the positive impact of diversified agriculture on nutrition becomes even stronger.

However, several challenges limit the adoption of nutrition-sensitive practices. Farmers often focus on crop yield and income rather than nutritional value. Awareness about balanced diets, biofortified crops and diversified farming systems is still limited. In addition, women frequently face constraints such as limited land ownership, restricted access to credit and training, and heavy household workloads.

Government Initiatives Promoting Nutrition

Recognizing the importance of improving nutrition, the Government of India has introduced several programmes. Mission POSHAN 2.0 (National Nutrition Mission) aims to reduce stunting, undernutrition, anaemia and low birth weight by integrating multiple nutrition-related schemes and promoting behaviour change through community participation. Integrated Child Development Services (ICDS), launched in 1975, provides supplementary nutrition, preschool education, health check-ups and immunization services for children under six years and their mothers. PM POSHAN Abhiyaan, formerly known as the Mid-Day Meal Scheme, is one of the world's largest school feeding programmes. It provides nutritious meals to school children and helps improve their nutritional status and learning capacity.

Conclusion

Nutri-Sensitive Agriculture offers an important pathway to address both food security and malnutrition. By promoting diversified farming systems, strengthening women's participation and integrating nutrition goals into agricultural policies, farming can move beyond simply producing food to producing healthy diets for all. Strengthening agricultural extension services, improving awareness about nutrition and supporting small farmers will be key to building a sustainable and nutrition-secure future.

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ORGANIC FARMING VS CONVENTIONAL FARMING: A COMPARATIVE STUDY

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Abstract

This comparative study examines organic farming and conventional farming across five dimensions: yield, soil health, environmental impact, human health, and economic viability. Evidence drawn from peer-reviewed literature shows that while conventional farming achieves higher short-term yields, organic systems deliver superior long-term soil fertility, lower ecological toxicity, and comparable nutritional outcomes. Neither system is universally superior; the optimal approach depends on regional context, policy support, and sustainability goals.

Introduction

Global agriculture faces dual imperatives: feeding a population projected to reach 9.7 billion by 2050 while reducing environmental degradation. Conventional farming relying on synthetic fertilisers, pesticides, and high-yield monocultures dominates modern food production but raises concerns about biodiversity loss, soil degradation, and chemical residues. Organic farming, governed by prohibitions on synthetic inputs and emphasising ecological balance, has grown to cover 72.3 million hectares worldwide as of 2019. Understanding the trade-offs between these systems is essential for evidence-based agricultural policy.

Comparative Analysis

Table 1 . Summary comparison of organic and conventional farming systems.

Dimension	Organic Farming	Conventional Farming
Crop Yield	19–25% lower than conventional on average	Higher short-term yields; world avg. 3.7 t/ha for cereals
Soil Health	Higher organic matter, microbial diversity and earthworm activity	Soil compaction and erosion from tillage; declining OM
Env. Impact	57% less energy use; lower GHG; higher biodiversity	High N ₂ O & CO ₂ from synthetic N; pesticide runoff
Human Health	Higher antioxidants & omega-3; lower pesticide residues	Pesticide residues linked to chronic disease risk
Economics	20–30% price premium; lower input costs	Higher yields but rising input/energy costs

Key Findings

Yield & Productivity

A landmark meta-analysis of 362 studies found that organic yields are on average 19.2% lower than conventional, though the gap narrows to ~8% for legumes and to near-parity when best organic practices are applied. The yield gap makes full organic conversion incompatible with feeding projected 2050 populations without major dietary shifts.

Soil Health & Biodiversity

Organic soils show significantly higher microbial biomass, fungal diversity, and earthworm populations. A 21-year DOK trial in Switzerland demonstrated that organic plots had 34% higher soil organic carbon and superior aggregate stability versus conventional plots. Synthetic nitrogen and pesticides suppress beneficial soil organisms and promote monoculture-driven erosion.

Environmental Impact

Conventional farming accounts for approximately 10-12% of global GHG emissions largely through synthetic nitrogen fertiliser (N₂O release) and deforestation. Organic systems use 57% less energy per unit area and support 30% greater plant, insect, and bird species richness. However, organic's lower yields mean more land may be needed per unit of food, a trade-off termed the "land-sparing" dilemma.

Human Health

Organic crops contain 19-69% more antioxidants and significantly lower cadmium and pesticide residues than conventionally grown equivalents. Conversely, Annex studies suggest organophosphate pesticide exposure from conventional produce is associated with elevated neurodevelopmental risks in children.

Economic Viability

Organic products command a 20-30% retail price premium, but certification costs and lower yields compress farm-gate margins. Conventional farms benefit from economies of scale and subsidy structures in most countries, yet face rising input costs as fossil-fuel-derived fertiliser prices fluctuate. Long-run total factor productivity analyses suggest organic systems become economically competitive over 10-15 year horizons as soil quality diverges.

Discussion & Conclusion

The evidence does not support a categorical judgment that one system is universally superior. Conventional farming's productivity advantage is real but achieved at measurable ecological costs. Organic farming's environmental and health benefits are well-documented, but the yield gap and land-use trade-offs require honest acknowledgment. A pragmatic synthesis integrating organic soil management, reduced-input precision agriculture, and agroecological diversification may offer the most viable path toward sustainable food systems.

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OIL PALM: A VERSATILE RESOURCE BEYOND EDIBLE OIL

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Abstract

One of the world's most productive and adaptable oil crops, oil palm is well known for its role in the production of edible oil. But its potential goes well beyond this main use. Every component of the oil palm tree can be turned into useful by products for the manufacturing, food processing, energy, and agricultural sectors. In addition to analyzing the nutritional profile, applications, health advantages, and possible hazards of palm oil, this article examines the wide variety of products made from oil palm, such as palm kernel oil, palm fatty acid distillates, palm kernel expeller, biomass residues, and renewable energy resources. The conversation focuses on how oil palm maximizes resource efficiency and reduces waste to promote a sustainable, circular economy.

Keyword: Health advantage, edible oil

Introduction: An important part of the world's economic and agricultural landscape is the oil palm sector. Oil palm farming, which is well-known for its high yield and efficiency, offers a consistent supply of raw materials for a variety of industries. The oil palm tree produces a variety of by-products that greatly support sustainability, innovation, and economic growth, even if edible palm oil continues to be its most well known commodity.

In addition to its economic significance, palm oil's stability, affordability, and extended shelf life make it a popular ingredient in food products and consumer goods. Evaluating its position in contemporary diets and industries requires an understanding of both its nutritional worth and its wider applications.

A one-tablespoon serving of palm oil provides: Calories: 120, Protein: 0 grams, Fat: 14 grams, Carbohydrates: 0 grams, Fiber: 0 grams, Sugar: 0 grams Palm oil is rich in fat, particularly saturated fat, and contains important micronutrients: Vitamin E: About 2.16 mg per tablespoon (~14% of daily requirement), Red palm oil: Higher in vitamin E and rich in carotenoids, which the body converts into vitamin A.

What Is Palm Oil Used For?

The most popular vegetable oil in the world, palm oil is used in many different products, such as baby formula, baked goods (bread, cookies), beverages (such as chocolate drinks), biofuels, cooking oil, cosmetics (lipstick, creams), detergents, margarine, nut butters (including peanut butter), processed foods (pizza dough, instant noodles), soaps, and shampoos. Alternative names like vegetable oil, palmate, glyceryl, or sodium lauryl sulfate may also be found on product labels.

Palm Oil Benefits

1. Treating Vitamin Deficiency

Red palm oil is rich in carotenoids, which help increase vitamin A levels in the body. Vitamin A is essential for vision, immune function, and child development. Including red palm oil in diets—especially in developing regions—can help prevent vitamin deficiencies and improve overall health.

2. Protecting Brain Health

Palm oil contains a special form of vitamin E known as tocotrienols, which have shown potential in reducing oxidative stress and inflammation in the brain. Early studies suggest that these compounds may help slow the progression of brain-related conditions such as dementia. However, more large-scale human studies are needed to confirm these effects.

3. Improving Heart Health

Research on palm oil's impact on heart health has produced mixed results:

- Diets high in saturated and trans fats are linked to unhealthy cholesterol levels.
- Palm oil may be a better alternative to trans fats but is less heart-healthy than oils rich in unsaturated fats (like olive oil).
- Some animal studies suggest red palm oil may protect against heart damage by reducing tissue injury and improving blood flow.

Further research is required to fully understand its cardiovascular effects.

Major Oil Palm By-Products and Their Applications

1. Palm Kernel Oil (PKO)

Because of its stability and high saturated fat content, palm kernel oil—which is extracted from the seed of the oil palm fruit—is frequently used in soaps, cosmetics, detergents, and processed foods.

2. Palm Fatty Acid Distillates (PFAD)

A by-product of refining crude palm oil, PFAD is used in biodiesel production, lubricants, and chemical manufacturing.

3. Palm Kernel Expeller (PKE)

This residue from oil extraction is rich in protein and fiber, making it a valuable livestock feed and a potential biofuel source.

4. Palm Biomass: Leaves and Empty Fruit Bunches (EFB)

Palm leaves are used in handicrafts, while EFB is utilized in biodegradable packaging, paper production, and bioenergy generation.

5. Palm Oil Mill Effluent (POME)

POME, a liquid waste product, can be converted into biogas for renewable energy and processed into organic fertilizers.

6. Palm Kernel Cake (PKC)

A nutrient-rich by-product used extensively in animal feed, contributing to sustainable livestock production.

7. Palm-Based Biodiesel

Palm oil serves as an efficient feedstock for biodiesel, helping reduce greenhouse gas emissions and dependence on fossil fuels.

8. Palm Sugar

Derived from palm sap, palm sugar is a natural sweetener rich in nutrients and widely used in health-conscious food products.

Industrial and Environmental Significance

With almost every component of the plant being used, the oil palm sector is a prime example of a circular economy. The sector lessens its influence on the environment while increasing economic value by turning trash into usable goods including biofuels, fertilizers, and biodegradable materials.

Conclusion

Oil palm is a highly adaptable and economically significant crop with uses in numerous industries; it is much more than just a source of culinary oil. Palm oil contributes significantly to global consumer goods and nutrition, as well as lucrative by-products such as biodiesel, PFAD, and palm kernel oil. Although palm oil has potential health benefits and perks like vitamin E, it must be consumed carefully due to its high saturated fat content and potential drug interactions. It is crucial to take a balanced approach that combines sustainable production methods with limited dietary consumption. Innovation in the oil palm industry is still being driven by companies like Henan Glory Oils & Fats Engineering Co., Ltd., who guarantee effective resource use and encourage ecologically friendly solutions. Oil palm continues to be a vital component of both ecological sustainability and economic growth as the demand for sustainable and multipurpose resources rises globally.

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OPTIMIZING WATER USE: A GUIDE TO EFFECTIVE IRRIGATION SCHEDULING

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Abstract

Crop water timing and amount are optimized based on crop requirements, soil capacity, and weather conditions, reducing losses such as runoff and deep percolation. Important considerations include crop characteristics (e.g., root depth, growth stages), soil properties (e.g., texture, water-holding capacity), weather (e.g., evapotranspiration), irrigation efficiency, and management constraints. Conventional irrigation scheduling is based on visual estimates, soil feel, neighbour's experience, or water supply, whereas scientific irrigation scheduling is based on soil moisture potential (tensiometers), plant water potential, climatological data ($ET_c = ET_o \times K_c$), and water balance (Change = Input – Output). The advantages include 15-35% water saving, reduced energy and labour costs, avoided nutrient leaching, and maximum productivity, which can change inefficient practices into accurate and efficient practices necessary for water-limited areas.

Introduction

A simple but efficient change is a beginning toward optimizing water use: irrigate crops according to their needs rather than habit or set dates. Making educated choices about when and how much water to apply in order to keep the crop root zone within a desired moisture range is known as irrigation scheduling. Effective scheduling promotes healthier roots, lowers preventable losses like runoff and deep percolation, and helps sustain yield even in situations where water supplies or pumping hours are constrained.

Each drop of irrigation water serves a purpose, such as encouraging plant growth, protecting output, and justifying the cost of pumping, but a large amount is often lost due to water being applied too early, too late, or in the wrong amount. Irrigation scheduling, which involves coordinating irrigation depth and timing with crop demand, soil water storage, and predicted weather to guarantee the crop receives right amount of water when it matters most, is the workable solution to this problem. Over-irrigation is not harmless; it can waste water and energy and even reduce yield by encouraging disease and nutrient leaching. However, well-planned scheduling can increase overall water-use efficiency and reduce unwanted runoff and deep percolation losses.

Every irrigation system has two deciding factors. The first one is timing: water the crop before it is subjected to intolerable stress. The second factor is depth: water should be applied just enough to replenish the effective root zone without causing water to flow below the roots, where plants are

unable to utilize it. To put it another way, the objective is "wet the soil within root zone depth not beyond" For this reason, efficient scheduling is a tool for both water management and increasing productivity.

When to irrigate and how much water needed are determined by a number of interrelated factors that influence irrigation scheduling decisions. These include crop characteristics, soil characteristics, environmental factors, system efficiency, and operational constraints.

Factors affecting irrigation scheduling:

a. Crop Factors

Stress tolerance and water demand are determined by crop characteristics. Sensitivity to water scarcity, critical growth stages (flowering or grain fill, where yield losses are greatest), effective root zone depth (shallower roots require more frequent irrigation), and economic value (high-value crops like vegetables require frequent irrigation) are important components.

b. Soil Characteristics

Water storage and movement are governed by soil properties. Texture affects available water-holding capacity; clays store more water but drain more slowly, while sandy soils hold less and require frequent light treatments. The amount of water that remains usable in the root zone is also influenced by field capacity, wilting point, and infiltration rate.

c. Weather and Climate Factors

Atmospheric demand influences daily crop water use. Evapotranspiration (ET) increases with high temperature, low humidity, wind speed, and solar radiation. Variability in rainfall lowers irrigation needs but requires considering effective infiltration only. Management allowable depletion (MAD) establishes stress thresholds based on these conditions.

d. Irrigation System Factors

The delivery method impacts application. Surface systems, such as furrow and basin, allow for larger depths but offer less uniformity. Sprinklers and drip systems require smaller, frequent applications and are more efficient, but they are prone to clogging. System capacity, uniformity, and application efficiency affect gross versus net depths.

e. Management and Human Factors

Practical constraints include water supply schedules since canal rotations limit timing, labour availability, pumping restrictions, and policy rules, like even/odd day watering. Economic factors, such as energy costs and yield goals, also shape allowable depletion levels.

Table 1 Factors affecting irrigation scheduling

Factor	Impact	Adjustment
Soil texture	Water holding capacity	Sandy soils need frequent, light irrigation
Crop type	Water requirement varies	Paddy needs more water than pulses
Growth stage	ET coefficient changes	Peak demand at flowering/grain filling
Weather	ET rate and rainfall	High temperature increases irrigation need
Climate	Long-term water availability	Arid regions need conservation techniques

Methods of Irrigation scheduling

Table 2 Methods of Irrigation Scheduling

Traditional Approach	Scientific Approach
Visual observation	Soil moisture potential
Soil feel method	Plant water potential
Neighbour field	Climatological parameter
Water availability	Water balance

i. Traditional Approach

a. Visual Observation

Farmers observe crop appearance. When crops show signs of stress due to water scarcity, they appear wilted with leaves rolled or have a blue tinge on the leaves. Irrigation practices are done only after the crop shows the above signs. In other words, the interval between irrigations could be 5 to 10 days.

b. Soil Feel Method

Plant growers can manually sample the soil roots at depths such as 30–60 cm, for example, either manually feel the soil, which crumbles when too dry and forms a ball when wet and needs water, or use a tool such as a soil auger. Sandy soils may require frequent checks near the surface, and clay soils may require checks at greater depths to determine water amounts, e.g., 50–75 mm.

c. Neighbour field

In neighbour field method, decisions regarding when and in what quantities to irrigate are based upon observations and imitation of what others in adjacent fields are doing with regard to water use in comparable conditions.

d. Water availability

Water availability method means the scheduling of irrigation mainly in proportion to the availability of canal water or the quantity of water in the source or delivery system through the turn system of canals, tanks or wells applicable during the start of irrigation and not in exact proportion as required during the growth of the crop.

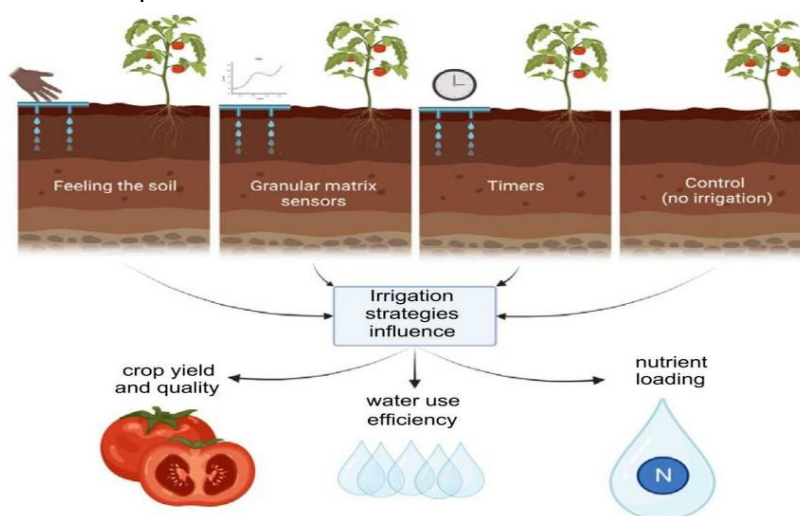


Fig 1 Irrigation scheduling and its effect
 (Source: Schattman *et.al.*, (2023))

ii. Scientific approach

a. Soil Moisture Potential

In this method tensiometers or gypsum blocks which measure soil water tension (matric potential) in specific rooting depths are used. Tension will typically be in the 20-100 centibars range, indicating that roots have available water. Irrigations occur when specific critical tensions for a given crop occur, i.e., 30-50 centibars for sandy soil or 70 centibars for clay. This technique measures water available to plants based on pressure potential of soil water.

b. Plant Water Potential

For instance, leaf water potential, as estimated through pressure plant chambers on stem or leaf material, such as -10 to -20 bars at midday, can be an accurate surrogate for actual plant stress. Irrigation scheduling can begin during periods when plant water stress levels drop below levels such as -1.5 MPa, accounting for actual transpiration stress.

c. Climatological Parameters

Evapotranspiration estimates derived using pan evaporation method, temperature, humidity, wind speed, and solar radiation enter crop scheduling decisions. Daily Crop Evapotranspiration (ET_c) requirements using the crop coefficient method consists of Reference evapotranspiration (ET_o) times a crop coefficient (K_c).

d. Water balance approach

Change in soil water is followed using the equation:

Change = Input – Output

Input includes rainfall and irrigation applied to the soil to replenish the deficits, which occur when the soil moisture depletion rate approaches 50% of the available water holding capacity (i.e., the difference between the field capacity and the wilting point). Root depth and the type of the soil are used for the refinement to obtain the needed updates.

Advantages of irrigation scheduling

- ❖ It also minimizes crop water stress, maximizing yields and quality through timely water application.
- ❖ Saves 15-35% of irrigation water without yield loss by reducing over-irrigation and evaporative loss.
- ❖ Lowers costs for the energy needed to pump the water and reduces labor costs from unnecessary uses.
- ❖ Helps to prevent nutrient leaching, salinity accumulation, and runoff, thus improving the quality of soil and protecting the environment at large.
- ❖ It maximizes economic benefits by fully utilizing available resources and applying precise crop management techniques.
- ❖ Helps in planning deficit irrigation.

Conclusion

Until the introduction of the concept of irrigation scheduling, the approach to water resources management was traditional and wasteful. For instance, the traditional methods included visual methods, feel methods, while the scientific methods included the soil moisture potential method, stress method, climatological evaporation method, and water balance method. All the methods are focused on refilling the root zone in a precise manner without flood or leaching. Benefits accrue

from the fact that 15 to 35 % savings are achieved, increased yields are obtained, along with the benefits bestowed on the soil, which are essential in a region where water is a scarce resource. It thereby enhances productivity and rewards from a resource point of view.

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STINGLESS BEES: SMALL POLLINATORS FOR A BIG FUTURE

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Abstract

Stingless bees, belonging to the tribe Meliponini, are small yet highly efficient pollinators native to tropical and subtropical regions. Despite their small size, they play a crucial role in enhancing agricultural productivity, maintaining biodiversity, and supporting ecosystem stability. Their ability to pollinate a wide range of crops, especially in enclosed or fragile environments, makes them valuable for sustainable agriculture. In addition, stingless bees produce medicinally important honey with high nutritional and therapeutic value. Promoting meliponiculture can improve rural livelihoods, strengthen food security, and contribute to the vision of sustainable and self-reliant development.

Keywords: Meliponiculture, Stingless bees, Sustainable agriculture, Food security

Introduction

The vision of Viksit Bharat 2047 focuses on sustainable development, innovation, environmental conservation, and inclusive growth. Agriculture remains central to this goal, supporting millions of livelihoods. Within agriculture, pollinators are vital for crop productivity and ecological balance, as they enable the reproduction of flowering plants and the formation of fruits and seeds. Among pollinators, bees are the most efficient. While honeybees are, well known, stingless bees (tribe Meliponini) are equally important yet often overlooked. Native to tropical regions, these small insects contribute significantly to agricultural productivity, biodiversity, and offer unique ecological and nutritional benefits.

Stingless Bees: Diversity and Nesting Behaviour

Stingless bees being social insects are, closely related to the commonly known honeybees. However, unlike the familiar honeybee species such as *Apis cerana* and *Apis mellifera*, stingless bees lack a functional sting, making them harmless and safe to manage. Their small size and gentle nature allow them to coexist easily with humans and makes them particularly suitable for beekeeping practices near homes, gardens, and farms. These bees build their nests in tree cavities, wall crevices, underground spaces, or other protected locations (Nayak *et al.*, 2013). Their colonies consist of a queen, workers, and brood, similar to other social bees, but their nesting structures and honey storage systems differ significantly. Unlike honeybees, stingless bees store honey in small, pot-like structures made from a mixture of wax and plant resins known as cerumen. These honey pots give stingless bee honey its unique composition, flavor, and physical properties.



Role of Stingless Bees in Pollination

The ecological importance of stingless bees lies in their critical role as pollinators, a natural service essential for agricultural productivity and ecosystem stability. Pollination enables the transfer of pollen from the male to female parts of flowers, facilitating fertilization and fruit development; without which, crop yields can decline, affecting food security and farmers' income. Stingless bees visit a wide-variety of crops, including vegetables, fruits, spices and medicinal plants, and their tiny size allows them to access flowers that larger bees cannot. Their continuous foraging throughout the day further enhances their efficiency (Souza *et al.*, 2021; Jaffe *et al.*, 2015). Beyond crops, stingless bees also pollinate numerous wild plants and forest species, supporting plant regeneration and maintaining biodiversity. Natural ecosystems such as forests and grasslands rely heavily on pollinators for species survival and ecological balance. In biodiverse tropical regions like India, stingless bees play a key role in sustaining both agricultural and natural ecosystems.

Importance of Stingless Bees in Agricultural Productivity

Stingless bees hold significant potential in promoting agriculture in a sustainable way, which aims to enhance productivity, minimizing the environmental impact and conserving natural resources. As efficient pollinators, they improve crop yield and quality without the need for chemical inputs or costly technologies. Integrating stingless bee colonies into farming systems, particularly in horticultural crops such as fruits, vegetables, and plantation crops, can lead to better fruit set, increased size, and improved quality, thereby boosting farmers' income and reducing reliance on synthetic inputs. Moreover, stingless bees are highly effective in controlled environments like greenhouses and polyhouses, where natural pollination is often limited. Crops such as tomatoes, peppers, cucumbers, and strawberries benefit greatly from their activity. Due to their small size, adaptability to confined spaces, and non-aggressive behavior, stingless bees are easy to manage and serve as an ideal pollination solution in modern protected cultivation systems.



Nutritional and Medicinal Value of Stingless Bee Honey

Beyond their ecological and agricultural roles, stingless bees produce a distinctive honey that is gaining increasing scientific and commercial attention. This honey differs from that of honey bees in composition, flavor, and medicinal properties, typically having higher moisture content, a thinner consistency, and a slightly sour or tangy taste. Its storage in cerumen pots contributes to its unique aroma and biochemical profile (Braghini *et al.*, 2022). Stingless bee honey is considered a functional food due to the presence of bioactive compounds such as phenolic acids, flavonoids, vitamins, and enzymes, which exhibit strong antioxidant activity and help reduce oxidative stress and cellular damage. Additionally, it shows antimicrobial properties against various fungi and bacteria attributed to compounds like organic acids and hydrogen peroxide. Traditionally used to treat wounds, infections, and digestive issues, this honey is now being explored scientifically for its therapeutic potential, making it valuable for pharmaceutical and nutraceutical applications.



Meliponiculture: Cultivation and Management

The high nutritional and medicinal value of stingless bee honey has led to growing demand in both domestic and international markets, where it is regarded as a premium product with higher economic returns than conventional honey. This increasing demand creates valuable income

opportunities for farmers and rural entrepreneurs through meliponiculture, the practice of rearing stingless bees for honey production and pollination services. Meliponiculture is particularly suitable for small-scale farmers due to its low investment requirements, minimal infrastructure, and ease of management. Colonies can be maintained in simple wooden boxes or natural cavities, relying on locally available floral resources. Additionally, the non-stinging nature of these bees makes them safe for handling by beginners, women, and elderly individuals. As a result, stingless beekeeping is highly accessible and can be adopted by self-help groups and community organizations, providing supplementary income and supporting livelihood.

Challenges Facing Stingless Bee Populations

Stingless bees, despite their ecological and economic importance, face several challenges that threaten their survival and productivity. Habitat loss due to deforestation, urbanization, and agricultural intensification has reduced the availability of nesting sites and floral resources. The excessive use of pesticides further harms these pollinators by disrupting their health and foraging behavior, while climate change alters temperature and rainfall patterns, affecting flowering cycles and the availability of nectar and pollen. To conserve stingless bees, it is essential to protect natural habitats and promote pollinator-friendly practices such as planting flowering species, maintaining hedgerows, and minimizing pesticide use. Additionally, scientific research is vital for understanding the biology and potential of stingless bees, particularly in studying the physicochemical and therapeutic properties of their honey. Establishing standardized harvesting, processing, and regulatory frameworks will further enhance product quality, consumer trust, and market opportunities.

Conclusion

In conclusion, stingless bees are remarkable pollinators that offer numerous ecological, agricultural, and economic benefits. Their role in pollination enhances crop productivity and supports biodiversity, while their unique honey provides nutritional and medicinal value. Protecting and promoting stingless bees requires collective efforts from researchers, farmers, policymakers, and communities. As India works toward the vision of a developed nation by 2047, the humble stingless bee may well become an important symbol of how nature and human progress can coexist harmoniously.

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PRECISION FARMING USING AI AND IOT TECHNOLOGIES

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Abstract

Precision farming integrates Artificial Intelligence (AI) and the Internet of Things (IoT) to transform traditional agriculture into a data-driven, resource-efficient system. By enabling real-time monitoring, predictive analytics, and automated decision-making, these technologies increase crop yields by up to 25%, reduce water use by 30-50%, and cut fertilizer waste by 15-50%. This article provides a concise overview of key technologies, benefits, challenges, and real world applications.

Introduction

Global food demand is projected to increase by 70% by 2050, yet arable land and water resources are shrinking. Conventional farming's one-size-fits-all approach wastes resources and reduces productivity. Precision agriculture addresses this by applying the right input, at the right place, at the right time guided by data from sensors, satellites, and AI models.

Key Technologies

IoT Devices & Sensors

Deployed across fields, IoT sensors continuously monitor soil moisture, pH, nitrogen, temperature, and humidity. Drone-mounted multispectral cameras generate NDVI (Normalized Difference Vegetation Index) maps to detect crop stress, disease, and pest zones. Smart irrigation systems triggered by soil-moisture thresholds reduce water consumption by up to 50%.

Artificial Intelligence

Machine learning models analyse historical yield data, weather patterns, and sensor inputs to forecast harvests weeks in advance. Deep learning (CNNs) identifies crop diseases from drone imagery with >95% accuracy. AI-powered autonomous tractors apply variable-rate treatments with millimetre precision, and mobile advisory platforms deliver personalised agronomic guidance in local languages to smallholder farmers.

Connectivity and Cloud

LPWAN, 5G, and low-earth-orbit satellite networks transmit sensor data to cloud or edge platforms. AI models process the data and close the loop — sense → transmit → analyze → decide → learn — enabling farms to continuously self-optimize.

3. Key Benefits

- **Productivity:** Crop yields increase by 15-25% through targeted input application.
- **Resource Efficiency:** Fertiliser use down 15%, water use down 30-50%, pesticide use down 20-40%.
- **Sustainability:** Reduced chemical runoff, lower GHG emissions, and improved soil health.
- **Economics:** Input cost savings of 10-20%; ROI achieved within 2-4 growing seasons.
- **Food Security:** Higher output per hectare reduces pressure to clear natural ecosystems.

Real-World Case Studies

Country / Company	Technology	Key Outcome
USA -John Deere	AI See and Spray (CV)	77% herbicide reduction
India - Mahindra	SmartAgri + satellite AI	20-30% yield increase
Japan —Fujitsu	Akisai IoT cloud	10% yield up, 20% energy down
Kenya -Apollo Agri	AI soil + credit scoring	Input access for small holders

Challenges

- High upfront cost of sensors, drones, and AI platforms limits smallholder adoption.
- Poor rural connectivity restricts cloud-based AI deployment in developing regions.
- Data ownership and privacy concerns require clear legal frameworks.
- Skills gap among traditional farmers demands targeted training and UX design.

Conclusion

Precision farming powered by AI and IoT offers a credible pathway to feeding a growing world sustainably. While barriers to adoption remain particularly for smallholder and developing-world farmers advances in satellite connectivity, open-source AI, and shared-service models are rapidly closing the gap. The future of agriculture is precise, connected, and intelligent.

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PROBIOTICS, PREBIOTICS, AND SYNBIOTICS FOR SUSTAINABLE AQUACULTURE

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Abstract

Aquaculture is one of the fastest-growing food production sectors, intensification in aquaculture has increased disease outbreaks, environmental stress, and reliance on antibiotics. Indiscriminate use of antibiotics leads to the development of antimicrobial resistance concerns. Probiotics, prebiotics, and synbiotics have emerged as sustainable alternatives for improving aquatic animal health and production efficiency. Probiotics enhance gut microbial balance, nutrient utilization, immune responses, and water quality, while prebiotics selectively stimulate beneficial intestinal microorganisms and strengthen host immunity. Synbiotics combine both approaches to provide synergistic benefits, including improved growth performance, feed efficiency, and disease resistance. Their application supports eco-friendly aquaculture practices, reduces antibiotic dependence, and promotes long-term sustainability of aquaculture systems.

Keywords: Aquaculture, Probiotics, Prebiotics; Synbiotics, Disease resistance

Introduction

Aquaculture is one of the most promising and rapidly growing food production industries in the world, having the greatest potential to meet the rising demand for aquatic food. Aquaculture has expanded rapidly to meet the increasing global demand for fish and shellfish protein. However, intensive farming practices often expose aquatic animals to stress, poor water quality, and disease outbreaks. Traditionally, antibiotics were widely used to control diseases, excessive use of these compounds led to antimicrobial resistance and environmental concerns. As a sustainable alternative, probiotics, prebiotics, and synbiotics are increasingly used in aquaculture to improve health, enhance immunity, and promote sustainable production. For the prevention and management of illnesses, Antibiotics have been utilized as a conventional approach in recent decades and also for promoting fish growth.as effectiveness of feed utilization. Nonetheless, the emergence of pathogens resistant to antimicrobial agents were acknowledged, yet there is a significant risk of transmitting resistant bacteria from aquatic surroundings to people. Dietary supplements like probiotics, prebiotics, and synbiotics offer nonspecific disease benefits. safeguarding and additionally function as factors that encourage growth. Numerous studies assessing. The efficacy of probiotics, prebiotics, and synbiotics in fish has garnered very limited attention up to now. focus and accessible information remain inadequate. Consequently, the aim of this examination is to gather the current information on the utilization of probiotics.

Probiotics in Aquaculture

Probiotics are living microorganisms, most often bacteria, yeast which helps to digest food and helps to prevent certain illness. When used in aquaculture, probiotics have a big effect on aquatic

creatures. Probiotics reduce the buildup of organic matter. And uphold water quality effectively. Contemporary probiotic organism can readily meet the needs of sustainability. Aquaculture advancement as it has the potential to enhance two significant essential elements of growth effectiveness and illness resilience. Probiotics are live beneficial microorganisms that, when administered in adequate amounts, confer health benefits to the host. In aquaculture, probiotics commonly include species of *Bacillus*, *Lactobacillus*, *Pseudomonas*, and *Saccharomyces*. These are applied through feed or directly into culture water. Probiotics improve gut microbial balance, enhance digestion and nutrient absorption, and inhibit the growth of pathogenic bacteria through competitive exclusion and production of antimicrobial substances. These compounds also improve water quality by reducing organic waste, ammonia, and harmful metabolites. As a result, probiotics help reduce disease incidence and improve survival and growth performance in fish and shellfish.

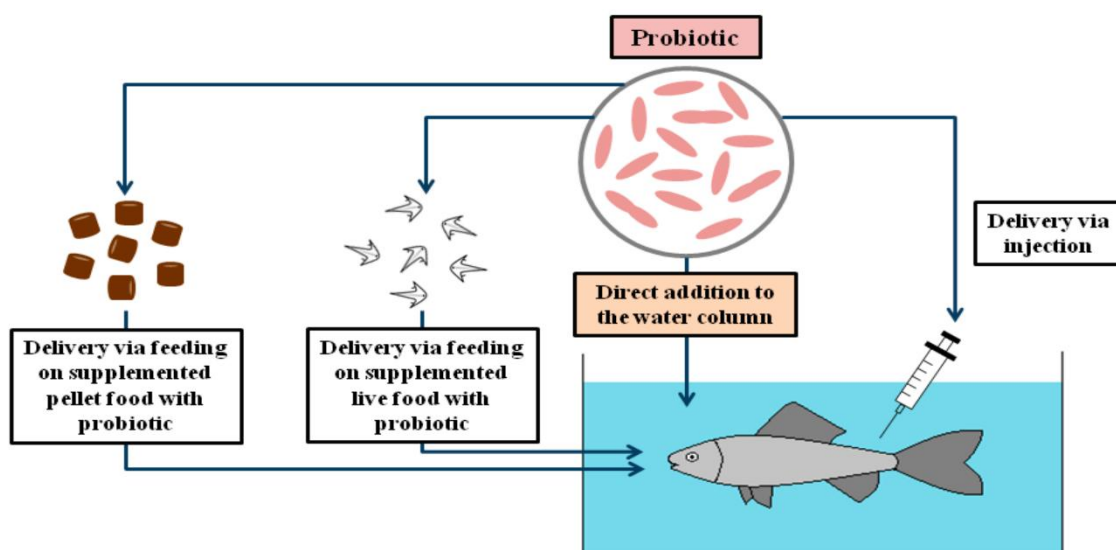


Fig 1: Probiotics in Aquaculture (Ladan Jahangiri et al)

Prebiotics in Aquaculture

Prebiotics are indigestible food ingredients that promote the growth or activity of good gut commensal bacteria in the host, that beneficially affects the host by enhancing host health/ growth. Prebiotic must meet certain requirements, including being able to withstand stomach acid, being broken down by digestive enzymes, being fermented by gastrointestinal microflora, and increasing the number of healthy bacteria in the gut. Prebiotics selectively stimulate the growth and activity of beneficial microorganisms in the digestive tract. Common prebiotics used in aquaculture include (FOS), mannan oligosaccharides (MOS), inulin, and β -glucans. Prebiotics enhance gut health by promoting beneficial bacteria and strengthening the intestinal barrier. These compound also stimulate the immune system, increasing resistance to bacterial and viral infections. Unlike probiotics, prebiotics are stable during feed processing and storage, making them a reliable dietary supplement in intensive aquaculture systems.

Synbiotics in Aquaculture

Synbiotics are products combining probiotics and prebiotics to work synergistically for improving gut health, It can be administered via supplements or bathing outside to enhance growth performance, suitable feed use, illness resistance, digestibility, and enhancement of the immune systems of marine organisms. The ways that synbiotics are used on various aquatic animals in

aquaculture systems are shown in Table 1 Synbiotics are a combination of probiotics and prebiotics designed to work synergistically. The prebiotic component provides a suitable substrate that enhances the survival and activity of the probiotic microorganisms in the host gut. Synbiotics offer combined benefits, including improved gut health, enhanced immune response, better feed utilization, and greater resistance to stress and disease. Their use has shown promising results in improving growth performance and reducing mortality in intensive fish and shrimp farming system.

Synbiotic (Probiotic/Prebiotics) Applications in Aquatic Organisms (Cerezeula *et al*)

Probiotic	Prebiotics,	Fish
<i>Bacillus clausii</i>	MOS, FOS, PHB	<i>Oncorhynchus mykiss</i>
<i>Bacillus subtilis</i>	Chitosan	<i>Rachycentron canadum</i>
<i>Bacillus subtilis</i>	FOS	<i>Larimichthys crocea</i>

Benefits and Importance in Sustainable Aquaculture

The use of probiotics, prebiotics, and synbiotics contributes significantly to sustainable aquaculture. These supplements reduce dependence on antibiotics, lower the risk of antimicrobial resistance, improve water quality, and enhance animal welfare. By promoting natural disease resistance and better environmental conditions, these support long-term productivity and eco-friendly aquaculture practices.

Conclusion

Aquaculture has heightened difficulties concerning disease control, environmental sustainability, and antimicrobial resistance. In this context, probiotics, prebiotics, and synbiotics are recognized as effective and sustainable supplements for traditional antibiotics. Probiotics improve the balance of gut microbes, aid digestion, strengthen immunity, and help enhance water quality by decreasing organic waste, harmful metabolites and growth. Prebiotics specifically encourage helpful gut microbes, boost intestinal wellness, and improve immune reactions, all while maintaining stability during feed production and storage. Synbiotics merge the benefits of probiotics and prebiotics, resulting in complementary effects that enhance growth performance, feed efficiency, stress resilience, and disease resistance in aquatic species. Incorporating these functional feed additives decreases reliance on antibiotics and mitigates the threat of antimicrobial resistance, thus protecting both aquatic environments and human well-being. In general, employing probiotics, prebiotics, and synbiotics offers a hopeful approach for enhancing sustainable, environmentally friendly, and efficient aquaculture systems

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QUALITY SEEDS PRODUCTION OF IN RIDGE GOURD CROPS UNDER SEMI ARID CONDITION IN RAJASTHAN

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Ridge gourd (*Luffa acutangula* Roxb.) is an popular vegetable crop for tropical and subtropical regions of the country, which belongs to the family Cucurbitaceae. The genus *Luffa* includes two cultivated species viz., ridge gourd (*Luffa acutangula* Roxb.) and sponge gourd (*Luffa cylindrica* Roem) and a semi cultivated species viz., *Luffa hermaphrodita* which is a wild form of *Luffa acutangula*. Ridge gourd is rich source of vitamin C (18 mg), phosphorus (26 mg), calcium (18 mg), iron (0.5 mg), protein (0.5%), moisture (92.5 g), fat (0.5 g), carbohydrate (3.4 %) and carotene (37 mg) per 100 g of fresh weight. As we know that seed is an important critical input for any crop. That's why quality seed is important aspect. Therefore, quality seed production in ridge gourd increases productivity. The seed recovery in this crop ranges 13-14%. Hence seed recovery percent is very less so quality seed availability is very less. Therefore, we need more focus on quality seed production with respect to following points: It's fruits are consumed as cooked vegetable or soups or curries. Fiber extract from dried fruits which has use in various industrial applications, including filters, bath spang, table mats, bathroom mats, pot holders also used as soles for slippers and shoes.



Field preparation

Field should be prepared with the help of clean and modernized farm tools to obtain tilth. Crop can be grown on the raised beds, furrows or pits. In the riverbeds the trenches or pits are prepared as furrow bed pit (deep or shallow) and mounds. Generally, seeds should be soaked 4-6 hrs before sowing, we have also transplanted seedling by raising pro-tray technology.

Seed Source: Seed source should be reliable and recognised. Mostly seeds used from ICAR institutes or SAU's or State Seed Corporation farms. Seed should be genetically pure and true to type.

Improved Varieties

Seed multiplication programme should be taken on the bases of adoption in suitable agroclimatic zones and farmer's demand. In this crops, SAU's and ICAR institutes developed several improved varieties which details given below in table:

Pusa Nutan	Early fruiting (45-50 DAS), Average fruit weight (105 g), high yielding (170-185 q/ha), Suitable for both summer and rainy season.

Thar Karni	Early fruiting (51-55 days), cylindrical and light green colour, fruit length (21.24 cm), fruit weight (95.74 g), fruit diameter (2.88 cm), number of marketable fruits/plant (21.03), Average fruit yield (150-160 q/ha).
Kashi Shivaani	Fruits are green, long straight, fruit diameter (3-4 cm). Average fruit weight (100 g to 150g). Harvesting of fruits (50-60 DAS). The yield potential of this variety is 180-200 q/ha.
Arka Prasan	Early variety, fruit green, long, tender fruits and ready to harvesting (42-45 DAS), excellent cooking quality and average fruit yields 260 q/ha.
Arka Vikaram	Fruits green, long, tender, early harvesting (46 DAS), excellent cooking quality, Average yields 340 q/ha.
Swarn Manjari	Fruit shape elongated, medium, Av. fruit weight (175 g), highly ridged, greenish colour with contain less fibre. Average fruit yield 180-200q/ha and tolerant to powdery mildew.
Swarna Uphar	Fruit shape is elongated, medium, Av. weight (200 g), long ridged with contain less fibre. Fruits are ready to harvest 65-70 days after sowing. Average fruit yield 200-300 q/ha.
Ridge gourd CoH-1 : Only one hybrid variety is available in public sector which as developed from TNAU, Coimbatore, Tamilnadu. Variety character has early fruiting (30-35 DAS) and average fruit yield (350 q/ha).	

(Source: SAU and ICAR website)

Sowing time

It can be grown in both seasons *i.e.*, summer (Feb-March) and rainy season (Jan-Feb). Generally seed crop grown during the summer season in the February-March month.

Sowing methods

Seed black in colour and flat. It's coat is hard; so that' seed should be soaked in water before sowing (6-8 hrs). Seed can be sown in two methods *i.e.*, direct seed sowing and transplanting method (raising the seedlings). In portray method, growing media prepared from cocopeat:vermiculite:perlite in the ratio of 3:1:1. At the time of media preparation cocopeat should thoroughly washed with water 2-3 times after draining water from growing media so that maintains growing media EC and pH . Filled this growing media one third in portray cavities and seed is sown keeping the pointed end of down side in each cavity after that seed should be covered with growing media. Seed should be treated with carbendazim @ 1.5 g per kg.

**Seeds sown in Protray****Watering in Nursery**

Seed rate: 4-5 Kg seed is required for raising the one hectare crop area.

Spacing: Seed should be sown in proper distance so that seeds sown 1.5 to 2.0 m in row to row distance whereas follow 60 to 80 cm plant to plant distance for better growth and development.

Isolation distance

Mostly flowers are monoecious nature. Anthesis timing of flower in 5.00 to 6.00 PM in Jaipur, Rajasthan condition. Nature of ridge gourd flowers are highly cross-pollinated. Genetic contamination is maintained by isolation distance *i.e.*, foundation seed 1000 m and certified seed 500 meter. In case of small land holding farmers, land availability is limited so the hybrid seed production programmes are done in polyhouse (protected structures) with skilled labour.



Fertilizer and manure

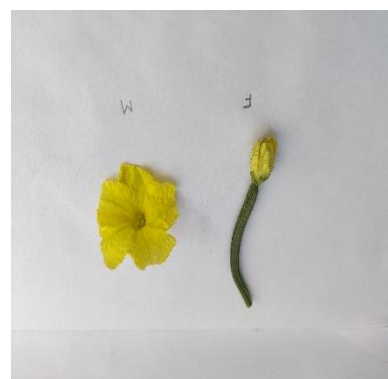
During seed production, recommended dose of manure and fertilizer should be applied *i.e.*, 200-250 q/ha FYM and fertilizer *i.e.*, N:P:K 100:40:40 kg per hectare. Nitrogen is given into three split doses and P & K should be given full dose during field preparation. Remaining Nitrogen should be given in split dose one and two month after seed sown.



Male flower



Female flower



Male and Female flower



Hand Pollination



Bagging



Fruit Set

Irrigation management and Intercultural operations: This crop require less water as compare to other vegetable crop. Three critical phases for irrigation are important for quality seed production *i.e.*, blooming of flowers, fruit set and at harvest. In Rajasthan conditions, drip irrigation system should be used for irrigation as well as for fertilizers application. In the summer season irrigation

should be done at an interval of 10-12 days and when the temperature rises it should be done at an interval of 5-7 days.

Rouging

It is very essential practices to overcome the genetic contamination, so time to remove off type or undesirable plants. Some times *Luffa* spp. i.e., *Luffa amara*, *Luffa cylindrica* (sponge gourd) or any other wild species seen near the seed production field quick remove these plants from the main field. Mostly it should be done at before flowering, at the time of flowering and after fruit set.

Intercultural operations

Weeding: Remove unwanted, weak and diseased or insect affected plants by hand weeding. Generally, first hand weeding is done 25-30 DAS and second hand weeding done 45-60 days after seed sowing (DAS).

Staking: Vine of plants stake with thread or tie with suthali on bamboo pandal. It is essential for better development of fruit to increase space for light, temperature and other climatic conditions.

Field Inspection

Field inspection in ridge gourd is done at three stages i.e., flowering, fruit set and harvesting to ensure seed quality, verify genetic purity, detect and manage pest and diseases, check cultivation practices, confirm isolation distances and plan for optimal harvest.

Plant protection

Powdery mildew: It is a fungal disease caused by *Sphaerotheca fuliginea*.

Crop should be grown in early and maintain proper humidity by mini sprinklers.

Spray Hexaconazole 5% EC (1ml/litre of water) and repeat 10-15 days interval if desired.

Fruit fly: This is the most serious pest of ridge gourd. Maggots of this fly (*Dacus cucurbitae* and *Dacus dorsalis*) cause severe damage to young developing fruits.

Use fruit fly trap or Methyl Eugenol traps – 10-15 traps/acre.

Malathion 50% WP bait spray (Protein hydrolysate + molasses mix) or Spinosad 45% SC (0.3ml/L) or Neem oil 3% spray (early stage IPM).

Harvesting: Mature and fully developed fruits and fruit colour changes to brown are ready to harvest for seed crop. At this stage, the seed consist of higher vigour and viability. When there is a symptom of hair line cracks on the edges of the fruit, it should be harvested without any delay. The harvesting should be done into regular picking intervals in ridge gourd. Avoid the first fruit set and last one or two fruit set, it may use as vegetable purpose.

Harvesting for seed purposes will be done after drying the fruits and it will turn brown. For simple seed extraction, the fruits can be dried for a day or two after harvest. Only medium-sized to large-sized fruits that are genetically pure should be used to extract seeds. The yield of high-quality seed recovery will rise as a result of these selection and grading processes.



Seed extraction method:

After the dried fruit harvest, only healthy fruits or true to type and free from pest/ disease fruit should be selected for seed extraction.

The selected fruits need to be dried for one or two days prior to seed extraction. Ridge gourd seeds are easier to extract. To extract the seeds, create holes or cut open the tapering end of the fruit, then easily separate the seeds. The white and pale yellow-coloured, poorly filled seeds should be manually removed from separated seeds as a pre-cleaning step.



Dried fruit



Quality Seeds

Field and Seed Standards: Follow field and seed standards because it is necessary for assure the seed quality to get the tags form certification agency.

Minimum seed certification standards prescribed for certified seed

Field standards	
Rogues (maximum limit)	0.2%
Seed standards	
Pure seeds (minimum limit)	98.0%
Inert matter (maximum limit).	2.0%
Other crop seeds (maximum limit)	None
Weed seeds (maximum limit)	None
Germination (minimum limit)	60.0%
Moisture content	
Moisture proof bag	6.0%
Moisture pervious bag	7.0%

SOIL VEGETATION INTERACTIONS IN DEGRADED ECOSYSTEM

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Abstract

Degraded ecosystems display altered soil properties and compromised vegetation cover, disrupting the critical interactions between soil and plants that support ecosystem functions. Understanding soil–vegetation feedbacks is essential for effective restoration and sustainable management. This paper synthesizes current knowledge on how soil properties and vegetation influence each other in degraded landscapes, outlines mechanisms driving degradation, and explores strategies for restoring soil–vegetation linkages. Key factors include soil compaction, nutrient depletion, erosion, microbial community shifts, and plant root dynamics. The paper also reviews case studies of successful restoration practices that re-establish soil–vegetation interactions and highlights future research directions.

Keywords: GIS, R.S, Monitoring, Degradation, Land.

Introduction

Soil and vegetation form the structural and functional foundation of terrestrial ecosystems. Their interactions regulate essential ecological processes, including primary productivity, nutrient cycling, carbon sequestration, water regulation, and biodiversity maintenance. However, increasing anthropogenic pressures and climate variability have accelerated ecosystem degradation worldwide, disrupting soil–vegetation linkages and compromising ecosystem resilience. Land degradation currently affects nearly one-quarter of the Earth’s terrestrial surface and threatens food security, biodiversity, and climate stability. Degradation processes—such as deforestation, overgrazing, unsustainable agricultural intensification, mining, salinization, and urban expansion lead to soil erosion, compaction, nutrient depletion, organic matter loss, and biodiversity decline. Soil properties strongly influence plant community composition, productivity, and resilience. Soil texture, structure, porosity, and bulk density determine water availability and root penetration capacity. Chemical characteristics such as pH, cation exchange capacity, and nutrient availability regulate plant nutrient uptake and metabolic processes. Biological components—including bacteria, fungi, earthworms, and mycorrhizal associations—mediate decomposition, mineralization, and nutrient cycling. According to Bardgett and van der Putten (2014), belowground biodiversity plays a critical role in maintaining ecosystem functioning, particularly under environmental stress.

Conceptual Framework: Soil–Vegetation Interactions Soil Properties Influencing Vegetation

Soil characteristics are foundational drivers of plant growth:

- **Physical properties:** texture, structure, porosity, bulk density.
- **Chemical properties:** pH, cation exchange capacity (CEC), nutrient availability (N, P, K).
- **Biological properties:** microbial diversity, mycorrhizal networks, soil fauna.

Healthy soils support seed germination, root penetration, water retention, and nutrient uptake—all crucial for vegetation establishment.

Vegetation Influencing Soil Processes

Vegetation modifies soil through:

- **Litter deposition and decomposition:** Adds organic matter and nutrients.
- **Root exudation:** Influences microbial communities and nutrient cycling.
- **Root systems:** Improve soil structure, reduce compaction, and stabilize soil.

These plant-driven processes feedback to regulate soil fertility and resilience.

Degraded Ecosystems: Disruptions in Soil–Vegetation Feedbacks

Drivers of Degradation

Key drivers include:

- **Agricultural intensification:** Continuous cropping, heavy machinery compaction, nutrient mining.
- **Overgrazing:** Removal of plant cover and damage to soil structure.
- **Deforestation:** Loss of organic inputs and increased erosion.
- **Industrial activities:** Soil contamination and physical disturbance.
- **Climate change:** Droughts and extreme rainfall events worsen soil conditions.

Consequences for Soil–Vegetation Interactions

- **Reduced organic matter:** Limits nutrient availability and water retention.
- **Soil erosion:** Removes topsoil rich in nutrients, hindering vegetation regrowth.
- **Salinization:** Toxic salt levels inhibit plant water uptake.
- **Altered microbial communities:** Reduced beneficial fungi and bacteria disrupt nutrient cycling.

These changes weaken plants' ability to access resources, suppressing productivity and resilience.

Mechanisms of Soil–Vegetation Feedbacks in Degraded Settings

Nutrient Cycling Alterations

Degradation disrupts biogeochemical cycles:

- Loss of nitrogen and phosphorus due to leaching and erosion.
- Impaired decomposer activity reduces mineralization rates.

Plants thus experience nutrient stress even where soil still contains baseline nutrients.

Hydrological Impacts

- **Soil compaction** reduces infiltration, increasing surface runoff.
- **Vegetation loss** reduces canopy interception and deep-water recharge.

Water limitation further compounds plant stress.

Biological Interactions

- Declines in mycorrhizal fungi reduce nutrient and water uptake.
- Root-associated microbes that promote plant growth decrease.

These biological disruptions create negative feedback loops.

Approaches to Restoration

Effective restoration re-establishes soil–vegetation linkages:

Soil Amendments

- **Organic matter addition:** Compost, biochar, and mulch improve structure and nutrient supply.

- **Lime or gypsum applications:** Adjust pH and reduce salinity.
- **Microbial inoculants:** Reintroduce beneficial fungi and bacteria.

Vegetation Interventions

- **Native species planting:** Deep-rooted perennials enhance soil structure.
- **Cover crops:** Protect soil, fix nitrogen, and build organic matter.
- **Assisted natural regeneration (ANR):** Promotes natural plant recruitment.

Integrated Practices

- **Contour trenches and terracing:** Reduce erosion and enhance infiltration.
- **Agroforestry:** Combines trees and crops to maximize soil benefits.
- **Adaptive grazing:** Rotational grazing that avoids overuse and allows recovery.

Case Studies

Grassland Restoration in Semi-Arid Regions

Studies show that the use of native bunchgrasses and soil mulch reduces erosion, increases infiltration, and enhances organic matter over five years, improving vegetation cover and soil microbial diversity.

Post-Mining Landscape Rehabilitation

Application of organic amendments and mycorrhizal inoculation facilitated rapid revegetation and increased soil carbon stocks, demonstrating that combining soil restoration with suitable plant species accelerates recovery.

Research Priorities

- Quantifying long-term soil–vegetation feedbacks in restored landscapes.
- Developing resilient plant species mixes for restoration under climate stress.
- Exploring microbial engineering to boost soil health.

Conclusions

Degraded ecosystems reflect compromised soil–vegetation interactions that impair ecosystem functions. Restoration requires integrated approaches targeting both soil and plant communities. Enhancing organic matter, encouraging diverse and native vegetation, and restoring hydrological balance rebuilds positive feedbacks essential for resilient systems.

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ROLE OF AFFORESTATION IN RECLAMATION OF DEGRADED AND PROBLEM LANDS

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Abstract

Land degradation due to erosion, salinity, desertification, mining, and deforestation reduces soil productivity and ecological stability. Afforestation is an effective strategy for restoring degraded and problem lands by improving soil structure, increasing organic matter, reducing erosion, and enhancing nutrient cycling. Tree plantations also help in regulating water balance, stabilizing sand dunes, and restoring biodiversity. Salt-tolerant and nitrogen-fixing species play an important role in reclaiming saline and nutrient-deficient soils, while plantations on mine spoils helps in ecological succession. Furthermore, afforestation contributes to carbon sequestration and microclimate improvement. With proper species selection and management, afforestation serves as a sustainable and cost-effective method for restoring degraded ecosystems and improving land productivity.

Keywords: Afforestation, Land reclamation, Soil conservation, Degraded lands.

Introduction

Land degradation is a serious environmental problem which is primarily caused due to deforestation, overgrazing, mining, unsustainable agriculture, and climate change. Degraded lands are less productive, have decreased soil fertility and ecological balance. Afforestation is defined as establishment of forests on non-forested or degraded lands. It is considered as an important strategy for restoring such ecosystems (FAO, 2015). Afforestation helps in improving soil properties, enhancing biodiversity, regulating hydrological cycles, and contributing to carbon sequestration. It therefore is an effective tool for land reclamation.

Degraded and Problem Lands

Problem lands are the lands which have very low soil productivity and vegetation growth is limited because of the physical, chemical, or biological constraints. Examples include:

- Saline and alkaline soils
- Ravine lands
- Desertified areas
- Mine spoils
- Waterlogged soils
- Barren and wastelands

These lands usually suffer from soil erosion, nutrient depletion, salinity, poor structure, and low water-holding capacity (Singh, 2010).

Role of Afforestation in Land Reclamation

Soil conservation

Tree roots help in binding soil particles and reducing erosion which is caused by wind and water. Tree canopies also reduce raindrop impact. Litter accumulation helps in improvement of soil organic matter and structure (Lal, 1997).

Improvement of Soil Fertility

Afforestation helps in enhancing nutrient cycling through litter decomposition and root turnover. Nitrogen-fixing species such as *Acacia* and *Leucaena* improve soil fertility by adding nitrogen to the soil (Nair, 1993).

Reclamation of Saline and Alkaline Soils

Salt-tolerant tree species help in restoring saline soils by improving soil permeability, reducing salt concentration, and lowering the water table. Species like *Prosopis juliflora* and *Eucalyptus camaldulensis* are commonly used for reclamation purposes (Tomar & Gupta, 1985).

Control of Desertification

Afforestation also helps in reducing wind erosion, stabilizing sand dunes, and conserving soil moisture through the building of shelterbelt plantations. This is widely practiced in arid and semi-arid regions (UNCCD, 2017).

Reclamation of Mining Areas

Mine spoil areas lack nutrients and soil structure. These areas can be restored through plantation of hardy, fast-growing species which initiates ecological succession and improves soil organic matter (Jha & Singh, 1991).

Water Regulation and Microclimate Improvement

Afforestation improves infiltration, reduces runoff, and increases groundwater recharge. Trees also help in regulating the local temperature and humidity which therefore helps in improving microclimatic conditions (Young, 1997).

Biodiversity Restoration

Afforestation supports ecological restoration by providing habitat for flora and fauna and increasing ecosystem recovery over time (Lamb, Erskine & Parrotta, 2005).

Conclusion

Afforestation plays an important role in reclaiming degraded and problem lands by improving soil fertility, preventing erosion, restoring biodiversity, and regulating water balance. With proper species selection and sustainable management, it can help in transforming the unproductive lands into ecologically stable and productive ecosystems.

It remains an important strategy for sustainable land management and environmental restoration.

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ROLE OF PLANT GROWTH PROMOTING RHIZOBACTERIA (PGPR) IN ENHANCING CROP IMMUNITY AND YIELD

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Abstract

The increasing world population and the demand that is in tandem with the food security has increased the burden on agricultural systems. In the past, this need has been addressed by the heavy use of synthetic fertilizers and chemical pesticides. Nevertheless the long-term ecological effects of such practice; such as soil erosion and water eutrophication as well as the introduction of pathogen resistance have led to the need to shift towards sustainable agriculture. Plant Growth-Promoting Rhizobacteria (PGPR) are a highly promising alternative that is eco-friendly. These useful soil bacteria can be found on the root surface of the plant (the rhizosphere) and promote the growth and immunity of the plant by a complex of mechanisms both direct and indirect. A holistic article delving into the biochemical, molecular and physiological functions of PGPR in enhancing crop productivity, strengthening plant defenses and reducing abiotic stresses provides an in-depth insight into the opportunities these compounds have had in transforming modern farming methods.

Keywords: Plant Growth-Promoting Rhizobacteria, Sustainable Agriculture, Plant Defenses

It has been forecasted that the world population will be close to 10 billion by the year 2050 and this will demand an approximate 60 % growth of food production. Agrochemicals are also essential in modern farming so that maximum yields can be achieved. Although this technique is effective in the short run, the constant use of synthetic nitrogen and phosphorus fertilizers changes the microbiomes of soils drastically, decreases the soil fertility, and leads to greenhouse gas emissions. Moreover, this practice of careless application of chemical pesticides has seen the bioaccumulation of toxins and the interference of non-target and positive ecosystems.

Taking advantage of the natural interactions between plants and their attached microbiomes has become one of the pillars of sustainable agriculture. Plant Growth-Promoting Rhizobacteria (PGPR) is an ecologically diverse cluster of naturally occurring soil bacteria which actively colonize plant roots and form a symbiotic, associative or endophytic association with the plant host. Agriculture may be reshaped into a biology-based ecosystem through taking advantage of these microbial allies.

Rhizosphere: The Stage for Microbe-Plant Crosstalk

The rhizosphere is a narrow belt of soil that is directly affected by root secretions and the microorganisms in the soil which is described by Lorenz Hiltner in 1904 as the rhizosphere.

Plants are active engineers of this environment. They also secrete as much as 30 % of what was fixed in their photosynthesis into the soil in root exudates. These exudates are a complicated mixture of:

- **Carbohydrates and Sugars:** Glucose, fructose and sucrose, which are prime carbon sources of microbes.
- **Amino Acids and Organic Acids:** Citric acid, malic acid and oxalic acid, which also act as chemoattractants and change local soil pH.
- **Secondary Metabolites:** Flavonoids, benzoxazinoids and other signaling molecules that specifically attract beneficial microbes and exclude pathogens.

PGPR have employed the chemotaxis of flagella in order to navigate towards the roots to create complex communities referred to as biofilms. Well-known genera of PGPR are *Pseudomonas*, *Bacillus*, *Rhizobium*, *Azospirillum*, *Azotobacter*, *Enterobacter* and *Serratia*.

Promotion of Plant Growth Directly through Mechanisms

PGPR increases the growth of plants directly by increasing access to resources and regulating the levels of plant hormones. Mechanisms make sure that the plant possesses the building blocks and the developmental cues required to achieve the maximum yield potential.

1. Biological fixation of Nitrogen (BNF)

The most limiting nutrient in the growth of plants is nitrogen as it is required in the synthesis of amino acid, nucleic acid, and chlorophyll. Some PGPR have conserved nitrogenase enzyme complex that reduces atmospheric nitrogen to ammonia (NH₃) which is a form of nitrogen that is biologically available.

- **Symbiotic Nitrogen Fixation:** Some bacteria like *Rhizobium* and *Bradyrhizobium*, develop a very specialised symbiotic association with leguminous plants resulting in root nodules.
- **Free-living and Associative Nitrogen Fixation:** Bacteria such as *Azospirillum* and *Azotobacter* fix nitrogen in the rhizosphere without any special structures and are important in the nitrogen economy of non-leguminous crops such as wheat, rice and maize.

2. Phosphate Mineralization and Solubilization

The second most significant macronutrient is phosphorus (P) as it plays a vital role in energy transfer (ATP), photosynthesis, and root development. Phosphate-Solubilizing Bacteria (PSB), such as strains of *Pseudomonas* and *Bacillus*, transform such insoluble forms into plant-soluble orthophosphates (H₂PO₄⁻ and HPO₄²⁻). They achieve this through:

- Low molecular weight organic acids production
- Enzymatic mineralization

3. Solubilization of Potassium and Zinc

Potassium and zinc are also commonly fixed by soil minerals as with phosphorus. PGPR exude organic acids and protons which break down clay mineral (such as illite and feldspar) and release potassium ions (K⁺) into the soil solution. The zinc-solubilizing bacteria elicit their action through the same acidifying and chelating process, which inhibits zinc deficiency, which is a typical factor that inhibits the growth of crops.

4. Modulation of Phytohormones

PGPR function as microscopic "hormone factories" or regulators, profoundly altering plant root architecture and developmental stages.

- **Auxins:** A lot of PGPR use tryptophan (released by plant roots) as a precursor to produce IAA. Bacterial IAA enhances the growth of root hair and lateral root growth that is significant in increasing the root surface area in the absorption of water and nutrients.
- **Cytokinins and Gibberellins:** When produced by PGPR, the hormones promote cell division, seed germination and stem elongation.
- **Ethylene Regulation:** During stress, ethylene is produced in excess, which leads to senescence, defoliation and retarded growth (the stress ethylene burst).

Enhancing Crop Immunity: Indirect Mechanisms (Biocontrol)

Other than being a direct plant nutritional source, PGPR serve as powerful biocontrol agents, and they protect crops against a myriad of phytopathogens (fungi, bacteria, viruses, and nematodes). This is an indirect promotion of growth which immensely minimizes the losses of crops and the use of chemical pesticides.

Systemic Resistance

Colonization of some of the PGPR on the roots causes release of elicitor molecules (flagellin, lipopolysaccharides and volatile organic compounds) by plant receptors. This signal triggers a signal cascade primarily signal of the Jasmonic Acid (JA) and Ethylene (ET) signal which occurs throughout the plant including leaves and stems. This is referred to as the Induced Systemic Resistance (ISR).

Unlike systemic acquired resistance (SAR) induced by genuine pathogens accompanied with the salicylic acid (SA) the ISR prepares immune system in the plant. The energy is not consumed in the synthesis of defensive chemicals in the plant during all times, but when the foliar or root pathogen invades, the primed plant reacts much faster and stronger with the quick production and secretion of defensive enzymes, structural defenses (deposition of callose), and antimicrobial compounds (phytoalexins).

Table 1: PGPR genera and their primary agricultural roles

PGPR genus	Primary mechanisms of action	Common agricultural uses
<i>Rhizobium</i>	Symbiotic nitrogen fixation	Biofertilizer for legumes (soybean, pea, alfalfa)
<i>Pseudomonas</i>	Phosphate solubilization, siderophores, antibiotics (biocontrol), ISR	Biopesticide and biofertilizer for wheat, rice and tomatoes
<i>Bacillus</i>	Endospore formation (high shelf life), lytic enzymes, volatile organic compounds	Broad-spectrum biocontrol agent, biostimulant
<i>Azospirillum</i>	Associative nitrogen fixation, extensive phytohormone (IAA) production	Root growth promoter for cereals and grasses

Production of Siderophores (Iron Competition)

Iron is widespread in the soil and it occurs primarily in the form of ferric (Fe^{3+}) which is highly insoluble and thus a highly competitive resource in the rhizosphere. The siderophores are low-molecular-weight molecules that have abnormally high affinity to bind Fe^{3+} and are produced by PGRs. PGPR outcompete and starve the deleterious soil pathogens who have less efficient iron-uptake systems by mopping up the available iron.

Volatile Organic Compounds (VOCs) and Hydrogen Cyanide (HCN)

There are those PGPR that release gaseous compounds that serve as long-range weapons or messengers.

- **VOCs:** substances such as 2,3-butanediol and acetoin have the ability to directly suppress the mycelial growth of fungi and to produce strong elicitors of the ISR in plants.
- **HCN:** Hydrogen cyanide generated by plant species such as *Pseudomonas* serve as a bio-fumigant in the rhizosphere, suppressing the cytochrome oxidase of pathogens and nematodes, which prevents such diseases as root-knot nematodes infections.

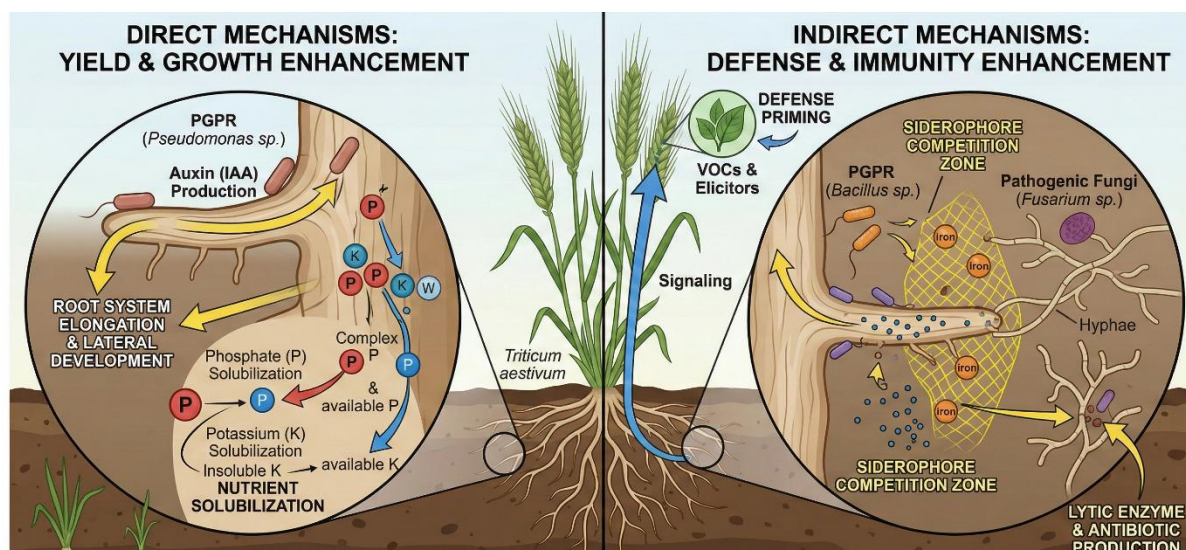


Fig. 1: Dual Mechanism for crop immunity and yield

Modern Agriculture and Commercialization Applications

PGPR translation of laboratory results in field-scale agricultural products is done through the development of biofertilizers and biopesticides. Commercial products of the PGPR are developed with carrier products that guarantee the bacterial survival under storage and proper delivery to the field. Typical expressions are:

- **Solid/Powder Formulations:** The carriers are peat, talc, and lignite. They are inexpensive yet they tend to deteriorate easily in the shelves.
- **Liquid Formulations:** Cell cultures in nutrient broths that are stabilized (using glycerol or PVP) to prevent cell drying. These have a high cell titers and longer viability.
- **Encapsulation/Granular:** Surveying bacteria in bio-polymers such as alginate. This gives it a slow-release system and better protection against severe soil environment.

Conclusion

Plant Growth-Promoting Rhizobacteria integration into the contemporary agriculture is not just an additional practice, but an ecological imperative. Agriculture can stop becoming reliant on chemicals that are harmful to the environment by utilizing the evolutionary synergies that have been formed between microbes and plants over millions of years. The forefront of this biological revolution is put by the use of PGPR, a scientifically sound sustainable solution of building immunity in crops, securing the crop global production, and healing the soils on the planet.

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BIOREMEDIATION OF POLLUTED SOILS: MICROBIAL AND PHYTOREMEDIATION STRATEGIES FOR SOIL RESTORATION

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Abstract

Soil pollution from heavy metals, petroleum hydrocarbons, and agrochemicals poses severe risks to ecosystems and human health. Bioremediation the use of microorganisms, plants, and their enzymes to degrade or immobilise contaminants, offers a cost-effective, ecologically sound alternative to physico-chemical treatments. This review examines the principal bioremediation strategies (*microbial degradation, phytoremediation, and mycoremediation*), the mechanisms involved, documented field efficiencies, and current limitations. Evidence demonstrates contaminant reduction rates of 60-95% under optimised conditions, with emerging biotechnological approaches further expanding applicability.

Introduction

An estimated 2.5 million contaminated sites exist across Europe alone, with global numbers far exceeding this figure. Common soil pollutants include petroleum hydrocarbons (PHCs), polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, heavy metals (Pb, Cd, As, Hg), and pesticides all of which disrupt soil microbial ecology, reduce fertility, and enter food chains. Conventional remediation methods (excavation, incineration, soil washing) are costly, energy-intensive, and frequently destroy soil structure. Bioremediation leverages naturally occurring biological processes to restore soil function *in situ* or *ex situ*, often at 50–80% lower cost than physicochemical approaches.

Types of Bioremediation & Mechanisms

Microbial Bioremediation

Bacteria and archaea are primary drivers of organic pollutant breakdown. Genera such as *Pseudomonas*, *Rhodococcus*, *Bacillus*, and *Sphingomonas* produce oxidases and oxygenases that mineralise PHCs and PAHs to CO₂ and H₂O. Bioaugmentation (inoculating degrader strains) and biostimulation (adding nutrients, O₂, or electron donors) are the two principal field strategies.

Phytoremediation

Plants achieve remediation through: phytoextraction (uptake of metals into shoots, e.g., *Thlaspi caerulescens* for Zn/Cd), phytodegradation (enzymatic breakdown in root zones), and phytostabilisation (immobilising metals in the rhizosphere). Hyperaccumulators can concentrate heavy metals 100-1,000× above background soil levels. A long-term trial by Salt *et al.* (1998) achieved 45% Pb reduction in 3 years using *Agrostis capillaris*. Rhizosphere microbiomes amplify plant uptake efficiency by up to 40%.

Mycoremediation

White-rot fungi (e.g., *Phanerochaete chrysosporium*) secrete lignin peroxidases and laccase enzymes capable of degrading recalcitrant compounds including PCBs, dioxins, and PAHs that resist

bacterial attack. Singh (2006) reported 90% anthracene degradation within 30 days under fungal treatment, compared to 23% in uninoculated controls.

Comparative Summary of Bioremediation Strategies

Strategy	Target Pollutants	Key Organisms	Efficiency
Microbial	PHCs, PAHs, solvents	Pseudomonas, Bacillus, Rhodococcus	60-95% degradation
Phytoremediation	Heavy metals, PAHs, nitrates	Thlaspi, Agrostis, Sunflower	30-70% metal reduction
Mycoremediation	PCBs, dioxins, PAHs	Phanerochaete, Trametes	70-90% degradation
Bioventing	Petroleum, BTEX, VOCs	Aerobic soil bacteria	50-80% in 6-12 months
Composting	Pesticides, PAHs	Thermophilic mixed microbiota	40-85% over 90 days

Factors Affecting Bioremediation Efficiency

Performance is governed by abiotic and biotic conditions:

- **Soil pH:** Optimal range pH 6.5-7.5 for most aerobic bacteria; acidic soils inhibit enzymatic activity.
- **Temperature:** Mesophilic organisms (20-40°C) dominate; cold climates require psychrophilic consortia.
- **Nutrient availability:** C:N:P ratio of 100:10:1 optimises microbial growth and contaminant mineralisation.
- **Oxygen supply:** Aerobic degradation is 10-100× faster than anaerobic for most hydrocarbons.
- **Contaminant bioavailability:** Ageing and sorption to soil organic matter reduce accessibility to microbes.
- **Microbial community diversity:** Higher diversity confers greater metabolic versatility and resilience.

Limitations and Emerging Approaches

Bioremediation is limited by slow rates at high contaminant concentrations, incomplete mineralisation of complex mixtures, and site-specific variability. Genetically engineered microorganisms (GEMs) such as dioxin-degrading *Burkholderia* strains show promise but face regulatory and ecological risk concerns. Nano-bioremediation (combining nano-zero-valent iron with microbial consortia) has achieved >95% chlorinated solvent removal in pilot studies. Metagenomics and biosensor technologies now enable real-time monitoring of microbial community shifts and pollutant degradation pathways, accelerating site management decisions.

Conclusion

Bioremediation represents one of the most ecologically and economically sound tools for soil restoration. Microbial degradation, phytoremediation, and mycoremediation each offer proven efficacy across distinct contaminant classes, and their integration in combined strategies yields superior outcomes. Continued advances in synthetic biology, metagenomics, and nano-enabled delivery systems are poised to overcome current limitations, positioning bioremediation as a cornerstone of 21st century environmental management.

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GYPSUM APPLICATION, EARTHING UP AND DRUM ROLLING AS A TRIPLE ACTION STRATEGY FOR YIELD ENHANCEMENT IN GROUNDNUT (*Arachis hypogaea* L.)

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Abstract

Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed crops in India, valued for its high oil and protein content. However, its productivity remains low due to nutrient deficiencies and poor peg-to-pod conversion. A significant constraint in bunch-type varieties is the formation of hanging pegs that fail to penetrate the soil, resulting in reduced pod formation. This article highlights the role of a triple-action strategy involving gypsum application, earthing up, and drum rolling in enhancing groundnut yield. Gypsum provides calcium essential for pod development, earthing up improves soil conditions for peg penetration, and drum rolling facilitates mechanical insertion of pegs into the soil. The integration of these practices improves peg-to-pod ratio, reduces empty pods and enhances yield and economic returns.

Keywords: Groundnut, Gypsum, Earthing up, Drum rolling, Peg penetration and Pod yield

Introduction

Groundnut (*Arachis hypogaea* L.), belonging to the family Fabaceae is the third most important oilseed crop in India after soybean and rapeseed–mustard. It is nutritionally rich, containing approximately 45% oil, 26–28% protein, 20% carbohydrates and 5% fibre, making it a major source of edible oil and vegetable protein. Groundnut is often referred to as the “King of oilseeds” due to its economic importance and diverse uses. It also plays a vital role in ensuring food and nutritional security, particularly for small and marginal farmers in arid and semi-arid regions. Being a day-neutral crop, it is cultivated in *kharij*, *rabi*, and summer seasons. However, about 85% of the cultivation area in India falls under rainfed *kharij* conditions.

Globally, Asia accounts for nearly 50% of the cultivated area and 60% of production. In India, groundnut contributes around 19.05% of the oilseed area and about 27.91% of production. Despite limited expansion in cultivated area, production has increased significantly due to improved varieties and agronomic practices.

Constraints in groundnut production

One of the major constraints in groundnut cultivation, particularly in bunch varieties is the formation of hanging pegs. Due to extended flowering periods and erratic rainfall, several pegs formed on upper branches fail to penetrate the soil, resulting in poor pod development. In addition,

groundnut is highly sensitive to nutrient deficiencies, especially calcium deficiency in the pegging zone. Improper nutrient management can result in yield reductions ranging from 30 to 70%. Therefore, addressing both physical and nutritional constraints is essential for improving productivity.

Triple action strategy for yield enhancement

An integrated approach involving gypsum application, earthing up and drum rolling may be regarded as the effective strategies in improving groundnut yield by enhancing peg penetration and pod development.

Gypsum application

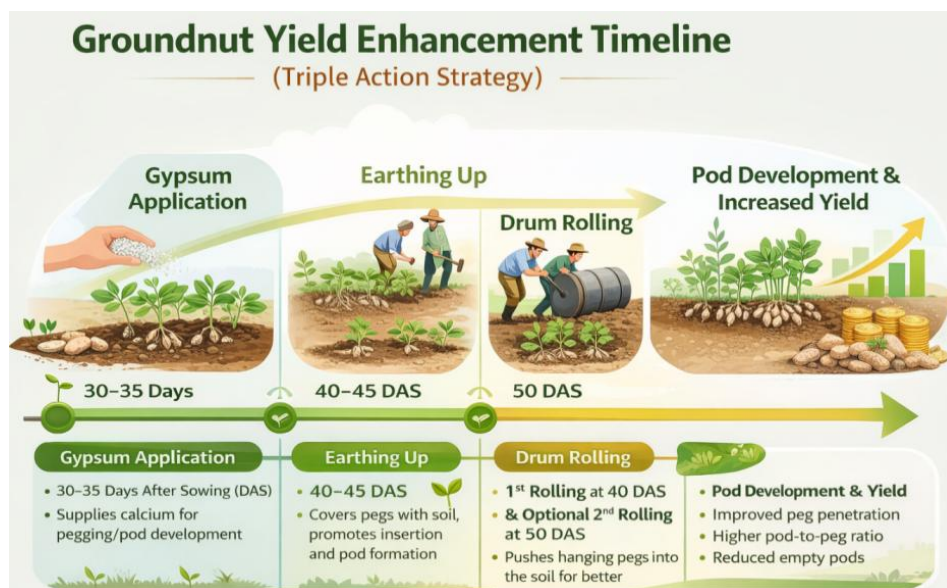
Gypsum is a vital soil amendment in groundnut cultivation, supplying calcium (29.2%) and sulphur (18.6%) that are crucial for pod development and overall crop productivity. Since calcium is directly absorbed by developing pods through pegs, its adequate availability in the pegging zone (0–5 cm soil layer) is essential during the early flowering and pegging stages, typically around 30–45 days after sowing (DAS). Application of gypsum at 250–500 kg ha⁻¹ significantly improves pod filling, reduces physiological disorders such as “hollow heart” caused by calcium deficiency and enhances kernel development. In addition to its nutritional benefits, gypsum improves soil structure by reducing surface crusting, thereby facilitating easier peg penetration into the soil. For efficient utilization, gypsum can be applied either as a single dose at early flowering or in split doses, with half applied at sowing and the remaining at flowering or pegging stage. The practice of band placement near the plant base, often combined with earthing up, ensures better nutrient availability in the root and pegging zone. Gypsum application is particularly beneficial in sandy and light-textured soils, thereby playing a critical role in enhancing yield and quality of groundnut.

Earthing up

Earthing up, carried out during the second or late hand weeding, particularly under herbicide-applied conditions, plays a vital role in creating a favourable soil environment for peg penetration and pod development in groundnut. This practice involves covering the base of plants with loose soil during the pegging stage, thereby enhancing soil aeration, promoting effective peg entry into the soil, conserving soil moisture and suppressing weed growth. The use of an improved long-handled hoe enables efficient operation with reduced labour drudgery. However, soil disturbance should be strictly avoided after 45 days after sowing (DAS), as it may adversely affect pod formation. Therefore, timely earthing up at around 40–45 DAS is considered critical for maximizing peg-to-pod conversion and improving yield potential in groundnut.

Drum Rolling

Drum rolling is an effective mechanical intervention in groundnut cultivation, wherein an empty iron/plastic drum is rolled over the crop to facilitate the insertion of hanging pegs into the soil, thereby enhancing pod formation. This practice significantly improves the peg-to-pod conversion ratio by reducing the number of unproductive pegs and ensuring more uniform pod development across the field. By aiding proper peg penetration, drum rolling contributes to increased yield potential and better crop uniformity. For optimal results, drum rolling is recommended to be carried out first at around 40 days after sowing (DAS) during the active pegging stage, followed by a second rolling at approximately 50 DAS, if necessary, to ensure maximum conversion of remaining aerial pegs into productive pods.



Synergistic effect of triple action

1. Gypsum ensures adequate calcium and sulphur supply
2. Earthing up provides a conducive soil environment
3. Drum rolling enhances peg insertion

This integrated approach results in

1. Increased peg penetration
2. Higher pod-to-peg ratio
3. Reduced empty pods
4. Improved yield and profitability

Conclusion

Groundnut productivity can be significantly enhanced by addressing both nutritional and physical constraints during the critical pegging stage. The integration of gypsum application, earthing up and drum rolling serves as an effective triple-action strategy for improving yield, especially under rainfed conditions. Adoption of this approach can help farmers achieve better resource use efficiency, higher economic returns and sustainable groundnut production.

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SENTINELS OF THE SEA: BIOINDICATOR FOR ASSESSING PLASTIC POLLUTION IN MARINE ECOSYSTEMS

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Abstract

The rapid increase in global plastic production has resulted in major environmental issues, particularly in marine ecosystems. Large quantities of plastic waste enter the oceans annually through both land-based and ocean-based sources, posing threats to marine biodiversity and ecosystem functioning. Monitoring the distribution and ecological impacts of plastic contamination is difficult due to the vast and dynamic nature of marine environments. In this context, bioindicator organisms act as natural environmental sentinels for monitoring environmental pollution, as they accumulate contaminants over time and indicate the biological effects of environmental stress on the marine ecosystem. Marine organisms including shellfish, fish, plankton, seabirds, and marine turtles can accumulate plastic particles and exhibit measurable physiological and ecological responses to plastic contamination, making them effective sentinel species for monitoring ecosystem health. The integration of bioindicator-based approaches into long-term monitoring frameworks can provide valuable insights into pollution trends and support the development of effective conservation and management strategies for the marine ecosystem.

Keywords: Bioindicator, Ecological impact, Environmental monitoring, Plastic pollution, Marine ecosystem

Introduction

Marine ecosystems play an important role in sustaining life on Earth by regulating climate, supporting biodiversity, and providing food and livelihoods for millions of people. Despite their importance, they are threatened by human activities. Pollution, habitat loss, overfishing, and climate change are among the major threats. Among these, plastic pollution is one of the most significant threats to marine ecosystems. It is estimated that more than five trillion plastic pieces weighing more than 260,000 tonnes are currently floating on the surface of the ocean. Around 80% of marine debris originated from land-based sources, including urban runoff, tourism and industrial activities, while the remaining 20% comes from ocean-based activities such as fishing, shipping and aquaculture. Once plastics enter the marine ecosystem, they can remain for decades and transported by ocean currents, spreading pollution from coastal waters to remote parts of the ocean (Jambeck *et al.*, 2015).

Plastic debris can impact marine life through ingestion, entanglement and the transfer of toxic substances and microorganisms. The monitoring of plastic pollution in marine ecosystems and its

ecological impacts is difficult because of the vast size and dynamic nature of the ocean. Conventional monitoring methods that mainly focus on measuring plastic concentrations only in water and sediments often provide limited information about their impacts on the marine ecosystem. Therefore, scientists rely on biological indicators to evaluate environmental pollution. Bioindicator organisms provide important information about ecosystem health and pollution levels, making them useful tools for environmental monitoring (Savoca *et al.*, 2025). This article highlights the importance of bioindicator species in detecting and evaluating plastic pollution in marine environments, discusses their ecological significance, and emphasises their potential role in strengthening marine environmental monitoring programs. It also highlights their ecological significance and their potential contribution to improving marine environmental monitoring.

Types of plastic debris found in marine environments

Plastic debris are found in different forms and sizes depending on its origin and degradation processes. These plastics are generally classified based on their size and source.

Table 1: Classification of plastic debris in marine environments based on size and sources.

Types of plastic	Size	Description	Common source/Examples
Macroplastics	>25 mm	Large plastic items that are easily visible to the naked eye.	Plastic bottles, bags, food packaging, and fishing nets
Mesoplastics	5-25 mm	Medium-sized plastic fragments are formed by the breakdown of large plastics by environmental factors.	Fragmented plastic items, degraded packaging materials
Microplastic	<5 mm	Small plastic particles formed through the fragmentation of larger plastic materials	Microbeads from cosmetics, synthetic fibers, fragmented plastics
Nanoplastics	<1 μ m	Extremely small plastic particles that result from further degradation of microplastics.	Degraded microplastics, industrial materials

Bioindicator

Bioindicators are living organisms used to assess the environmental quality of an ecosystem. Variations in their presence, behavior, population size, or levels of accumulated contaminants can indicate pollution or environmental stress in a particular ecosystem. Because living organisms react immediately to changes in their environment, bioindicators are commonly used in environmental monitoring.

In marine ecosystems, several organisms can be used as bioindicators of plastic pollution. These include Plankton, Shellfish such as mussels and oysters, Fish species, seabirds, and Marine turtles and mammals. These species interact with plastic waste in different ways, which can lead to the accumulation of plastic particles in their bodies. This makes them useful indicators for understanding the occurrence and spread of plastic pollution in marine environments (Parmar *et al.*, 2016).

Marine organisms as indicators of plastic pollution

Marine organisms can act as bioindicators of plastic pollution because they interact with plastic debris present in their habitats. Different groups of marine organisms serve as indicators at various levels of the marine food web.

Plankton

Plankton are microscopic organisms that form the base of the marine food chain. Plankton live in the water column and are continually exposed to the surrounding environment, making them sensitive to plastic particles. Recent studies have shown that planktons can ingest microplastics and nanoplastics from the surrounding water. These microplastics can accumulate in their bodies. This plastic can transfer to higher trophic levels when plankton are eaten by fish and shellfish. Accumulation of microplastics in plankton can indicate the early entry of plastic particles into the marine food web and provide valuable information about the level of contamination in the aquatic environment. Therefore, studying plankton helps to understand the distribution, transport and ecological impacts of microplastics in marine ecosystems and highlight their roles as early warning indicators of plastic pollution (Pastorino, P. and Barceló, D., 2024).

Bivalves (Mussels and Oysters)

Mussels and oysters are filter-feeding organisms. They filter a large amount of water every day, and along with their food, microplastics also enter their tissues and digestive tracts. Microplastics have been reported in the tissues, gills, and digestive tracts of mussels and oysters, indicating the presence and concentration of plastic pollution in their habitat. Their widespread presence and sedentary lifestyle make mussels and oysters good indicators of plastic pollution in their surrounding environment. Monitoring bivalves gives a practical and effective approach to assess marine plastic pollution, track temporal and spatial pollution trends and support conservation strategies (Ward *et al.*, 2019).

Fish

Fish play an important role as a bioindicator of plastic pollution in marine ecosystems. Many fish species accidentally ingest plastic particles when feeding on plankton, small invertebrates, or contaminated prey. These plastic particles can accumulate in the digestive system of fish and sometimes in their tissues. Fish occupy different trophic levels in the marine food web and live in a wide range of habitats, so they can provide valuable information about the presence and spread of plastic pollution in marine environments. Fish are useful for studying the presence, distribution and potential impacts of plastic particles in the ocean. (Banaee *et al.*, 2025).

Seabirds

Seabirds are widely used as bioindicators of plastic pollution in the marine ecosystem. They spend most of their lives in marine environments and feed on fish, shellfish and other marine organisms. Plastic debris has been reported in the stomachs and digestive tracts of many seabird species. By analyzing the size, type and chemical composition of plastics accumulated in the digestive tract of seabirds, we can identify pollution hotspots, assess changes in plastic composition over time and track pollution sources. Seabirds are relatively easy to observe and monitor, making them useful sentinel species for tracking marine plastic pollution and evaluating its impacts on marine wildlife (Xess and Sharma, 2021).

Marine turtles and mammals

Marine turtles and mammals are vital indicator species for tracking plastic waste in the marine environment. Their long lifespans, wide distribution and position at higher trophic levels make them highly vulnerable to the impact of plastic pollution. Therefore, the presence of plastic in their

tissues, digestive track and surrounding ecosystems can provide important information on the extent and ecological impact of marine plastic pollution. Plastic bags, fishing lines and fragments can accumulate in their digestive system, leading to intestinal blockage, reduced feeding and sometimes death. Since marine turtles and mammals migrate across large oceanic regions, the plastic detected in their bodies can reflect plastic pollution levels in different marine environments. These organisms are effective bioindicators for assessing marine ecosystem health, guiding conservation efforts and raising awareness about plastic pollution (Nelms *et al.*, 2016).

Challenges and Future Directions

The use of bioindicators to assess plastic pollution faces several challenges. Variations in species behavior, feeding patterns and habitat preferences can significantly influence plastic uptake, making it difficult to standardize results across regions. Limited long-term data and the influence of multiple environmental stressors also affect accurate assessments. Future research should focus primarily on developing standardized protocols, improving detection technologies and integrating multidisciplinary approaches. Expanding long-term monitoring programs and integrating bioindicator data with modelling and remote sensing can provide a more comprehensive understanding of plastic pollution.

Conclusion

Marine bioindicator species act as crucial “sentinels of the sea”, providing valuable insights into the presence, distribution and impacts of plastic pollution in marine environments. From tiny plankton to top predators, these organisms reflect plastic pollution across different trophic levels and help in identifying pollution sources, pathways and ecological consequences. Despite existing challenges, bioindicators provide a strong and effective approach for monitoring plastic pollution. Integrating bioindicator-based assessments into environmental management and policy frameworks is essential for mitigating plastic pollution, protecting marine biodiversity and ensuring the long-term sustainability of the marine ecosystem.

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SMART DRINKS IN THE MODERN BEVERAGE INDUSTRY: TECHNOLOGIES, BENEFITS, APPLICATIONS AND CHALLENGES

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Abstract

Smart drinks represent an emerging innovation in the beverage industry, integrating digital technologies such as QR codes, embedded sensors, Bluetooth connectivity and smart displays to deliver real-time nutritional information and interactive consumer experiences. These technologies enable consumers to access detailed data on calorie, sugar and caffeine content through smartphones or integrated displays, thereby promoting informed consumption and personalized hydration management. Smart drink systems also employ advanced sensing technologies such as electrical impedance spectroscopy to identify beverage type, volume and composition with high accuracy. In addition to improving consumer awareness and engagement, smart drinks are increasingly used in applications such as smart water bottles, self-service beverage dispensers and interactive packaging systems. The adoption of these technologies provides several advantages including enhanced consumer experience, improved health management and stronger brand differentiation in the competitive beverage market. However, the implementation of smart drink technologies also faces challenges such as increased production costs, technological complexity, consumer privacy concerns and the need for wider market acceptance. Despite these limitations, ongoing advancements in digital food sensing, augmented reality and intelligent packaging are expected to expand the capabilities and applications of smart drinks in the future.

Keywords: Smart drinks, smart packaging, QR codes, embedded sensors, nutritional information, consumer engagement, digital food sensing and intelligent beverages.

Introduction

Smart drinks, which incorporate embedded sensors or QR codes to provide nutritional information, represent a significant advancement in the beverage industry. These technologies aim to enhance consumer engagement by offering real-time data about the drink's nutritional content, thereby promoting informed consumption choices. The integration of smart technologies into beverages not only facilitates better health management but also opens new avenues for interactive consumer experiences. The following sections describes the concept, technologies, applications, benefits, challenges and future perspectives of smart drinks.

Concept of Smart Drinks

- Smart drinks are beverages equipped with technologies such as QR codes or sensors that provide nutritional information and other interactive features. These innovations not only elevate consumer awareness regarding health but also align with the growing trend of digital food sensing technologies in the beverage sector (Amarasinghe & Ranasinghe, 2024).
- Smart drinks aim to enhance consumer interaction by offering detailed insights into the beverage's content, promoting healthier choices and personalized consumption

experiences (Kuswandi & Moradi, 2019). Furthermore, the integration of smart technologies can significantly contribute to the quality and sustainability of beverages, aligning with recent trends in the industry.

Technologies Used in Smart Drinks

- **QR Codes and Interactive Codes:** These are used to link consumers to detailed nutritional information and promotional content via smartphones (Kuswandi & Moradi, 2019). Additionally, the use of QR codes in smart drinks can facilitate access to manufacturer-verified nutritional information, enhancing consumer trust and engagement in their beverage choices.
- **Sensors and Bluetooth Connectivity:** Used in smart water bottles to track and manage water intake, providing personalized hydration goals and reminders (Varun *et al.*, 2023). These technologies not only enhance consumer engagement but also pave the way for improved quality control in beverage manufacturing, ensuring safety and satisfaction for consumers (Vasudevan & Chengaiyan, 2024).
- **Electrical Impedance Spectroscopy:** Utilized in platforms like SipBit to recognize beverage types, volume and sugar content with high accuracy (Amarasinghe & Ranasinghe, 2022). This technology exemplifies the potential of smart drinks to leverage advanced sensing techniques for improved consumer awareness and health management, ultimately transforming the beverage industry.
- **Display Screens:** Integrated into beverage containers to show real-time data about the drink, enhancing user interaction. This interactive display can provide nutritional information, suggest healthier alternatives and engage consumers in making informed choices about their beverage consumption (Varun *et al.*, 2023).

Nutritional Information and Consumer Engagement

- Smart drinks provide real-time nutritional information, such as calories, sugar and caffeine content, directly to consumers, often through mobile apps or display screens. This immediate access to nutritional data empowers consumers to make informed choices, promoting healthier lifestyles and enhancing overall satisfaction with their beverage selections.
- This information can be used to compare different beverages and make healthier choices, thereby increasing consumer engagement and satisfaction. Moreover, the ability to track and analyze personal consumption patterns through smart drink technologies can further enhance consumer awareness and foster long-term healthy habits.

Applications in the Beverage Industry

- Smart drinks are used in various types, including self-service soda dispensers and smart water bottles, to promote better hydration and health outcomes (Varun *et al.*, 2023). These applications demonstrate the versatility of smart drinks in enhancing consumer experiences and promoting healthier choices in diverse environments.
- They also serve as a marketing tool, offering interactive brand experiences and promotions through scan-able codes (Butler, 2013). Moreover, the integration of smart drink technologies can facilitate personalized hydration tracking, ultimately leading to improved health outcomes and consumer satisfaction in beverage consumption (Varun *et al.*, 2023).

Benefits of Smart Drinks

- **Enhanced Consumer Experience:** By providing detailed nutritional information and interactive features, smart drinks improve the overall consumer experience (Butler, 2012). This enhanced experience not only fosters informed decision-making but also encourages healthier lifestyle choices among consumers.
- **Health Management:** They assist consumers in making informed dietary choices, potentially leading to better health outcomes (Varun *et al.*, 2023). Furthermore, the adoption of smart drinks aligns with the growing consumer demand for health and wellness, as individuals increasingly seek products that support their personalized nutrition goals (Bogue & Troy, 2016).
- **Brand Differentiation:** Smart drinks help brands stand out by offering unique, interactive experiences that align with modern consumer expectations (Butler, 2012). This differentiation is crucial in a competitive market, as consumers increasingly prefer brands that prioritize transparency and innovation in their product offerings.

Challenges and Limitations

- **Technological Complexity:** The integration of advanced technologies can increase production costs and complexity (Bogue & Troy, 2016). To address these challenges, manufacturers must invest in training and development to ensure effective implementation and maintenance of smart drink technologies.
- **Consumer Privacy:** Collecting and managing consumer data raises privacy concerns that need to be addressed. Manufacturers must prioritize transparency in data usage to build consumer trust and mitigate privacy concerns associated with smart drink technologies (Ünalán & Yapraklı, 2017).
- **Market Adoption:** Widespread adoption requires consumer education and acceptance of new technologies. To facilitate market acceptance, brands must effectively communicate the benefits of smart drinks and address potential barriers to consumer engagement.

Future Perspectives

- The future of smart drinks lies in further technological advancements, such as augmented reality and more sophisticated sensors, to enhance consumer interaction and data accuracy. These developments may lead to even more personalized beverage experiences, aligning with the growing trend of functional beverages that cater to individual health needs and preferences (Bogue & Troy, 2016) (Alalwan, 2025).
- There is potential for expanding the range of beverages and attributes recognized by smart technologies, thereby broadening their application and impact (Amarasinghe & Ranasinghe, 2022). The evolving landscape of smart drinks presents an opportunity for manufacturers to innovate and meet the rising consumer demand for health-focused beverage options, ultimately enhancing market competitiveness.

Conclusion

Smart drinks offer numerous benefits, including enhanced consumer engagement and health management, they also face challenges such as technological complexity and privacy concerns. The future of smart drinks will likely see further integration of advanced technologies, expanding their capabilities and applications in the beverage industry. As these technologies evolve, they will continue to transform the way consumers interact with beverages, offering new opportunities for health management and brand engagement.

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THE GREEN GOLD PARADOX: BIO-MECHANICAL VALORISATION OF SUGARCANE RESIDUE FOR RATOON SUSTAINABILITY

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Abstract

India's sugarcane industry, commanding a 20% share of global production, faces a critical "Green Gold Paradox": the annual generation of nearly 60 million tonnes of lignocellulosic residue, traditionally managed through the destructive practice of open-field burning ("Pyrogenics"). This review delineates a strategic transition toward "Bio-Mechanical Valorisation," a dual-protocol approach designed to convert this ecological liability into a nutrient asset ("Pedogenesis"). We analyse the structural recalcitrance of sugarcane trash specifically its lignin-encased cellulose and high Carbon-to-Nitrogen (C:N) ratio (80:1) which historically drives nitrogen immobilization and necessitates burning. The proposed solution integrates Ratoon Management Devices (RMDs) for mechanical shredding and sub-surface fertilizer placement with microbial inoculation (*Trichoderma viride*) to accelerate lignocellulosic depolymerization. This synergy mitigates the 40-50% volatilization losses associated with surface-applied urea and facilitates the mineralization of approximately 40-50 kg N, 15-20 kg P and 80-100 kg K per hectare back into the soil sink. Conclusively, adopting this bio-engineering framework not only aligns with Net Zero targets but is projected to enhance ratoon yields by 10-15% and conserve 3-4 irrigations per cycle, securing both the edaphic health and economic viability of the Indian *Kisan*.

Key words: Bio-Mechanical Valorisation, Lignocellulosic Residue, Nitrogen Immobilization, Ratoon Management

Introduction: India's Sugarcane Supremacy

India stands as a colossus in the global sugar landscape, commanding a formidable 20% share of world production and solidifying its rank as the planet's second-largest producer. As the sector navigates a strategic transition towards the Ethanol Blended Petrol (EBP) program targeting a 20% blending mandate the resilience of Indian agriculture is underscored by the robust 2025-26 projections of nearly 475-500 million tonnes of cane. For this massive output, sugarcane remains the undisputed 'Green Gold' of the Indian economy, anchoring the livelihoods of over 50 million farmers and driving a value chain worth billion. However, this productivity comes with a silent, colossal footprint; for every hectare of cane harvested, nearly 10 to 12 tonnes of dry trash are left behind, totalling an estimated 60 million tonnes of residue annually across the nation. Traditionally, this lignocellulosic legacy is managed through open-field burning, a practice that transforms 'Green Gold' into 'Black Carbon,' stripping the soil of its biological vitality. The challenge for the modern Indian sugar belt is no longer just about growing more cane, but about the Bio-Mechanical Valorisation of this residue turning a massive waste-disposal crisis into a nutrient-banking opportunity that secures the economic and ecological future of the ratoon system.



Fig 1. Conventional Residue Dynamics: Unmanaged Trash Retention and Open-Field Burning

The Executive Summary: The Fire vs. Fertility Paradox

In the intensive sugarcane belts of India spanning Uttar Pradesh, Maharashtra, and Karnataka harvest season brings a visual and ecological paradox. While the fields have produced a record tonnage of sugar, they are often blanketed in smoke shortly after. This is the "burning season," where farmers set fire to the massive load of trash (10-15 tonnes per hectare) left behind by the harvest. This practice, driven by the need for quick field clearance for the ratoon crop and labour shortages, represents a critical failure in resource management (Hemalatha *et al.*, 2022). The central conflict is one of immediate convenience versus long-term sustainability. Burning the trash blanket effectively "cleans" the field, allowing for easy fertilizer application and irrigation. However, this pyrogenic approach destroys the very biological engine required to sustain yields: the soil microbiome. Recent estimates suggest that burning one hectare of sugarcane trash releases approximately 26 kg of nitrogen, 16 kg of phosphorus, and significant quantities of potassium and sulfur into the atmosphere as aerosols and gases, rather than returning them to the soil sink (Yadav *et al.*, 2023).

The Chemistry of Loss: The Volatilization Crisis

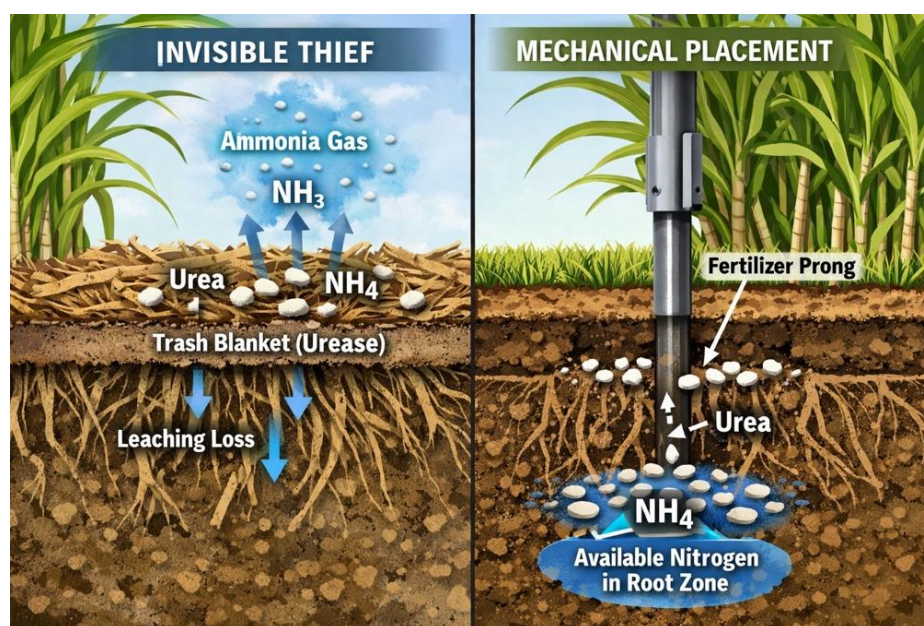


Fig 2. Comparative Nitrogen Dynamics: Volatilization Losses vs. Sub-surface Placement Efficiency

Volatilization in sugarcane systems occurs through two distinct but equally destructive pathways: the thermal decomposition of biomass during burning and the enzymatic hydrolysis of urea applied over trash blankets. When a farmer burns residue, the immediate loss is visible as smoke, but the invisible chemical loss is far more severe. Nitrogen contained in the plant tissue is oxidized into nitrogen oxides (NO_x) and elemental nitrogen (N₂), permanently exiting the soil system. Furthermore, sulfur is lost as sulfur dioxide (SO₂), and carbon the energy currency for soil life is released as CO₂ and particulate black carbon (Singh *et al.*, 2021). The second form of volatilization is arguably more insidious because it happens during crop management. In ratoon systems where trash is retained but not managed, farmers often broadcast urea on top of the residue. The trash layer, rich in the enzyme urease, facilitates the rapid hydrolysis of urea into ammonium (NH₄⁺). Without direct soil contact to adsorb this ammonium, high surface temperatures and pH levels drive the equilibrium toward ammonia gas (NH₃), which volatilizes into the atmosphere. Research indicates that surface-applied urea on trash blankets can suffer volatilization losses of up to 40–50% (Cantarella *et al.*, 2020). Furthermore, the act of burning induces a "heat shock" to the topsoil, where temperatures can spike to 300-400°C at the surface, thermally sterilizing the environment and killing beneficial microbes essential for nutrient cycling.

Table 1: Comparative Nutrient and Biological Loss from Conventional Management

Loss Pathway	Nutrient / Component	Estimated Loss Quantity	Environmental Impact	Source Citation (APA)
Open-Field Burning	Nitrogen (N)	~26 kg/ha	Atmospheric release as NO _x and N ₂	Yadav <i>et al.</i> , (2023)
Open-Field Burning	Phosphorus (P)	~16 kg/ha	Permanent loss from the soil nutrient sink	Yadav <i>et al.</i> , (2023)
Open-Field Burning	Sulfur (S)	Significant traces	Released as Sulfur Dioxide (SO ₂)	Singh <i>et al.</i> , (2021)
Open-Field Burning	Soil Temperature	300–400°C (Surface)	Thermal sterilization of beneficial microbes	Cantarella <i>et al.</i> , (2020)
Unmanaged Trash	Nitrogen (N)	40–50% of applied Urea	Ammonia (NH ₃) gas volatilization	Cantarella <i>et al.</i> , (2020)

The Lignocellulosic Barrier: Understanding the Material

To valorise sugarcane trash, one must first understand why it is so difficult to decompose. Sugarcane residue is a complex "lignocellulosic" matrix, consisting roughly of 40-50% cellulose, 25-30% hemicellulose, and most critically, 20-25% lignin (Dotaniya *et al.*, 2023). Cellulose is a polymer of glucose, but it is encased in lignin, a complex phenolic polymer that acts like "biological concrete," protecting the energy-rich fibers from degradation. This structural stubbornness is why untreated trash can remain intact for months, obstructing intercultural operations.

The second hurdle is the Carbon-to-Nitrogen (C:N) ratio; sugarcane trash typically has a massive ratio of 80:1 to 100:1, whereas soil microbes operate best at 24:1. When this high-carbon material is incorporated without adjustments, the microbial population explodes to utilize the abundant carbon. However, since the trash lacks sufficient nitrogen to support this growth, these microbes aggressively scavenge available inorganic nitrogen from the soil solution. In this biological competition, the microbes effectively outcompete the ratoon crop for the limited nitrogen pool. This process, known as "Nitrogen Immobilization," results in a temporary nitrogen deficiency for

the plant, leading to the characteristic yellowing of ratoon shoots (Kumari *et al.*, 2022). This biological barrier dictates the engineering solution: mere incorporation is not enough. The residue must be physically fractured to increase surface area and biologically primed to ensure the "trash blanket" becomes a source of fertility

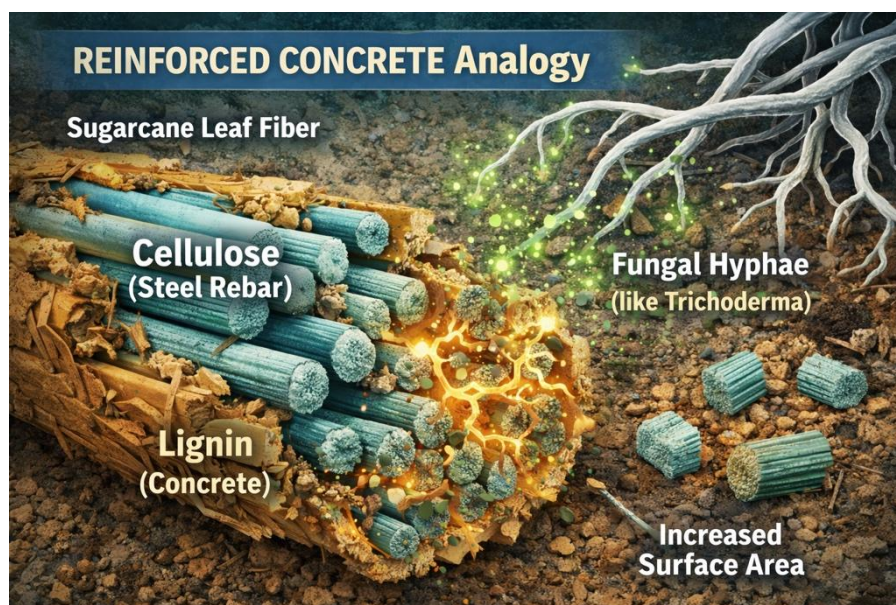


Fig 3. Lignocellulosic Recalcitrance: Structural Matrix and Microbial Depolymerization

The Bio-Mechanical Protocol: A Two-Pronged Strategy

The solution to the residue problem lies in the marriage of mechanical precision and microbial efficiency. The first stage of this protocol is the mechanical intervention using Ratoon Management Devices (RMDs). Unlike simple mulchers, modern RMDs shred the trash into fine particles (5–10 cm), shave old stubble to encourage uniform sprouting, and place fertilizer sub-surface. By drilling the fertilizer below the trash layer, the RMD creates a "soil seal" that prevents ammonia gas from escaping, effectively reducing volatilization losses to negligible levels (Geethalakshmi *et al.*, 2021). The second stage is microbial inoculation—the "engine" of the system. Once the trash is shredded, it is treated with a specific consortium of lignolytic and cellulolytic fungi, such as *Trichoderma viride* or *Aspergillus*. These microbes secrete extracellular enzymes that degrade the tough lignin structure in a process of "Solid-State Fermentation" occurring directly on the field floor. Recent field trials demonstrate that when mechanical shredding is combined with microbial waste decomposers, the decomposition rate doubles, releasing nutrients precisely when the ratoon crop enters its grand growth phase (Kumar & Sharma, 2023).

The Mineralization Pathway: Turning Waste into Wealth

The ultimate goal of bio-mechanical valorisation is "Mineralization" the biological conversion of organic matter into plant-available inorganic ions (NH_4^+ , NO_3^- , PO_4^{3-}). A standard yield of 10 tonnes of trash per hectare contains approximately 40–50 kg of N, 15–20 kg of P and 80–100 kg of Potassium (K) (Dotaniya *et al.*, 2023). By accelerating decomposition, we return these nutrients to the soil pool, significantly reducing the requirement for synthetic fertilizers. Beyond nutrient recycling, the trash blanket serves as a "Hydrothermal Buffer," regulating soil thermodynamics to keep the root zone 2–4°C cooler during peak summer. This moderation is critical for the survival of soil mesofauna,

while the organic cover minimizes evapotranspiration, effectively saving 3-4 irrigations per crop cycle (Yadav *et al.*, 2023). Long-term adoption leads to substantial Carbon Sequestration as decomposed residue transforms into humus, increasing the soil's Cation Exchange Capacity (CEC) and restoring its physical structure. The field transitions from a chemically dependent substrate to a self-regenerating ecosystem.

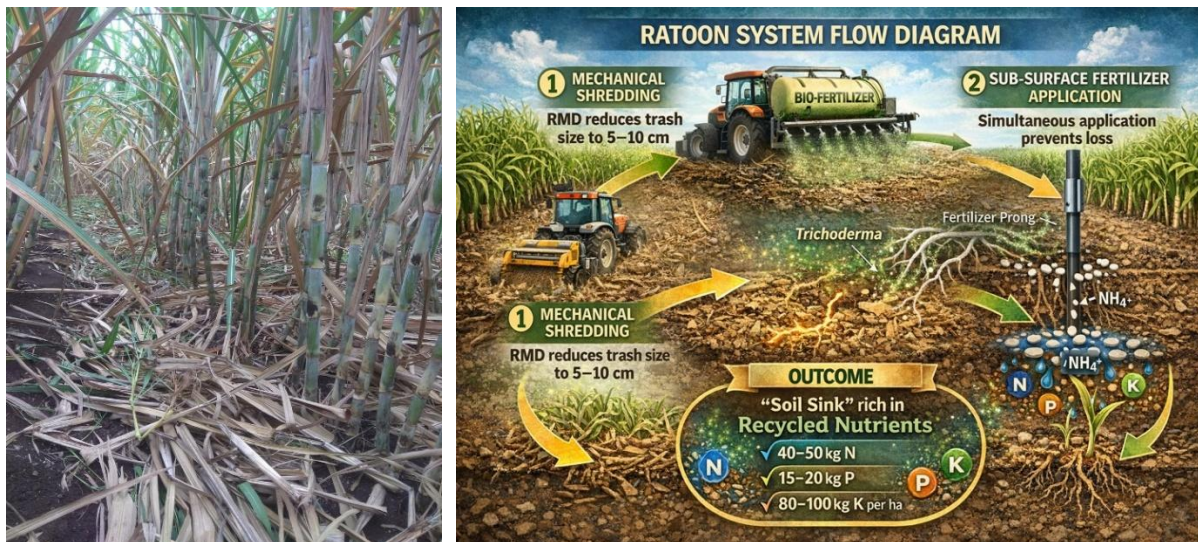


Fig 4. The Hydrothermal Buffer: In-Situ Mulching for Soil Moisture Conservation and Thermal Regulation

Table 2: Potential Resource Recovery through Bio-Mechanical Valorisation

Parameter	Impact	Agronomic Benefit	Source Citation (APA)
Recycled Nitrogen (N)	40-50 kg/ha	Reduces synthetic fertilizer requirement	Dotaniya <i>et al.</i> , (2023)
Recycled Phosphorus (P)	15-20 kg/ha	Enhances long-term soil P-bank	Dotaniya <i>et al.</i> , (2023)
Recycled Potassium (K)	80-100 kg/ha	Critical for sugarcane stalk strength	Dotaniya <i>et al.</i> , (2023)
Water Conservation	3-4 irrigations	Minimizes evapotranspiration via trash mulch	Yadav <i>et al.</i> , (2023)
Yield Improvement	10-15% increase	Enhanced ratoon sustainability and profit	Singh <i>et al.</i> , (2021)
Soil Cooling	2-4°C reduction	Protects root zone during peak summer	Yadav <i>et al.</i> , (2023)

Socio-Economic Engineering and the Future Shift

Implementing bio-mechanical valorisation is an economic necessity in India's sugar belts, where labour scarcity makes manual management expensive. Data from the ICAR-Indian Institute of Sugarcane Research indicates that integrated trash management can increase ratoon yields by 10-15%. This approach aligns with India's National Mission for Sustainable Agriculture (NMSA) and Net Zero targets, potentially opening new revenue streams through carbon credits for farmer cooperatives.

To practically access these markets, cooperatives can aggregate smallholder fields into a single project block, using digitized RMD logs and soil organic carbon (SOC) testing to verify the "avoided emissions" from non-burning and the carbon sequestered through mulch decomposition. These verified offsets can then be traded on voluntary carbon markets or national platforms to provide direct financial dividends to the members. The transition from "Pyrogenics" (fire-based) to "Pedogenesis" (soil-building) is the defining challenge for the modern farmer. By using engineering to facilitate biology, the Indian sugar belt can send its carbon back into the soil as life-giving humus rather than into the atmosphere as pollutant smoke. Empowering the *Kisan* with bio-mechanical literacy is the prerequisite for the next revolution in sugarcane, ensuring that every stalk of trash becomes a silent investment in the longevity of the land.

Conclusion

The transition from traditional open-field burning to bio-mechanical valorisation represents a critical shift from "Pyrogenics" (fire-based) to "Pedogenesis" (soil-building) within India's sugarcane sector. By integrating Ratoon Management Devices (RMDs) with microbial inoculants like *Trichoderma*, farmers can bypass the structural and chemical barriers of lignocellulosic trash to double decomposition rates and return vital nutrients approximately 40-50 kg of N, 15-20 kg of P, and 80-100 kg of K per hectare-back to the soil sink. This dual approach not only eliminates the atmospheric loss of nitrogen and sulfur caused by fire but also mitigates the 40-50% volatilization losses associated with surface-applied urea. Ultimately, adopting these sustainable practices can increase ratoon yields by 10-15%, conserve water by reducing the need for 3-4 irrigations, and foster a self-regenerating ecosystem that secures both the economic livelihood of the *Kisan* and the long-term ecological health of the land.

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BLOSSOMING INDIA: THE RISING SUPPLY AND DEMAND OF FLOWER CROPS. HOW FLORICULTURE IS RESHAPING AGRICULTURE, MARKETS AND RURAL INCOME IN INDIA

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Introduction

Floriculture in India has emerged as a high-value agricultural enterprise. Flowers are deeply connected with Indian culture, religion, weddings, festivals, and modern decorative practices. The sector includes loose flowers, cut flowers, ornamental plants, and nursery products. With increasing urbanization and export opportunities, both supply and demand are growing steadily.

Top traditional flower markets in India

- Ghazipur Flower Market (Delhi)
- Madurai Flower Market
- Devaraja Market (Mysore)
- KR (Huvina) Market (Bengaluru)
- Mullick Ghat Flower Market (Kolkata)
- Dadar Flower Market (Mumbai)
- Gandhi Bazaar (Bangalore)



Figure: Traditional flower market showing loose flower trade in India

Growing Supply of Flower Crops

India is steadily increasing its flower production because its varied climate allows flowers to be grown throughout the year. States like Karnataka, Tamil Nadu, West Bengal, Maharashtra, Andhra Pradesh, and Uttar Pradesh are major producers of crops such as marigold, jasmine, rose,

chrysanthemum, tuberose, gladiolus, and carnation. In recent years, more farmers have shifted from cereals to flower cultivation because flowers provide higher income and faster returns. This expansion has increased the total area under floriculture. As a result, India's flower supply is growing continuously and meeting both domestic and export demand.

Government support through schemes under the National Horticulture Mission (NHM) and Mission for Integrated Development of Horticulture (MIDH) has encouraged expansion by providing subsidies for quality planting material, protected cultivation structures, and post-harvest infrastructure. The adoption of drip irrigation, fertigation, polyhouse and shade-net cultivation, along with tissue culture raised high-yielding and disease-free varieties, has significantly improved productivity and quality. Additionally, improved market linkages, cold storage facilities, and increasing domestic and export demand have further strengthened India's floriculture production capacity, making it one of the leading producers of flowers in Asia.

Demand Dynamics in India

Demand for flowers in India is driven mainly by religious, cultural, and social traditions throughout the year. Daily temple worship ensures steady demand for loose flowers like marigold, jasmine, rose, and chrysanthemum, especially in southern and eastern states. Major festivals such as Diwali, Navratri, Ganesh Chaturthi, and Onam sharply increase flower consumption for decorations and garlands. The wedding industry also creates high demand for roses, orchids, lilies, and marigolds for stage and bridal décor. In cities, gifting culture, corporate events, hotels, and online flower services further boost the market. Continuous ceremonies and rituals maintain regular sales, making India one of the world's largest flower-consuming countries.

Online flower delivery platforms and retail chains have further boosted demand for cut flowers such as roses, lilies, and gerberas.

Online Flower Delivery Platforms and Retail Chains in India

S.No	Platform / Brand	Type	Coverage in India	Key Services	Special Features
1	Ferns N Petals (FNP)	Online + Retail Chain	19000+ PIN codes	Flowers, cakes, plants, gift hampers	Same-day and night delivery, strong retail presence
2	Floweraura	Online Platform	600+ cities	Bouquets, cakes, personalized gifts	Occasion-based collections, secure packaging
3	Winni	Online Platform	Pan India	Floral arrangements, combos	Heart-shaped bouquets, exotic flowers
4	YuvaFlowers	Online Platform	550+ cities	Flowers, cakes, gifts	30-minute delivery in select cities
5	Flowera.in	Online Platform	550+ cities	Flowers + gift combos	Midnight & same-day delivery
6	Florikart	Online Platform	Major Indian cities	Flowers, plants, cakes	5-hour express delivery option
7	Bloomsy	Online Platform	200+ cities	Fresh bouquets & gifts	Same-day metro delivery
8	FloriTribe	Florist Network Platform	PAN India	Connects with local florists	Location-based florist search



Figure: Flower decoration used in Indian weddings and events

Export Opportunities

India accounts for only 0.3-0.6% of global floriculture exports, as reported by the Agricultural and Processed Food Products Export Development Authority (APEDA), with export earnings of about USD 88-90 million in FY 2023-24. Its main export destinations include the USA, the Netherlands, Germany, the UAE, and the UK, and key products are cut roses, carnations, chrysanthemums, and foliage. However, compared to major exporters like the Netherlands (49-60% global share) and Colombia (14-15%), India's global presence remains limited due to constraints in cold-chain infrastructure and logistics. With better post-harvest management and export-focused strategies, India has strong potential to expand its share in the global flower market.

Challenges in Supply and Demand Balance

Despite growth, the sector faces challenges such as price volatility, lack of cold chain infrastructure, post-harvest losses, and dependency on middlemen. Seasonal fluctuations affect supply and market prices.

Improving storage, transportation, and direct farmer-to-market linkages can stabilize the market and increase profitability.

Conclusion

The floriculture sector in India is transitioning into a commercially vibrant industry. With increasing domestic consumption and expanding export potential, flower crops provide significant opportunities for income generation and rural employment. Strengthening infrastructure and market integration will ensure a sustainable and profitable future for Indian floriculture.

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***Termitomyces*: NATURE'S HIDDEN TREASURE FROM TERMITE MOUNDS**

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Overview

Termitomyces is a highly valued wild edible mushroom in India that commonly appears during the monsoon season. It typically grows in areas with cocoa, oil palm, and rubber plantations, maintaining a symbiotic relationship with termites. The genus was first described in 1942 by the French mycologist Roger Heim. Almost all the species of *Termitomyces* are edible and are well known for their culinary appeal. The genus shows remarkable variation in size, ranging from the very small *T. microcarpus* (cap ≤ 2 cm) to the giant *T. titanicus*, which is regarded as the world's largest edible mushroom. *T. titanicus* is commonly found in West Africa and Zambia, where it is widely consumed, and it can attain an impressive cap diameter of up to 1 meter with a stipe height of about 57 cm. A number of species of *Termitomyces* have also been reported from India which is widely consumed across different states and is frequently sold in local markets and roadside stalls during the rainy season, reflecting its strong traditional demand. The country harbors rich species diversity, including *T. heimii*, *T. clypeatus*, *T. eurhizus*, and *T. microcarpus*, with around 22 species reported from different regions, reflecting its ecological adaptability and significance. About two-thirds of the global *Termitomyces* species are reported from the Western Ghats and the west coast of India.

Termitomyces mushrooms are known by different local names in various regions, reflecting their cultural importance. In China, they are called "Jizong" (chicken mushroom) and "Yizong" (ant-planted mushroom). In Thailand, they are known as "Hed Khone." In Malaysia, common names include "Cendawan busut," "Cendawan meluku," "Cendawan anai-anai," and "Kulat tahun." In Laos, species-specific names are used, such as "Phuak tab fai," "Pouak tam fan," "Pouak jik," "Het khon kao," and "Pouak kai noi." In India, they are generally known as termite mushrooms, with regional names varying across states. These names highlight the regional recognition and traditional use of *Termitomyces* mushrooms.

Taxonomy and Symbiotic Association

Taxonomically, *Termitomyces* belongs to the family Lyophyllaceae under the order Agaricales. A distinctive feature of this genus is its obligate mutualistic association with fungus-growing termites of the subfamily Macrotermitinae. More than 330 termite species are known to be associated with *Termitomyces*, particularly those belonging to the genera *Odontotermes*, *Macrotermes*, and *Microtermes*.

Variation in Morphological Characteristics

Species of *Termitomyces* show wide variation in both macroscopic (visible) and microscopic features, which are important for their identification and classification. These variations occur in size, texture, pileus structure, pseudorrhiza, veil, and microscopic features such as cystidia are summarized in the table below.

Character	Variation	Examples
Basidiocarp Size	Small to very large (2 cm to >30 cm; extreme up to 1 m in <i>T. titanicus</i>)	Small: <i>T. medius</i> , <i>T. microcarpus</i> ; Large: <i>T. heimii</i> , <i>T. reticulatus</i> ; Giant: <i>T. titanicus</i>
Texture	Soft, membranous, fragile to fleshy, cartilaginous, tough	Soft: <i>T. microcarpus</i> , <i>T. badius</i> ; Tough: <i>T. heimii</i> , <i>T. mammiformis</i>
Pileus (Cap)	Convex to expanded; may have depressed center; umbo shape varies (spiniform, acute, obtuse, broad)	Spiniform: <i>T. clypeatus</i> ; Acute: <i>T. tylerianus</i> ; Broad: <i>T. heimii</i>
Pseudorrhiza	Absent, short, or very long; color may vary	Absent: <i>T. microcarpus</i> ; Long: <i>T. reticulatus</i> ; Dark crust: <i>T. eurhizus</i>
Pileus Colour	White to various shades of brown; umbo may be same or different color	Variable across species
Stipe (Stem)	Long, cylindrical, often tapering into pseudorrhiza	Common in most species
Veil	Absent, evanescent, persistent, or modified (fibrillose/scaly)	Absent: <i>T. clypeatus</i> ; Persistent: <i>T. heimii</i> ; Evanescent: <i>T. tylerianus</i>
Cystidia (Microscopic)	Present or absent (pleurocystidia & cheilocystidia)	Absent: <i>T. radicans</i> ; Both present: <i>T. heimii</i> , <i>T. clypeatus</i>
Basidiospores	Little variation in shape and structure	Similar across species

Life Cycle: A Unique Partnership

The life cycle of *Termitomyces* begins with the nuptial flight of winged male and female termites (alates), usually before or during the onset of monsoon rains. After mating, the fertilized pair establishes a new colony in the soil, where the queen starts laying eggs and produces the first generation of worker termites. As the colony develops, worker termites collect plant materials such as dry grass, wood fragments, and leaf litter. These materials are ingested, partially digested, and excreted as pseudo-faecal matter, which is used to construct fungal combs inside the termite nest. These combs serve as a nutrient-rich substrate for the growth of the fungus. Spores of *Termitomyces*, either obtained from the environment or present in the termite gut, are introduced into the comb. Under suitable conditions, the spores germinate and form a dense mycelial network. The fungus secretes enzymes that break down complex compounds like cellulose and lignin into simpler nutrients, which are then utilized by termites as food. Within the comb, the fungus produces nodules rich in asexual spores. These nodules are consumed by worker termites and help in continuous inoculation of new comb material, ensuring the persistence of the fungus within the colony. As the colony matures and environmental conditions become favorable, especially after monsoon rains, the fungus produces fruiting bodies (mushrooms) that emerge from the termite mound above the soil surface. These mushrooms release basidiospores into the environment, which disperse and can establish new associations with termite colonies. Thus, the life cycle of

Termitomyces represents a highly specialized and interdependent system where the fungus provides nutrition to termites, and termites in turn provide a suitable habitat and substrate for fungal growth.

Nutritional and Medicinal Importance

Termitomyces mushrooms are an important source of nutrition in India, especially for rural and tribal communities, as they are rich in proteins (27–36%), vitamins, minerals, and ascorbic acid. In addition to their nutritional value, they contain several bioactive compounds such as phenolics, polysaccharides, cerebrosides, ergostanes, saponins, and fatty acid amides, which contribute to strong antioxidant activity. These compounds are associated with various health benefits including immunomodulatory, antimicrobial, antitumor, and neuroprotective effects, highlighting their potential as a functional food. In traditional Indian systems, species like *T. heimii* and *T. microcarpus* are commonly used for treating fever, cold, and fungal infections, while *T. heimii* is also valued as a blood tonic and for promoting wound healing. *T. eurhizus* is used in managing conditions such as diarrhea, rheumatism, and high blood pressure. Thus, in the Indian context, *Termitomyces* not only contributes to nutritional security but also plays a significant role in ethnomedicine and rural healthcare practices.

Constraints in Cultivation and Future Opportunities

Although *Termitomyces* is valued for its rich nutrition, medicinal importance, and economic potential, its large-scale cultivation is still limited. This is mainly because the fungus depends on a highly specialized association with termites, which is difficult to reproduce artificially. In contrast to commonly grown mushrooms like *Agaricus bisporus* and *Pleurotus*, it requires a unique natural environment involving termite activity, making controlled cultivation challenging. However, with advancing research on domestication and improved techniques, it has strong potential to contribute to nutritional security and rural income generation in the future.

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THE HIDDEN INTERFACE OF PLANT–SOIL–MICROBE INTERACTIONS: RHIZOSPHERE AND ROOT EXUDATES

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Abstract

Beneath every plant lies the rhizosphere — a narrow but highly active zone where roots, soil, and microorganisms interact continuously. Plants release chemical compounds called root exudates that shape microbial communities, attracting beneficial organisms while suppressing pathogens. These interactions regulate nutrient cycling, carbon flow, and plant defense, making the rhizosphere essential for plant health and soil fertility. Advances in microbiome research now allow scientists to manage this underground ecosystem through bioinoculants and targeted microbial strategies. Harnessing the rhizosphere offers a promising path toward sustainable agriculture, improving crop productivity, disease resistance, and environmental resilience while reducing reliance on chemical inputs.

Introduction

Beneath every plant lies a hidden world of intense biological activity. This underground region, known as the rhizosphere, is where plant roots, soil, and microorganisms interact continuously through complex chemical exchanges. First described by Lorenz Hiltner in 1904, the rhizosphere is a narrow zone of soil surrounding plant roots, yet it plays a central role in plant growth, soil fertility, and ecosystem functioning (Hiltner, 1904). Plant roots release a wide range of chemical compounds that shape the surrounding microbial community. Some of these substances attract beneficial microorganisms that support plant growth, while others suppress harmful pathogens. Because of this active biochemical communication, the rhizosphere functions as the primary interface connecting plants with the living soil environment.

Rhizosphere Structure and Function

The rhizosphere is structurally divided into three zones: the endorhizosphere (internal root tissues), the rhizoplane (root surface), and the ectorhizosphere (soil adjacent to the root surface). Together, these regions host an enormous diversity of microorganisms, bacteria, fungi, and other microscopic life forms collectively known as the rhizomicrobiome (Clark, 1949). Despite extending only a few millimetres from the root, the rhizosphere is one of the most biologically active regions in soil. Scientists often compare it to the human gut microbiome because of its vast microbial diversity and strong influence on host health (Mendes *et al.*, 2013).

The Rhizosphere Effect

One of the defining characteristics of the rhizosphere is the rhizosphere effect, which describes how soil near roots differs from bulk soil in its biological and chemical properties. Roots release a portion

of the carbon produced during photosynthesis into the surrounding soil, providing energy for microbial growth (Philips *et al.*, 2013). This carbon supply stimulates microbial activity, increasing nutrient cycling and organic matter breakdown near roots. In some cases, it also accelerates soil carbon turnover a process known as the rhizosphere priming effect, which plays an important role in global carbon cycling (Dijkstra *et al.*, 2021). The strength of this effect varies depending on plant species, soil type, and environmental conditions, showing how closely plant biology is linked to soil ecology.

Root Exudates: Composition and Function

A key driver of rhizosphere processes is root exudation, the release of organic compounds from growing roots. Root exudates serve as the main food source for microorganisms in the rhizosphere, creating a nutrient-rich environment that supports active microbial growth. They include small molecules like sugars, amino acids, organic acids, and phenolics, as well as larger substances such as mucilage and proteins that help protect roots and improve root–soil contact (Bais *et al.*, 2006; Bertin *et al.*, 2003). Beyond nutrition, root exudates function as chemical signals that shape plant–microbe interactions. They help recruit beneficial microbes, regulate nutrient competition, support symbiotic relationships, and trigger plant defense responses against pathogens. In this way, plants actively shape the microbial communities surrounding their roots rather than passively depending on the soil environment (Bais *et al.*, 2006).

Microbial Interactions and Signaling in the Rhizosphere

The rhizosphere is a highly active zone around plant roots where diverse microorganisms bacteria, fungi, and others interact with each other and with the plant. These interactions can be beneficial, harmful, or neutral, but together they shape microbial communities and strongly influence plant health. Many beneficial microbes protect plants by suppressing pathogens, improving nutrient uptake, and activating plant defenses such as induced systemic resistance. Plants also help select helpful microbes by releasing specific root exudates that influence microbial composition (Harbort *et al.*, 2020). Microorganisms communicate through chemical signals such as quorum sensing molecules and volatile compounds, which regulate their behavior and can also affect plant growth and immunity. At the same time, plants send chemical signals that attract symbiotic microbes like rhizobia and mycorrhizal fungi, while microbes release signals that influence plant growth and defense responses (Pieterse *et al.*, 2014).

Rhizodeposition and Carbon Flow

Plants continuously release carbon into the soil through a process called rhizodeposition, which includes root exudates, secretions, and shed root cells. These materials provide energy for soil microorganisms and influence nutrient availability, soil structure, and carbon storage (Curl 2012). It includes root exudates, mucilage, secretions, lysates, and sloughed-off root cap cells. The process is influenced by plant characteristics such as species, growth activity, and root structure, as well as environmental factors like soil type, moisture, and temperature.

Rhizodeposits mainly contain sugars, amino acids, and organic acids, which provide energy and nutrients for soil microorganisms. By supplying organic carbon to soil, rhizodeposition helps regulate nutrient availability, soil structure, carbon storage, and microbial community composition. Some compounds, such as isoflavonoids, also support plant defense and promote beneficial symbiosis with nitrogen-fixing bacteria (White *et al.*, 2017).

Rhizosphere Microbiome Engineering: The Future of Agriculture

Recent advances in research have led to the concept of rhizosphere microbiome engineering the deliberate management of root-associated microbial communities to improve plant health and

productivity. Plants naturally shape their rhizosphere microbiome through root exudates that attract beneficial microbes such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi while limiting harmful pathogens. Modern approaches build on this natural process by introducing beneficial microbial inoculants, modifying farming practices, or selecting plant traits that promote disease-suppressive and growth-enhancing microbiomes. Strategies include applying bioinoculants, stimulating helpful microbes through targeted root exudation, and harnessing microbial signaling processes like induced systemic resistance (ISR) and nutrient mobilization. Advances in omics technologies and synthetic microbial community design are helping scientists identify key microbes and functions, making it increasingly possible to manage the rhizosphere for sustainable and productive agriculture (Ferreira *et al.*, 2024). As a result, microbiome engineering is increasingly viewed as a promising strategy for sustainable agriculture, with the potential to improve nutrient efficiency, disease resistance, and crop yield while reducing dependence on chemical inputs (Dubey *et al.*, 2025).

Conclusion

The rhizosphere is a highly dynamic and biologically active interface where plants, soil, and microorganisms interact through complex physical and chemical processes. Root exudates and rhizodeposits play a central role in shaping microbial community structure, regulating nutrient availability, and mediating plant defense responses. Through continuous plant–microbe and microbe–microbe communication, the rhizosphere significantly influences plant health, soil fertility, and ecosystem functioning. Recent advances in understanding rhizosphere signaling, microbial competition, and carbon dynamics highlight the potential of harnessing beneficial microbiomes for sustainable disease management and improved crop productivity.

An integrated understanding of rhizosphere processes therefore provides a strong scientific foundation for developing eco-friendly and microbiome-based agricultural strategies to enhance plant resilience against soil-borne pathogens.

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USE OF PLAIN PAPER EGG TRAYS AS A SMOKE-BASED MOSQUITO CONTROL METHOD IN RURAL INDIA

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Abstract

Mosquito-borne diseases remain a persistent public health challenge in rural India, where environmental conditions, limited infrastructure, and economic constraints favor mosquito breeding and transmission. While chemical-based mosquito control measures are widely promoted, their affordability, accessibility, and potential health risks limit their adoption among rural populations. Consequently, indigenous and household-level practices continue to play an important role in mosquito nuisance management. One such practice involves the controlled burning of plain paper egg trays to generate smoke that repels mosquitoes from human dwellings and animal shelters. This article reviews the rationale, method of application, mode of action, advantages, limitations, and public health relevance of this traditional practice. The study highlights the potential role of such low-cost, locally available, and environmentally benign methods as supplementary tools within integrated mosquito management strategies in rural India.

Keywords: Mosquito repellent, smoke-based control, egg tray burning, rural households, traditional practices

Introduction

Mosquitoes are among the most significant arthropod vectors affecting human health worldwide. They transmit a wide range of pathogens responsible for diseases such as malaria, dengue, chikungunya, lymphatic filariasis, Japanese encephalitis, and Zika virus infection. According to the World Health Organization, vector-borne diseases collectively account for more than 17% of all infectious diseases globally, with a disproportionately high burden in tropical and subtropical regions (WHO, 2023).

India, due to its diverse agroclimatic conditions, supports a wide range of mosquito species belonging primarily to the genera *Anopheles*, *Aedes*, and *Culex*. Rural areas are particularly vulnerable because of favorable breeding habitats such as stagnant water in fields, ponds, irrigation channels, poorly managed household water storage, and cattle sheds. Limited access to health services and preventive tools further exacerbates the impact of mosquito-borne diseases on rural communities. Chemical insecticides, mosquito coils, vaporizers, and aerosols are commonly recommended for mosquito control. However, their repeated use raises concerns regarding affordability, insecticide resistance, indoor air pollution, and adverse health effects, especially among children, elderly individuals, and livestock. As a result, rural populations often rely on traditional or improvised methods using locally available materials. One such method is the burning of plain paper egg trays to produce smoke that repels mosquitoes during peak biting hours.

Traditional Smoke-Based Mosquito Control Practices

The use of smoke as a means of repelling mosquitoes is one of the oldest known forms of insect deterrence. Historical records indicate that communities across Africa, Asia, and Latin America have

used burning plant materials, cow dung cakes, leaves, and agricultural residues to protect themselves from biting insects (Rozendaal, 1997). Smoke interferes with mosquito host-seeking behavior by masking carbon dioxide, body odors, and heat cues that mosquitoes use to locate hosts.

Service (2012) noted that “mosquitoes are extremely sensitive to airborne irritants and particulate matter, which disrupt their orientation and feeding behavior.” In rural India, smoke-based repellents are commonly used in outdoor or semi-outdoor settings, particularly in the evenings when mosquito activity is highest and people remain active outside their homes.

Within this context, the burning of plain paper egg trays represents a modern adaptation of traditional smoke-based practices, utilizing an easily available waste product rather than plant biomass or fuel materials.

Plain Paper Egg Trays: Characteristics and Availability

Plain paper egg trays are manufactured from recycled paper pulp and are widely used for packaging eggs in poultry farms, markets, and retail shops. These trays are biodegradable, lightweight, and porous, allowing them to burn slowly when ignited.

In rural India, egg trays are:

- Easily obtainable from poultry shops and households
- Often discarded as waste material
- Free from added insecticides or synthetic chemicals

When compared to loose paper or cardboard, egg trays burn at a slower rate, producing sustained smoke rather than a quick flame. This characteristic makes them suitable for short-term mosquito repellent use in open spaces.

Method of Application

The burning method involves a simple and standardized procedure commonly practiced at the household level:

1. Collection: Dry plain paper egg trays are collected from poultry vendors or household waste.
2. Preparation: Trays are sun-dried to remove moisture and ensure slow smouldering.
3. Ignition: A portion of the tray is ignited and placed on a fire-resistant surface such as an earthen pot, metal plate, or brick.
4. Placement: The smouldering tray is positioned near doorways, verandahs, outdoor sitting areas, or cattle sheds.
5. Timing: The method is typically used during evening hours when mosquito activity peaks.

The smoke produced repels mosquitoes from the immediate vicinity, providing temporary relief from biting.

Rozendaal (1997) emphasized that “smoke-based repellents function primarily as spatial repellents, reducing mosquito–human contact without directly killing the insects.”

Mode of Action

The repellent action of burning egg trays is primarily physical rather than chemical. The smoke generated contains particulate matter and combustion by-products that interfere with mosquito sensory receptors. These particles:

1. Mask human odors such as lactic acid and ammonia
2. Disrupt carbon dioxide gradients used by mosquitoes for host detection
3. Cause irritation to mosquito spiracles and antennae

As a result, mosquitoes avoid smoky environments and move away from treated areas. Unlike insecticides, this method does not exert lethal pressure on mosquito populations, thereby minimizing the risk of resistance development.

Advantages of Egg Tray Burning Method

The practice offers several advantages, particularly in rural settings:

1. **Economic Feasibility:** The method requires no financial investment, making it accessible to economically disadvantaged households.
2. **Environmental Safety:** Being composed of recycled paper, egg trays are biodegradable and do not introduce toxic residues into the environment.
3. **Community Acceptance:** The practice aligns with traditional smoke-based methods already familiar to rural communities, facilitating easy adoption.
4. **Compatibility with Integrated Vector Management:** WHO (2017) defined Integrated Vector Management (IVM) as “a rational decision-making process for the optimal use of resources for vector control.” Egg tray burning fits well as a supplementary, non-chemical intervention within IVM frameworks.

Limitations and Health Considerations:

Despite its benefits, the egg tray burning method has certain limitations:

- **Temporary effect:** Protection lasts only while smoke is present.
- **Health concerns:** Prolonged inhalation of smoke may cause respiratory irritation, particularly in enclosed spaces.
- **No population reduction:** The method repels mosquitoes but does not reduce breeding or larval populations.

Curtis and Lines (2000) cautioned that “repellents provide personal protection but should not be considered substitutes for vector population control measures.”

Therefore, careful use in well-ventilated or outdoor areas is essential.

Role in Rural Public Health and Extension Programs

The documentation of such practices is important for rural health extension and community education programs. Incorporating locally acceptable methods into awareness campaigns can enhance participation and compliance.

Egg tray burning can be promoted as:

- An emergency or short-term relief measure
- A complementary practice during power outages
- A supportive tool alongside sanitation and source reduction

Sharma and Dev (2015) highlighted the need to “integrate traditional knowledge with scientific vector control approaches to achieve sustainable outcomes in rural India.”

Integration with Other Mosquito Control Measures

For effective mosquito management, egg tray burning should be combined with:

- Elimination of stagnant water sources
- Proper solid and liquid waste management
- Use of bed nets and window screens
- Improved drainage around homes and animal shelters

WHO (2017) emphasized that “no single intervention is sufficient for effective vector control, and a combination of methods is essential.”

Conclusion

The burning of plain paper egg trays represents a low-cost, locally available, and culturally acceptable mosquito repellent practice in rural India. While it does not replace conventional vector control measures, it provides immediate and affordable relief from mosquito nuisance when used appropriately. Recognizing and scientifically documenting such indigenous practices can strengthen community-based mosquito management strategies and support integrated approaches to vector control.

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AGRONOMIC BENEFITS OF NANOFERTILIZERS IN AGRICULTURAL SUSTAINABILITY UNDER CLIMATE UNCERTAINTY

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Abstract

Agriculture sustains nearly half of India's population and contributes about 18% to the GDP, yet it faces growing pressure from rising temperatures, erratic rainfall, droughts, and extreme weather. This paper explores pathways to sustainable farming under increasing climate uncertainty, with a focus on India. It examines scientific, technological, ecological, and policy approaches central to climate-resilient agriculture, including soil health restoration, water conservation, integrated nutrient management, crop diversification, and the use of digital tools. The study also highlights the importance of institutional reforms, coherent policies, and community participation in strengthening long-term resilience. Drawing on insights from published work it provides a comprehensive roadmap for adopting sustainable practices that can safeguard food production, nutrition, and rural livelihoods for future generations.

Keywords: Sustainable agriculture, climate uncertainty, resilience, adaptation, India

Introduction

Agricultural productivity is increasingly threatened by climate change, with rising temperatures, irregular rainfall patterns, increased frequency of droughts, and soil degradation contributing to productivity declines and food insecurity (Goyal *et al.*, 2025). Conventional fertilizers, critical for high yields, face limitations due to inefficiencies that cause nutrient losses and environmental contamination such as runoff, leaching, and emission of greenhouse gases (Mejias *et al.*, 2021). As a result, sustainable, climate-resilient agricultural practices demand innovations that optimize nutrient delivery and minimize environmental harm. Nanofertilizers, leveraging nanotechnology principles, represent a pivotal advancement in this context. Their minute particle size and engineered properties enable improved nutrient bioavailability, controlled release, and enhanced interactions at the plant-soil interface (Nongbet *et al.*, 2022). This empowers precision nutrition management tailored to plant demands and environmental conditions, making nanofertilizers promising tools to balance productivity with sustainability in the climate uncertainty era. This paper explores pathways to sustainable farming under increasing climate uncertainty, with a focus on India.

Enhanced Nutrient Use Efficiency and Delivery

Nutrient use efficiency (NUE) is pivotal in modern agriculture to maximize crop yields while preserving environmental integrity. Conventional fertilizers often suffer from poor NUE due to losses by leaching, volatilization, and fixation, which result in economic inefficiency and environmental pollution (Mejias *et al.*, 2021). Nanofertilizers, nanoscale formulations designed for targeted and controlled nutrient delivery, have emerged as innovative solutions to improve NUE by synchronizing nutrient release with crop demand and minimizing losses to the environment (Goyal *et al.*, 2025; Yadav *et al.*, 2023).

Mechanisms Underlying Enhanced Nutrient Use Efficiency

Nanofertilizers enhance NUE via several mechanisms:

- **Controlled and Sustained Nutrient Release:** Nanofertilizers often employ nano-encapsulation or coatings that enable slow and controlled nutrient release, aligning nutrient availability with plant growth stages. For instance, urea encapsulated in hydroxyapatite nanoparticles releases nitrogen slowly over several weeks, significantly reducing losses through volatilization and leaching while maintaining crop nutrient supply (Maaz *et al.*, 2025; Mejias *et al.*, 2021). Similarly, nano-phosphorus fertilizers embedded in mesoporous carriers limit phosphorus fixation in soils, improving plant accessibility (Yadav *et al.*, 2023).
- **Increased Nutrient Solubility and Mobility:** Nanoparticles possess large specific surface areas and enhanced reactivity, improving nutrient solubility. This facilitates greater diffusion to root surfaces and interaction with plant transporters (Kumar *et al.*, 2020). For example, nano-zinc oxide formulations increase zinc solubility in soil solutions, enhancing uptake efficiency compared to conventional zinc salts (Kale & Gawade, 2021).

Improved Uptake Through Root and Foliar Pathways

Due to their small particle size and surface properties, nanoparticles penetrate root epidermal layers and stomata more effectively than bulk fertilizers (Nongbet *et al.*, 2022). Foliar application of nanoformulated nutrients like nano-urea and nano-zinc increases direct absorption, circumventing soil fixation and enhancing plant nutrient status especially under nutrient-limited soils (Kale & Gawade, 2021; Mim *et al.*, 2025).

Nanofertilizers promote root proliferation and rhizospheric microbial activity essential for nutrient solubilization and cycling (Mim *et al.*, 2025). Enhanced root surface area increases exploration capacity, improving nutrient acquisition. Simultaneously, nano-enabled micronutrient supply sustains beneficial microbial communities, indirectly boosting nutrient availability (Nongbet *et al.*, 2022).

Yield Increase and Crop Quality Enhancement:

With the increasing global population and the intensifying impacts of climate change, boosting agricultural yield and improving crop quality have become essential goals to sustain food security and nutritional adequacy. Nanofertilizers, utilizing nanotechnology for precision nutrient delivery, have emerged as pivotal tools to achieve these aims by enhancing nutrient use efficiency and plant physiological functioning. Recent research across various crops and agroecologies demonstrates significant yield increases and quality improvements using nanofertilizers, positioning them as transformative inputs for sustainable agriculture (Goyal *et al.*, 2025; Mejias *et al.*, 2021).

Yield Enhancement Through Improved Nutrient Use Efficiency:

Several studies document NUE improvements and associated yield gains with nanofertilizer use. Nanofertilizers increase crop yields by providing nutrients in forms and timings closely aligned with plant demand, thereby minimizing nutrient stress and maximizing uptake efficiency (Yadav *et al.*, 2023). Controlled-release nanoformulations slow the dissolution of nutrients, maintaining optimal soil nutrient levels throughout critical growth phases. Wheat yield improvements between 20% and 55% have been widely documented using nano-urea, nano-NPK, and nano-DAP applications compared to conventional fertilizers (Goyal *et al.*, 2025; Rajput *et al.*, 2023). Enhanced spike development, increased tillering, and better grain filling associated with steady nitrogen supply

underpin these gains. Similarly, rice crops experience 20% to 40% higher yields with nano-formulated nitrogen and zinc, through improved panicle number and grain filling (Kale & Gawade, 2021; Mejias *et al.*, 2021). The sustained phosphorus availability contributed by nanophosphate formulations reduces nutrient limitation during critical reproductive stages. Maize biomass and grain yields are bolstered by 20-40% through combined nano-nitrogen and nano-zinc treatments, which enhance kernel size, cob length, and nutrient assimilation efficiency (Nongbet *et al.*, 2022; Rajput *et al.*, 2023). Foliar nano-sprays timed to key developmental stages improve nutrient translocation and stress resilience. Vegetables and tuber crops such as potato also benefit, showing 25-40% yield increases linked to nano-NPK applications that enhance nutrient availability and reduce chemical input needs (Rajput *et al.*, 2023).

Crop Quality Improvements Enabled by Nanofertilizers:

Improved yield must be complemented by quality enhancements to ensure nutritional and market value. Nanofertilizers enhance crop quality by:

- **Micronutrient Enrichment:** Nano-zinc and nano-iron applications raise grain and fruit micronutrient concentrations by 20-30%, addressing 'hidden hunger' micronutrient deficiencies in human populations (Kale & Gawade, 2021; Yadav *et al.*, 2023). Biofortified staple crops with higher zinc and iron content improve nutritional security.
- **Protein Content Enhancement:** Sustained and optimized nitrogen supply through nanofertilizers enables increased protein synthesis during grain development. In wheat and maize, protein content rises by 10-15%, improving food quality (Gopinath *et al.*, 2025; Mejias *et al.*, 2021).
- **Antioxidant and Functional Metabolite Augmentation:** Nanofertilizer treatments increase antioxidant enzymes and phenolic compounds contributing to stress tolerance, shelf-life extension, and enhanced sensory qualities in fruits and vegetables (Nongbet *et al.*, 2022).
- **Physical Quality Attributes:** Increased grain size, weight, improved tuber shape and firmness, and better colour and aroma in vegetables result from optimized nano-nutrient delivery and plant metabolic health (Rajput *et al.*, 2023).

Underlying Physiological and Biochemical Processes:

Nanofertilizers modulate several key physiological and biochemical pathways:

- **Root Growth and Nutrient Uptake:** Enhanced root proliferation and hyphal development increase nutrient and water absorption surface area, aiding biomass accumulation and grain filling (Yadav *et al.*, 2023).
- **Improved Photosynthesis:** Maintenance of chlorophyll content and photosynthetic enzyme activities ensures robust carbon assimilation, energy production, and biomass synthesis critical for yield (Mejias *et al.*, 2021).
- **Antioxidant Defense:** Nano-enabled micronutrients enhance antioxidant enzyme function, protecting chloroplasts and cellular organelles from oxidative stress during critical development phases (Nongbet *et al.*, 2022).
- **Hormonal Regulation:** Nanoparticles influence phytohormones (auxins, cytokinins), affecting cell division, elongation, and reproductive organ development, ultimately enhancing yield components (Goyal *et al.*, 2025).

Application Strategies and Timing for Maximal Benefit: Nanofertilizers can be applied via soil incorporation, foliar sprays, seed/seedling roots/tuber soaking, or fertigation, with each method influencing efficacy. Foliar nano-urea sprays during tillering and panicle initiation stage maximize nitrogen uptake particularly under water-stressed or infertile soils (Nongbet *et al.*, 2022).

Seed priming with nanonutrient solutions enhances germination and early seedling vigor, establishing a foundation for higher yield (Yadav *et al.*, 2023). Soil-applied slow-release nanoformulations provide steady nutrient supply across crop life cycle with fewer applications, reducing labor and costs (Rajput *et al.*, 2023).

Integration with precision agriculture tools (remote sensing, soil sensors) facilitates tailored, site-specific nanoformulation application, optimizing nutrient use and yield responses (Mim *et al.*, 2025).

Regional and Crop-Specific Responses: While the overall trend supports yield and quality improvements, response magnitude varies by crop species, soil type, and climatic conditions. Semi-arid and drought-prone zones typically show greater relative yield gains due to amelioration of moisture and nutrient stresses (Verma *et al.*, 2024).

High-rainfall and irrigated environments benefit predominantly from reduced nutrient leaching and environmental losses through controlled-release nanofertilizers (Mejias *et al.*, 2021). Cereals consistently show grain yield and quality boosts, while horticultural and tuber crops display pronounced improvements in sensory and nutritional qualities (Rajput *et al.*, 2023).

Economic and Market Implications:

Yield and quality improvements from nanofertilizers translate to higher farmer incomes due to better product quantity, reduced input costs due to higher nutrient-use efficiency, and better market prices from enhanced product quality (Rajput *et al.*, 2023). Nanofertilizer-enabled biofortification aligns with global nutrition targets.

Nanofertilizers significantly improve crop yield and quality through efficient nutrient use, physiological optimizations, and stress mitigation. Their versatile delivery modes and compatibility with digital farming advance climate-resilient agricultural productivity. Tailored applications considering regional and crop-specific conditions will maximize benefits while supporting sustainable intensification.

Economic and Environmental Benefits

Improved NUE translates into reduced fertilizer input costs through decreased application frequency and rates, lowering production cost for farmers (Rajput *et al.*, 2023). Additionally, precise nutrient targeting reduces environmental pollution from nutrient runoff, leaching, and greenhouse gas emissions (Mejias *et al.*, 2021). These benefits collectively contribute to sustainable intensification and climate-smart agricultural practices (Yadav *et al.*, 2023).

Integration with Precision Agriculture Technologies: Nanofertilizers complement precision agriculture by enabling site-specific nutrient management through sensor data and variable rate technologies (Mim *et al.*, 2025). Real-time soil nutrient monitoring facilitates adaptive dosing of nanofertilizers ensuring nutrient supply matches spatial and temporal crop requirements (Goyal *et al.*, 2025). This integration maximizes NUE gains and sustainable resource use.

Abiotic Stress Tolerance in Plants Enhanced by Nanofertilizers

Abiotic stresses—such as drought, salinity, temperature extremes, and heavy metal toxicity—pose substantial threats to global food security by adversely impacting plant growth and yield (Abdel-Aziz, 2023; Yang *et al.*, 2025). The intensification and unpredictability of these stresses under climate change necessitate advanced approaches for augmenting crop resilience. Nanofertilizers, nanoscale nutrient formulations, have emerged as promising tools that enhance abiotic stress

tolerance by improving nutrient delivery, regulating antioxidant defenses, and modulating stress-responsive physiological and molecular pathways (Goyal *et al.*, 2025; Mim *et al.*, 2025).

Challenges and Future Perspectives:

Despite substantial benefits, challenges remain regarding nanofertilizer cost, production scalability, regulatory pathways, and long-term environmental safety (Ayenew, 2024). Future research aims to develop biodegradable nanomaterials, cost-effective nanoformulations, and robust safety evaluations to foster widespread adoption.

Nanofertilizers enhance nutrient use efficiency through controlled release, increased solubility, improved plant uptake, and synergistic root-microbial interactions. Empirical evidence supports their role in reducing fertilizer use while improving yields and environmental sustainability. Their integration with precision agriculture augurs well for future sustainable food production systems.

Mechanisms Underpinning Stress Tolerance Enhancement: Nanoparticles improve plant abiotic stress tolerance primarily through:

- **Activation of Antioxidant Defense Systems:** Abiotic stresses generate excess reactive oxygen species (ROS) leading to oxidative damage of proteins, lipids, and DNA. Nanofertilizers elevate activity of antioxidant enzymes including superoxide dismutase, catalase, and peroxidase, and increase levels of non-enzymatic antioxidants such as ascorbate and glutathione, mitigating ROS toxicity and preserving cellular integrity (Kumari *et al.*, 2022; Abdel-Aziz, 2023).
- **Optimizing Nutrient Uptake and Homeostasis:** Nanofertilizers efficiently supply essential macro- and micronutrients (N, P, K, Zn, Fe, Mn), supporting metabolic functions impaired by abiotic stresses and enabling osmotic balance, enzymatic reactions, and photosynthesis under adverse conditions (Yang *et al.*, 2025; Ahmad *et al.*, 2025).
- **Regulation of Stress-Responsive Genes and Phytohormones:** Nanoparticles influence gene expression involved in stress adaptation pathways and regulate hormone levels (abscisic acid, auxins, cytokinins), facilitating enhanced root growth, stomatal regulation, and metabolic adjustments.
- **Osmotic Adjustment and Membrane Protection:** Nanofertilizers promote accumulation of osmolytes (e.g., proline, soluble sugars) that preserve cell turgor and stabilize membranes, reducing electrolyte leakage and supporting cellular homeostasis during drought and salinity stress (Abdel-Aziz, 2023).
- Protecting photosystems enable plants to sustain photosynthesis and energy production under stress, supported by improved nutrient status from nanofertilizers (Nongbet *et al.*, 2022).

Applications and Effectiveness in Specific Stresses:

Drought Stress: Si nanoparticles (SiNPs) significantly alleviate drought-induced water stress in crops like wheat and maize by improving relative water content, photosynthetic efficiency, and antioxidative capacity (Verma *et al.*, 2024; Desoky *et al.*, 2023). Nano-urea and micronutrient formulations enhance root hydraulic conductance and nutrient uptake, fostering drought resilience (Nongbet *et al.*, 2022).

Salinity Stress: Salinity stress disrupts ionic balance and increases oxidative damage. Nano-zinc oxide and nanosilicon mitigate ionic toxicity by regulating Na⁺/K⁺ ratios and activating antioxidative mechanisms. Improvements in biomass, chlorophyll retention, and enzyme activities

under saline conditions have been documented in rice and barley treated with these nanoforms (Kale & Gawade, 2021).

Temperature Stress: Heat and cold stresses damage membranes and proteins. TiO₂ nanoparticles protect chloroplast membranes and increase antioxidant enzyme activities, reducing heat stress damage. Nanosilicon aids cold tolerance by stabilizing membrane structures and osmolyte accumulation.

Heavy Metal Toxicity: Nanofertilizers also alleviate heavy metal toxicity by chelating metals, reducing their uptake, and enhancing enzymatic detoxification. Studies show silica and metal oxide nanoparticles protect wheat seedlings exposed to copper and cadmium by elevating glutathione and antioxidative enzyme systems.

Integration with Smart Precision Agriculture:

Advances in nanosensor technologies enable real-time stress monitoring and tailor nanofertilizer application accordingly, optimizing plant response and resource use efficiency. This integration promises to refine stress mitigation strategies in variable field conditions.

While nanofertilizers bolster abiotic stress tolerance effectively, challenges include assessing long-term environmental impacts, cost-effective nanoparticle synthesis, and developing regulatory standards for safety (Ayenew, 2024). Further multi-disciplinary research is essential to realize their full potential sustainably.

Climate Change Mitigation and Adaptation:

Climate change poses unprecedented challenges to global agriculture through increased frequency of extreme weather, temperature fluctuations, altered rainfall patterns, and heightened pest pressures. Sustainable agricultural intensification to meet growing food demands necessitates technologies that enhance crop productivity while reducing greenhouse gas (GHG) emissions and improving system resilience (Goyal *et al.*, 2025). Nanofertilizers, an emerging nanotechnology innovation in nutrient management, offer promising contributions to climate change mitigation and adaptation by improving nutrient use efficiency, reducing environmental losses, and bolstering plant stress tolerance (Yadav *et al.*, 2023; Mejias *et al.*, 2021).

- **Minimizing Greenhouse Gas Emissions:** Agriculture contributes approximately 30% of total global GHG emissions, with nitrous oxide (N₂O) from nitrogen fertilizer use as a major source. Conventional fertilizers often exhibit low nitrogen use efficiency, leading to excess soil nitrogen susceptible to microbial transformations producing N₂O and ammonia volatilization.

Nanofertilizers mitigate GHG emissions through controlled-release formulations that synchronize nitrogen availability to crop uptake, dramatically reducing excess soil nitrogen pools fueling emissions (Mejias *et al.*, 2021). Field studies demonstrate reductions of 20-40% in N₂O emissions using nano-urea relative to conventional urea across crops like wheat and maize (Nongbet *et al.*, 2022). Improved synchrony diminishes nitrogen losses via leaching and denitrification pathways, contributing to climate change mitigation.

Also, certain nano-enabled micronutrients (e.g., nano-silicon) modulate soil microbial communities and redox conditions, further reducing methane emissions in flooded systems like rice paddies, reinforcing GHG mitigation (Singh *et al.*, 2024).

- **Enhancing Resource Use Efficiency for Climate Adaptation:** Nanofertilizers enhance crop resilience to climate-induced abiotic stresses by ensuring efficient nutrient delivery under variable moisture and temperature regimes. Their small particle sizes improve solubility and bioavailability even under constrained conditions, reducing nutrient deficiencies that limit stress tolerance (Nongbet *et al.*, 2022).

Sustained nutrient supply fosters physiological processes such as osmotic adjustment, antioxidative enzyme activities, and photosynthetic efficiency critical for drought, salinity, and heat stress tolerance (Verma *et al.*, 2024). Silicon and zinc oxide nanoparticles enhance antioxidant enzyme production, protecting cellular functions during oxidative stress episodes induced by climate extremes (Kale & Gawade, 2021).

Improved root development and microbial rhizosphere interactions stimulated by nanofertilizers also bolster water and nutrient uptake efficiency, enhancing survival and yield stability under climate variability (Mim *et al.*, 2025).

- **Supporting Carbon Sequestration and Soil Health:** Climate-smart fertilizer practices also target soil health preservation and carbon sequestration. Controlled nutrient release via nanofertilizers reduces over-fertilization that can accelerate soil organic matter mineralization and carbon loss (Ayenew, 2024). Enhanced nutrient availability without excessive inputs fosters greater biomass production and root exudate release, assets for soil organic carbon accrual.

Moreover, nanofertilizers promote soil microbial activities essential for organic matter turnover and nutrient cycling, underpinning soil carbon stabilization processes (Kalwani *et al.*, 2022). These combined effects improve soil structure, moisture retention, and resilience to erosion, contributing to sustainable agroecosystem function amid climate pressures.

- **Integration with Digital and Precision Agriculture:** Nanofertilizers are integral to emerging precision agriculture systems that optimize input use in space and time for climate resilience. Nano sensors provide real-time monitoring of soil nutrient status, moisture, and crop physiological indicators, enabling adaptive nanofertilizer application fine-tuned to dynamic field conditions.

Such integration markedly enhances nutrient use efficiency and mitigates off-target environmental impacts, key to sustainable intensification under climate uncertainty. Digital platforms enhance farmer decision-making facilitating effective nanofertilizer use even in smallholder and resource-poor contexts.

Challenges and Future Priorities

Despite proven potentials, challenges include ensuring long-term environmental safety of nanoparticles, cost-effective production at scale, regulatory oversight, and inclusive policies supporting adoption (Ayenew, 2024; Shoukat *et al.*, 2024). Life cycle assessments quantifying net climate benefits of nanofertilizers under diverse cropping systems and geographies are critical.

Future research should focus on developing multifunctional nanofertilizers integrating nutrients with biostimulants and stress protectants, enhancing synergistic climate adaptation benefits (Mim *et al.*, 2025). Public-private partnerships and capacity building programs will be essential to disseminate climate-smart nanofertilizer technologies globally.

Nanofertilizers contribute significantly to climate change mitigation by reducing nutrient-related greenhouse gas emissions and enabling precise input efficiency. Their role in enhancing plant resilience to climate-induced abiotic stresses supports adaptation efforts. Integration with precision agriculture and sustainable soil management positions nanofertilizers as vital components for resilient and low-carbon food production systems.

Future Directions

Nanofertilizers represent a transformative advancement in sustainable agriculture, offering prospects for enhanced nutrient use efficiency, yield improvement, and environmental conservation under climate uncertainty. Yet, to fully harness their potential, ongoing research, innovation, policy support, and field implementation strategies require comprehensive future directions focusing on technological, agronomic, environmental, and socio-economic dimensions (Goyal *et al.*, 2025; Nongbet *et al.*, 2022). This section elaborates key future avenues critical for advancing nanofertilizer benefits and integration into climate-resilient agricultural systems.

- **Advanced Nanomaterial Synthesis and Customization:** Future efforts must prioritize green, cost-effective, and scalable synthesis techniques producing biodegradable and environmentally benign nanomaterials customized to specific crop nutrient requirements and agroecological conditions (Mejias *et al.*, 2021). Nanocarriers combining macro- and micronutrients with biostimulants or stress ameliorators will offer multifunctional solutions enhancing crop resilience and nutritional quality (Mim *et al.*, 2025).

Stimuli-responsive “smart” nanofertilizers that release nutrients triggered by specific soil or plant cues, such as pH, moisture, or root exudates, will enable unprecedented precision in nutrient management, reducing wastage (Yadav *et al.*, 2023). Development of such advanced systems demand interdisciplinary research bridging nanotechnology, plant physiology, and soil science.

- **Integration with Precision and Digital Agriculture:** Nanofertilizers are poised for synergy with precision agriculture technologies like remote sensing, soil nutrient mapping, and AI-driven decision support systems (Mim *et al.*, 2025). Real-time soil and crop nutrient status data will guide adaptive, site-specific nano-nutrient applications, optimizing input use and economic returns while mitigating environmental harms.

Such integration requires development of nano sensors capable of detecting soil nutrient fluxes, crop stress markers, and environmental variables, enabling data-informed fertilizer management at a micro-scale. Investment in digital infrastructure and extension services will be critical to reach smallholder farmers and ensure adoption efficacy.

- **Expanding Crop and Agroecological Coverage:** While current research predominantly focuses on major cereals and commercial crops, future work must broaden to minor crops, horticulture, spices, and medicinal plants across diverse agroecological zones, including marginal and rainfed areas prone to climate stress. Tailored nano-nutrient formulations and crop-specific protocols will maximize applicability and impact on livelihoods.

Field trials and long-term monitoring across heterogeneous soils and climate regimes will refine recommendations, promote region-specific adaptation, and build robust evidence for policymaking.

- **Environmental and Food Safety Evaluations:** Robust assessments of nanoparticle fate in soils, potential bioaccumulation, ecotoxicity, and food safety remain urgent priorities

(Ayenew, 2024; Nongbet *et al.*, 2022). Developing standards, regulatory frameworks, and safe-by-design principles will foster responsible innovation ensuring human and environmental health preservation.

Research into green synthesis using natural polymers and biodegradable nanomaterials will mitigate potential ecological risks associated with nanoparticle persistence.

- **Socio-economic Research and Extension Models:** Adoption studies analysing farmer perceptions, economic costs and benefits, and barriers across smallholder contexts are needed to design effective diffusion strategies (Rajput *et al.*, 2023). Participatory extension models coupling demonstration trials, localized training, and digital advisory services will enhance acceptance and appropriate application.

Policy incentives such as subsidies, certification for quality assurance, and inclusion in climate-smart agriculture programs will catalyse wider dissemination.

- **Multifunctionality and Integration with Biofertilizers:** Developing composite formulations integrating nanofertilizers with biofertilizers (beneficial microbes) and organic amendments offers potential for synergistic enhancement of soil health, nutrient cycling, and plant resilience (Nongbet *et al.*, 2022). Exploring molecular interactions between nanomaterials and microbial consortia will guide tailored product design maximizing benefits.

Integration supports circular bioeconomy principles and regenerative agriculture frameworks, enhancing sustainability and resilience.

Summary and Conclusion

Nanofertilizers represent a significant advancement in nutrient management, offering a scientifically robust pathway toward enhancing agricultural sustainability under increasing climate uncertainty. Their unique physicochemical properties—such as high surface area, controlled release mechanisms, and targeted nutrient delivery—enable substantial improvements in nutrient-use efficiency (NUE) compared to conventional fertilizers. This results in reduced nutrient losses through leaching, volatilization, and runoff, thereby mitigating environmental pollution and enhancing soil health.

From an agronomic perspective, nanofertilizers contribute to improved crop productivity, enhanced physiological efficiency, and greater tolerance to abiotic stresses such as drought, salinity, and temperature extremes. Their role in modulating plant metabolic pathways, stimulating root architecture, and improving nutrient uptake dynamics is particularly relevant in climate-stressed agroecosystems. Additionally, their compatibility with precision agriculture and fertigation systems strengthens their potential as a core component of climate-smart agriculture.

Environmental co-benefits include reduced greenhouse gas emissions, lower chemical load in soils and water bodies, and improved microbial activity, contributing to long-term soil resilience. Economically, reduced input requirements and enhanced yield stability can improve farm profitability, particularly for smallholder farmers facing climate variability.

However, the transition from experimental success to large-scale adoption requires addressing critical challenges. These include the need for standardized production protocols, comprehensive risk assessment frameworks, long-term environmental and toxicological studies, and clear regulatory guidelines. Capacity building, farmer awareness, and integration into existing nutrient management policies are equally essential.

In conclusion, nanofertilizers hold transformative potential to redefine sustainable nutrient management. When supported by robust policy frameworks, interdisciplinary research, and responsible deployment strategies, they can play a pivotal role in building resilient, resource-efficient, and climate-adaptive agricultural systems for the future.

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ROLE OF WOMEN EMPOWERMENT IN RURAL DEVELOPMENT

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Abstract

Women's empowerment and rural development play a crucial role in India's overall development. Sustainable development is unimaginable without improving the social, economic, and political status of women in rural India. The period from 2026 to 2030 is crucial for India, as it marks the final stage in achieving the Sustainable Development Goals (SDGs). This paper presents a detailed analysis of the current status, challenges government efforts, technological interventions, and future prospects of women's empowerment in the context of 2026–2030. The study clearly demonstrates that if education, skill development, digital inclusion, and social awareness are strengthened, women's empowerment can become the most effective means of rural development.

Keywords: Women Empowerment, Rural Development, 2026–2030, Self-reliant India, Sustainable Development

Introduction

India is an agricultural country, with approximately 65 percent of the population living in rural areas. Women form the backbone of rural society, playing crucial roles in agriculture, animal husbandry, domestic work, family decision-making, and social traditions. Despite this, women have long been deprived of education, health, employment, and decision-making. Women empowerment does not only mean providing employment to women, but also empowering them. Decision-making ability, self-respect, equal opportunities and rights The period 2026– 2030 is important because it will enable India to developed nations This is the decade that will lead us towards becoming. Concept of Women Empowerment

Meaning of women empowerment

Women's empowerment is the process by which women:

- Able to make their own decisions about their lives
- Become financially independent
- Free from social discrimination
- Participate in political and administrative processes.

Dimensions of women empowerment

- **Social empowerment** – education, health respect
- **Economic empowerment** – employment, entrepreneurship, sources of income
- **Political empowerment** – Panchayats and participation in policy-making
- **Digital Empowerment** – Access to Technology and Information

Nature of Rural Development

Rural development does not only mean increasing agricultural production, but it also includes

the following aspects:

- Poverty eradication
- Education and health services
- Infrastructure (roads, electricity, internet)
- Social justice and equality

Women in rural development driving force because they affect both the family and the community .

4. Status of rural women by 2026 State of education

- Enrolment of girls has increased, but the dropout rate is still a matter of concern.
- Participation in higher education and technical education is limited.

Economic situation

- contribute 70% to agricultural work, but land ownership is low.
- Women working in the unorganized sector do not get social security.

Health and Nutrition

- Anemia, maternal mortality and malnutrition are major problems.

2026–2030: opportunities and prospects

2026–2030 for women Transformative decade: This can happen if special attention is paid to the following points:

- Skill-based education
- Use of digital technology
- Women Entrepreneurship
- Social awareness campaign

Women Empowerment in Education and Skill Development Importance of education

Education is the cornerstone of women's empowerment. Educated women:

- Prioritizes children's education
- nutrition awareness
- Opposes social evils.

Expected improvement in 2026–2030

- Digital school for rural girls
- Skill Development Centre
- agriculture, dairy, food processing

Economic Empowerment and Rural Women Self Help Groups (SHGs)

SHGs empower women to:

- The habit of saving
- collective decision
- loan facility
- Provides entrepreneurial opportunities.

Women Entrepreneurship

Key areas for women entrepreneurship in 2026–2030 :

- Agro-based industries
- handicrafts

- Dairy and Poultry
- rural tourism

The role of digital empowerment

Digital technology for rural women **Game Changer** It can be proven:

- mobile banking
- E-marketing
- online education
- Telemedicine

Digital literacy allows women to connect to information and opportunities.

Social barriers and challenges

Major obstacles in women empowerment:

- Patriarchal thinking
- domestic violence
- illiteracy
- social stereotypes

To overcome these obstacles Legal aid, education and social movements are necessary.

The relationship between women empowerment and sustainable rural development

From Women Empowerment:

- The family income increases,
- The future of the children is secure.
- Community development is faster.

Hence women empowerment Key to sustainable rural development is.

Future Strategies (2026–2030)

- Women-centric policies
- Promoting rural women's leadership
- Digital and Financial Literacy
- Coordination of education, health and employment

Conclusion

Women's empowerment and rural development are complementary. By 2026–2030, if women are provided with education, skills, technology, and respect, India's rural areas can become self-reliant, inclusive, and empowered. Empowered women build a strong nation.

VEGETABLE GRAFTING: A REVIEW OF PRINCIPLES, MECHANISMS, AND APPLICATIONS

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Abstract

Vegetable grafting has emerged as an effective, eco-friendly, and sustainable technology for improving crop productivity, quality, and stress tolerance in vegetable cultivation. This review consolidates existing scientific knowledge on the origin, principles, grafting techniques, physiological and molecular mechanisms, mechanization, and the role of grafting in climate-resilient agriculture. Originating in East Asia, vegetable grafting has evolved into a globally adopted practice for mitigating soil-borne diseases, alleviating abiotic stresses, and enhancing crop performance. In India, its application is expanding particularly in solanaceous and cucurbitaceous crops under protected and open-field conditions. The review emphasizes the contribution of grafting to sustainable intensification, improved plant vigor, and the integration of traditional horticultural practices with modern biotechnology and engineering innovations.

Keywords: Vegetable grafting, Rootstock, Scion, Stress tolerance, Yield, Sustainability

Introduction

Vegetable grafting is a horticultural technique in which the aerial portion (scion) of one plant is physically joined with the root system (rootstock) of another compatible plant to form a composite individual. Successful graft union results in vascular continuity that enables the movement of water, nutrients, hormones, and signaling molecules between the two plant parts (Lee *et al.*, 2010). This technique is widely used to enhance plant vigor, suppress soil-borne diseases, improve tolerance to abiotic stresses, and increase yield and fruit quality.

Over the last three decades, vegetable grafting has shifted from a specialized nursery practice to a mainstream crop management strategy worldwide (Kyriacou *et al.*, 2017). It is now an integral component of protected cultivation systems, particularly for tomato, brinjal, chilli, cucumber, melon, and watermelon (Nie & Wen, 2023). The growing interest in grafting reflects its capacity to address major limitations of intensive vegetable production.

Need and Importance of Vegetable Grafting

Vegetable grafting has become crucial due to several pressures on global agriculture:

- **Soil-Borne Diseases:** Continuous monocropping has intensified problems of Fusarium wilt, Verticillium wilt, bacterial wilt (*Ralstonia solanacearum*), and Phytophthora rot in solanaceous and cucurbitaceous crops (Pradhan *et al.*, 2017).
- **Declining Soil Health:** The global ban on methyl bromide and other chemical fumigants has created the need for non-chemical disease management alternatives (Lee *et al.*, 2010).
- **Abiotic Stresses:** Climate change has increased the frequency of drought, salinity, and heat stress, necessitating robust root systems capable of maintaining physiological stability (Singathiya *et al.*, 2025).

- **Yield and Quality Enhancement:** Consumers increasingly demand high-quality, residue-free vegetables. Grafting improves nutrient uptake efficiency and enhances fruit traits such as firmness, size, color, and shelf life (Khopadeet *et al.*, 2025).
- **Sustainability:** Grafting reduces pesticide use, supports organic farming, and enhances nutrient-use efficiency.

Historical Background

The practice of grafting dates back nearly 1,500 years to ancient China, where gourds were grafted to enhance fruit size and storability. Scientific application of vegetable grafting began in Japan during the 1920s when Ukichi Takenaka grafted watermelon onto pumpkin rootstocks to manage Fusarium wilt (Kubota, 2016). Large-scale commercial adoption expanded during the 1950s in Japan and Korea due to disease pressure under greenhouse cultivation. By the 1980s, Mediterranean countries such as Spain, Italy, and Greece incorporated grafting in tomato and melon production. Presently, vegetable grafting is widely practiced in East Asia, Europe, and increasingly in South Asia (Lee *et al.*, 2010). India began grafting research in the early 2000s through the ICAR–Indian Institute of Horticultural Research (IIHR) and private nurseries, which now produce millions of grafted seedlings each year.

Principles and Methods of Vegetable Grafting

Successful grafting depends on rootstock–scion compatibility, precise alignment of vascular cambium, and suitable healing conditions including temperature, humidity, and light. Common methods include:

- **Splice (Tube) Grafting:** Both the scion and rootstock are cut at matching angles and joined with clips. This technique suits tomato, cucumber, and pepper and is compatible with automation.
- **Cleft Grafting:** A wedge-shaped scion is placed into a slit in the rootstock. This method works well for brinjal and tomato.
- **Approach Grafting:** Both plants remain connected to their roots until the graft heals, commonly used for woody species and research.
- **Side Grafting:** Used for thicker stems and certain cucurbits.

Healing usually requires 5–7 days at 25–28 °C and 90–95% relative humidity (Lee *et al.*, 2010). Recent automation systems can perform up to 900 grafts per hour with success rates exceeding 98%, making grafting economically feasible at commercial scale (Yu *et al.*, 2025).

Physiological and Molecular Mechanisms

Graft union formation begins with callus development at the cut surfaces, followed by differentiation of new xylem and phloem tissues. Plant hormones such as auxins, cytokinins, gibberellins, and abscisic acid regulate this process (Nie & Wen, 2023). Molecular studies reveal that messenger RNAs, small RNAs, proteins, and metabolites are transported across the graft junction, influencing gene expression and stress tolerance in the scion (Kyriacou *et al.*, 2017).

Rootstocks enhance scion performance by:

- Improving uptake of N, P, K, Ca, and Mg
- Modulating hormonal balance
- Enhancing antioxidant enzyme activity
- Maintaining water relations under stress

These interactions confer greater resistance to drought, salinity, and heat stress while sustaining fruit yield and quality.

Advantages of Vegetable Grafting

a) Management of Biotic Stresses

Grafting effectively reduces soil-borne pathogens like *Fusarium oxysporum*, *Verticillium dahliae*, *Ralstonia solanacearum*, and *Phytophthora capsica* (Pradhan *et al.*, 2017). Disease-resistant rootstocks provide both physical and biochemical barriers that limit the spread of pathogens.

b) Tolerance to Abiotic Stresses

Vigorous root systems enhance water and nutrient transport, improving tolerance to salinity, drought, and temperature extremes (Singathiya *et al.*, 2025).

c) Yield and Quality Enhancement

Grafted tomato plants yield 30–50% more fruit, while cucurbits show increases of 20–40% compared to non-grafted plants (Khopade *et al.*, 2025). Fruits from grafted plants typically offer better firmness, flavor, and nutrient content.

d) Environmental Sustainability

Grafting eliminates the necessity for soil fumigants like methyl bromide, aligning with global bans and sustainable agriculture objectives. It also lessens pesticide reliance and supports organic and hydroponic systems (Lee *et al.*, 2010).

Mechanization and Automation

Labour costs account for 40–50% of grafted seedling production. Robotic grafting systems developed in Japan and Korea employ machine vision and automated cutting units (Yu *et al.*, 2025). India is progressing with semi-automatic grafting tools for tomato, cucumber, and chilli through ICAR partnerships with private nurseries. Automation guarantees uniformity, speed, and consistency, enabling large-scale seedling production for commercial farms.

Role in Climate-Resilient and Sustainable Agriculture

Climate change has intensified salinity, heat waves, and water scarcity. Grafting provides a rapid, non-transgenic solution for improving physiological resilience. Grafted tomato plants show 46–50% higher yield and improved water-use efficiency under polyhouse conditions (Khopade *et al.*, 2025). Cucumber grafted on pumpkin rootstock tolerates saline soils by restricting sodium uptake (Singathiya *et al.*, 2025). Brinjal rootstocks enhance antioxidant activity under drought stress.

Challenges and Future Prospects

Despite its success, grafting encounters challenges:

- High production costs and the need for skilled labor.
- Limited compatible rootstocks for various plant types.
- Physiological incompatibility that can affect yield or flavor.
- Lack of awareness among small-scale growers.

Future plans include:

- Developing multi-stress tolerant rootstocks through molecular breeding.
- Implementing marker-assisted selection to forecast graft compatibility.
- Integrating AI and robotics for full automation (Yu *et al.*, 2025).

Conclusion

Vegetable grafting is a scientifically validated and environmentally sustainable technology that improves crop productivity and resilience. By combining traditional horticultural practices with modern biotechnology and automation, grafting contributes to climate-smart, high-value vegetable

production. Wider adoption supported by research, mechanization, and policy incentives will strengthen sustainable vegetable farming systems.

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AGRICULTURAL MARKETING REFORMS AND STRUCTURAL TRANSFORMATION IN INDIA: A POST-LIBERALIZATION SCENARIO

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Abstract

Agricultural marketing reforms in India have intensified in the post-liberalization era to enhance market efficiency, improve price realization and raise farmers income. The traditional APMC regulated system was marked by fragmented markets, high transaction costs, limited competition and inadequate infrastructure, constraining farmers access to remunerative markets. Successive policy interventions including the model APMC Act 2003, e-NAM 2016, Model Contract Farming Act 2018 and the 2020 Farm Laws sought to liberalize agricultural trade, promote private participation strengthen value chains and enable nationwide market integration. These reforms aim to reduce intermediation, improve transparency and facilitate efficient price discovery. Notwithstanding this effort the long-term effectiveness of this reform depends on the coherent implementation, institutional capacity and the ability to balance the interests of farmers, consumer and other stakeholders.

Introduction

Agricultural marketing in India has undergone significant changes since independence, driven by the need to improve efficiency and increase farmer income. The concept of agricultural marketing encompasses all activities involved in moving goods from production to consumption, creating time, place, form, and possession utilities. The controlled agricultural markets in India have its roots in the British colonial era, with the first regulated market established in 1886 in Karanjia. The Berar Cotton and Gramin Market Act of 1897 became a model for subsequent legislation across the nation. The Royal Commission on Agriculture's 1928 report highlighted the necessity for regulated markets to address chaotic conditions in agricultural produce markets.

Necessity of Reforms

The number of issues made the necessity of agricultural marketing reforms evident. India achieved impressive growth in agricultural production since independence, with foodgrain production increasing from 51 million tonnes in 1950-51 to 329 million tonnes in 2022-23. However, markets became highly fragmented due to APMC Acts of various states, hindering proper market access for farmers and infrastructure development (DMI). Despite an increase in the number of regulated markets from 236 in 1951 to 7,566 in 2006, there were not enough markets to handle the growing agricultural produce.



Fig 1.1 Drivers of the need for Agriculture Marketing Reforms

High market fees and charges, with APMCs authorized to collect fees ranging from 0.50% to 2.0% of the sale value, plus additional commission charges and other fees, led to total charges reaching about 15% of the produce value in some states. Infrastructure in markets remained underdeveloped despite market taxes, only two-thirds of regulated markets had covered and open auction platforms, and less than one-tenth had cold storage units. Post-harvest losses were significant, with a 2015 study by CIPHET-ICAR finding that the economic value of quantitative losses for 45 major crops/commodities was around Rs. 92,651 crores. The licensing system for commission agents in regulated markets led to monopolies, creating entry barriers for new entrepreneurs and stifling competition. Intermediation costs in India's agriculture supply chain are a significant concern, with a high number of intermediaries contributing to increased final costs. The inefficiencies in the supply chain led to spoilage rates of 25% to 30%. Farmers often did not have market information, as traders and commission agents withheld it, leading to sales to local middlemen at unfavourable prices. Despite improvements in formal credit access, informal credit channels still leading Indian agriculture. From 1951 to 2013, the portion of institutional credit agencies increased from 10.2% to 64%, but non-institutional agencies continued to play a significant role.

Agricultural Marketing Reform Implemented:

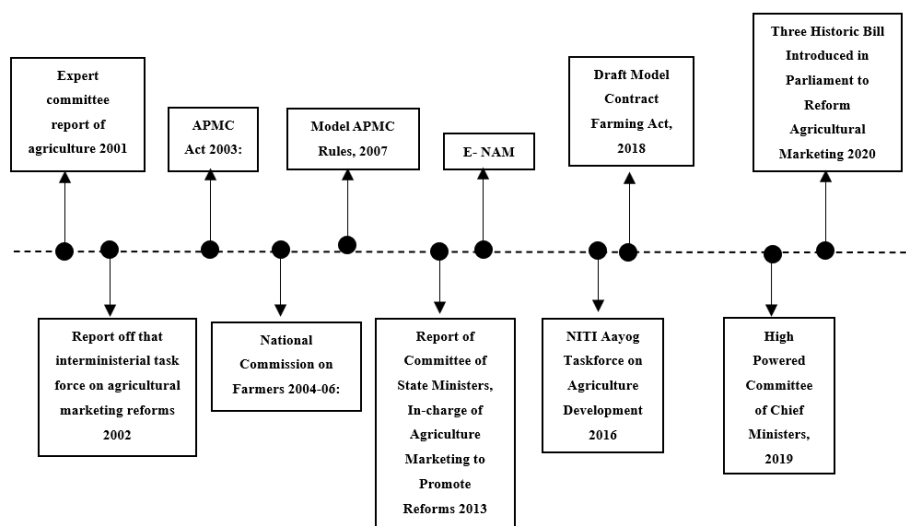


Figure 1.2 Timeline of Agriculture Marketing Reforms in India

The Liberalization, Privatization, and Globalization (LPG) reforms introduced in 1991 had significant impacts on Indian agriculture. While they facilitated the availability of modern agricultural technologies and opened up international markets for Indian agricultural exports, they also led to negative consequences such as the crash in domestic crop prices and increased input costs. To address these issues, the government initiated several agricultural marketing reforms, the focus remains on developing better infrastructure, policies and balancing the interests of farmers, consumers, and other stakeholders in the agricultural value chain. The success of these reforms will depend on their effective implementation and the government's ability to address the concerns of all stakeholders.

Agricultural marketing in India has undergone significant reforms over the past two decades, aiming to improve efficiency, increase farmer income, and modernize the sector. The reforms began with expert committees and task forces identifying bottlenecks in the existing system, particularly with the functioning of Agricultural Produce Marketing Committees (APMCs) and the monopolistic nature of mandis. In 2001, an expert committee chaired by Shankarlal Guru recommended comprehensive reforms, including amendments to the existing APMC Act. The committee suggested allowing private sector participation and providing farmers with greater flexibility in selling their produce. Following this, in 2002, an interministerial task force chaired by Sharad Joshi proposed similar reforms, emphasizing direct marketing, infrastructure development, and reduced market fees. Based on these recommendations, the government drafted the Model APMC Act of 2003. This act provided for direct marketing, contract farming, private and cooperative sector markets, and rationalization of market fees. It aimed to reduce the role of middlemen and ensure better prices for farmers. Sixteen states adopted reforms along these lines, paving the way for more competitive agricultural markets. The National Commission on Farmers, led by Professor M.S. Swaminathan, submitted reports between 2004 and 2006 with further recommendations. These included allowing private players to set up markets, promoting direct marketing and contract farming, reducing fees, introducing a single market fee for entire states, and encouraging the formation of Farmer Producer Organizations (FPOs). In 2007, the government introduced Model APMC Rules, which focused on the structure and functions of Market Committees, licensing procedures, dispute resolution mechanisms, and financial management of markets. These rules provided a framework for implementing the reforms suggested in the Model APMC Act of 2003.

A significant milestone in agricultural marketing reform was the launch of the electronic National Agriculture Market (e-NAM) in 2016. This pan-India electronic trading portal aims to unify agricultural markets nationwide by creating a central online platform for price discovery. The e-NAM system has since expanded to cover 1,389 markets across 23 states and 4 union territories, promoting transparency and efficiency in agricultural trade.

The NITI Aayog Taskforce on Agriculture Development in 2016 further emphasized the need for adopting the model Agriculture Produce and Livestock Marketing (APLM) Act, expanding e-NAM, and developing efficient value chains for agricultural commodities. In 2018, the government introduced the Model Contract Farming Act to encourage buyer support for producers and protect farmers' land rights. This act aimed to simplify contract farming arrangements and provide a more balanced framework for farmers and buyers to engage in pre-harvest agreements. In 2019, a High-Powered Committee of Chief Ministers was set up to discuss measures to transform agriculture and raise farmers' income. This committee was tasked with suggesting modalities for the adoption and implementation of various reforms by states and union territories.

The pace of reforms accelerated in 2020 with the enactment of three significant bills in Parliament. The Farmers' Produce Trade and Commerce (Promotion and Facilitation) Act 2020 (FPTC Act) allows farmers to sell their produce outside of APMC mandis anywhere in the country. This act aims to create a more competitive market and provide farmers with additional selling options. The Farmers' Empowerment and Protection Agreement on Price Assurance and Farm Services Act 2020 (APAFS) simplifies contract farming arrangements. It focuses on guaranteeing predetermined prices for farmers' produce and providing farm services and inputs. The act includes provisions to protect farmers' interests and establishes a dispute resolution mechanism at the local level. The Essential Commodities (Amendment) Act 2020 modifies the government's ability to regulate the supply of essential commodities. It sets specific criteria for imposing stock limits and aims to encourage private investment in storage and logistics infrastructure.

These reforms have been met with both support and opposition. Proponents argue that they will lead to better price realization for farmers, reduce intermediaries, and attract private investment in agricultural infrastructure. Critics, however, express concerns about the potential weakening of the APMC system and the Minimum Support Price (MSP) mechanism. The government has emphasized that these reforms do not mandate the closure of APMC markets or eliminate the MSP system. Instead, they aim to provide farmers with more options and create a more competitive environment. The reforms are expected to benefit smallholder farmers by creating opportunities for diversification into high-value crops and facilitating direct sales to consumers or processors. Successful examples of contract farming, such as Nestlé's partnership with dairy farmers in Punjab, demonstrate the potential benefits of these reforms. This long-standing arrangement has provided farmers with technical guidance, inputs, and a stable market for their produce. As India continues to implement these agricultural marketing reforms, the focus remains on balancing the interests of farmers, consumers, and other stakeholders in the agricultural value chain. The government's ability to address concerns and fine-tune the implementation of these reforms will be crucial in determining their long-term success and impact on the agricultural sector.

Conclusion

Agriculture marketing reform in India has evolved significantly since independence addressing the challenges such as market fragmentation, high market fees and inadequate infrastructure. The reforms accelerated the post liberalization aim to improve efficiency, increase farmers income. Key initiative including the model APMC Act of 2003, e-Nam in 2016 and the 2020 farm law. These reforms focus on allowing the private sector participation, direct marketing, contract farming and creating a unified national market. While proponents argue these changes will benefit farmers through better price realization and reduced intermediaries, critics express concerns about weakening the APMC system and MSP mechanism. The success of reforms hinges on effective implementation and balancing stakeholder interest. As India continues to modernise its agricultural sector the focus remains on the developing better infrastructure, policy to support the farmer and improved overall agriculture.

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CLIMATE CHANGE AND ITS EFFECT ON AQUACULTURE

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Abstract

Aquaculture is one of the fastest-growing sectors of the food production industry, yet it is seriously threatened by the unavoidable impacts of climate change. The current investigation examines how aquaculture production is affected by climate change and provides need-based solutions for its sustainable management with an emphasis on climate-resilient techniques. In this article, innovative scientific studies and climate-resilient aquaculture tactics are meant to increase the adaptability of aquaculture methods. The study focuses at the many ways that climate change affects aquaculture, including changes in water temperature, rising sea levels, acidity of the ocean, dangerous algae blooms, harsh weather, and changes in biological dynamics.

Introduction

There is mounting evidence in recent years that climate change and increased unpredictability, especially catastrophic conditions like droughts and floods, can have a major global influence on water quality. Increased precipitation intensity, longer periods of time during low flows brought on by rising temperatures, and deteriorating water quality are all signs of how climate change is affecting aquatic ecosystems and human health. Food production is threatened in terms of both quality and quantity due to climate change. Numerous climatic factors have the potential to impact future food production and human food demands, and many developing nations, particularly those experiencing poverty, are extremely concerned about the effects of these changes. Following the release of the Intergovernmental Panel on Climate Change's Fourth Assessment Report, much focus has been placed on the threats that climate change poses to human society and its natural resources. As the frequency and intensity of storms and rainfall increase, it is clear from recent events that both semi-arid and arid regions are getting drier. Furthermore, there is a tendency toward larger extremes in both dry and semi-arid regions.

The effects of climate change have been receiving a lot of attention lately, partly because of the importance of aquaculture to global nutrition, food security, and livelihoods due to the industry's substantial contribution to international trade. Since the aquaculture sector is now heavily reliant on the weather, climate change may endanger the sector's capacity to develop and produce fish in the future. Numerous fish species are predicted to suffer in the future due to the warming of ocean and inland surface waters, sea level rise, and glacier melting.

According to data and analysis, these factors generate greenhouse gasses that tend to shade the earth, causing floods, global warming, and ozone layer depletion. Increased frequency and severity of droughts, floods, and other extreme weather events are among the predicted effects, which will put further pressure on infrastructure, food security, infrastructure, health, and water resources. A significant danger to the stability and productivity of aquaculture operations across the world is posed by these issues taken together. The purpose of this study was to offer helpful details on

climate-smart solutions that might improve aquaculture's sustainability. Aquaculture systems can adapt to and lessen the effects of climate change by using techniques and tactics that are identified and evaluated.

Climate change's effects on aquaculture production systems

Aquaculture output is directly and indirectly impacted by climate change, which has both immediate and long-term effects on the industry. Rising temperatures, ocean acidification, toxic algal blooms, and other effects of climate change can have a direct impact on the physiological and physical traits of shellfish and finfish. Among the implications of climate change on aquaculture include decreased output, unexpected mortality, and changes in spawning seasons and quantity.

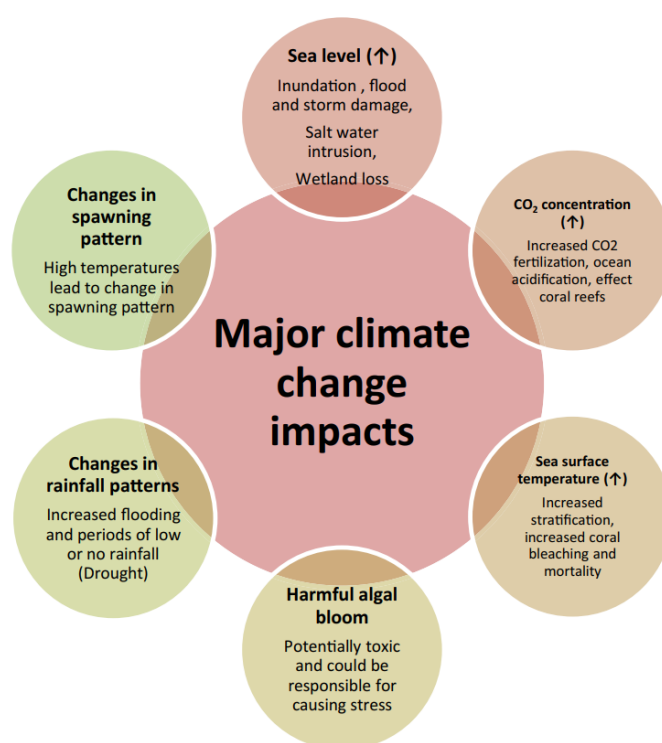


Fig.1 Major climate change impact on aquaculture

Temperature increase

Fish and aquatic invertebrates are examples of aquatic species that are poikilothermic, meaning that their internal temperatures vary in relation to the water's surrounding temperature. Their survival depends heavily on their sensitivity to temperature fluctuations outside of their typical environment. Numerous finfish and shellfish species are expected to be impacted, along with their physiology, metabolism, feeding patterns, and growth performance. The impacts of rising temperatures and global warming affect pond aquaculture. Many research suggests that increasing temperatures in freshwater ponds may have negative effects on the ecology, such as altering how the ponds work together. Heat-tolerant cyanobacteria in ponds can develop quickly as a result of global warming, causing extreme eutrophication from increased temperatures and pollution. Even other cyanobacteria species are impacted by massive cyanobacteria blooms in eutrophic ponds, which decrease diversity. As shown in streams, higher temperatures, like those brought on by the Urban Heat Island (UHI) effect, may drastically change the growth season for aquatic life. A slight rise in water temperature (1-2 °C) may have sub-lethal physiological consequences on tropical fish.

Effects of rising temperatures on the health of aquatic animals

Temperature variations are anticipated to have unexpected effects on aquaculture-related bacterial, parasite, viral, and fungal illnesses. Rising temperatures may promote the spread of exotic diseases, and heat stress increases the susceptibility of cultured animals to disease. Increases in water temperature can directly affect fish and their diseases, but multivariate environmental change may have unanticipated impacts on both. The incidence and severity of the disease may increase, decrease, or simply fluctuate across time and space depending on the combined impact of all three interconnected components. Climate change will most certainly have an effect on disease emergence by making certain diseases more common in already-existing regions and bringing them to new ones. Climate change is predicted to impact the aquatic ecosystem and increase factors that encourage the entry of exotic fish species, increasing the likelihood of the establishment and spread of exotic parasites and diseases. Rising temperatures are predicted to enhance the replication rate, virulence, duration of life cycles, and transmission of infections in a number of finfish and shellfish species. In aquaculture, rising temperatures may potentially increase the development of epizoonotic illnesses, posing major financial challenges. In many parts of the world, epizootic disease outbreaks are already one of the main challenges to the viability of aquaculture production systems.

HABs

Many scientific studies have focused on the impact of HABs on climate change, particularly warming. In order for a HAB to increase in a particular area, temperatures below those that enable maximal growth must exist. This is a prerequisite for higher temperatures increasing the intensity of the HAB. As water temperatures get closer to the ideal range for HAB development, it has been noted that these blooms become more intense. From an environmental perspective, algal bloom poses a major danger to the sustainability of aquaculture output. According to certain reports, the taxonomic groupings of flagellates and dinoflagellates, together with other dangerous species, may be poisonous and might be the cause of stress or even death in shellfish and finfish. According to some research, fish and bivalve mollusks may experience necrosis, atrophy, and inflammation of various animal organs as a result of harmful algal blooms. Based on multiple case studies, the HABs caused by cyanobacterial blooms in freshwater are the most evident example of warming-induced intensification. These blooms show that the temperatures that yield maximum growth rates for many cyanobacterial HABs are evenly higher than those that yield maximum growth rates for non-harmful eukaryotic algae. The water column experiences simultaneous hypoxia and acidification during the spring diatom blooms in temperate latitudes because surface waters quickly warm and stratify, preventing incoming water with dissolved oxygen and lower CO₂ concentrations from reaching the bottom waters.

Sea level increase

The susceptibility of many coastal ecosystems, such as coral reefs and coastal wetlands like salt marshes and mangroves, to sea level rise or direct effects from human activity has come to light in recent decades. A graphic depiction of the direct and indirect effects of climate change on aquaculture is provided in Fig. 2. In reaction to the consequences Freshwater cultivation methods are becoming increasingly susceptible to rising sea levels and an increase in saline incursions upstream as a result of climate change. Sea level rise may cause salty water from rising sea levels to overwhelm aquaculture equipment, such as ponds, cages, tanks, and pens, particularly in lowlands and coastal locations. Sea level rise will have a significant effect on estuarine zones,

including biotic changes and salty water incursion. These will have a negative effect on coastal ecosystems, such as mangroves, salt marshes, and other areas crucial to maintaining wild fish populations and supplying aquaculture seeds. According to earlier studies, intertidal habitat is predicted to decline by 13 to 64% over the course of the next century due to sea level rise in ecologically sensitive bays with steep topography and man-made features like sea walls. Because of the steep terrain and man-made features (such sea walls), mudflats and sandy beaches do not move inward. Aquaculture operators can shift their operations upstream, create or switch to more salt-resistant strains of these species, or import species that can withstand high salinity in order to adjust to environmental changes. The expense of such changes and their impact on the socioeconomic standing of the communities involved are undeniable.

Rainfall pattern

Typhoons, hurricanes, and unplanned floods have damaged cage culture systems along rivers and lakes and caused large-scale economic losses in recent years, which has led to the escape of numerous finfish. According to a study by Schewe and Levermann (2012), the rise in temperatures in the late 21st and early 22nd centuries is expected to cause regular fluctuations in monsoon precipitation levels, which might drop by as much as 70% below average. Excessive monsoon flooding has become a problem in some places of Southeast Asia in recent years and has to be addressed. Extreme weather, poor water quality from plankton blooms, and destructive discharge from floods are just a few of the negative consequences of climate change that cause structural damage and force aquaculture enterprises to relocate. Floods, which are categorized as natural catastrophes, affect aquaculture productivity and earnings when water floods in typically arid locations. Flooding alters the fish populations' natural habitats or makeup in a given location. The number and distribution of different fish species that are farmed or produced for aquaculture purposes have changed as a result. Farmers reported higher Indian major carp (IMC) death rates as a result of low dissolved oxygen levels following rains on hot summer days. Fish movement from one pond to another after storms or significant floods was also seen. Additionally, floods disrupt the food chain in the river, which has a negative impact on fish populations. A hazard to public health, economic stability, and international commerce can occasionally arise from water stress, which varies greatly throughout areas. Furthermore, it may serve as a trigger for major migrations and wars.

Ocean acidification

Although there is far less information available than on temperature changes, an increase in ocean salinity may be an indirect but sensitive indicator of several climate change processes, such as precipitation, evaporation, river runoff, and ice melt. Ocean acidification is caused by a number of reasons, including rising atmospheric CO₂, which the oceans absorb and cause low pH levels. The most common exchange of CO₂ with the atmosphere occurs in the seas. Nearly half of the CO₂ emissions from cement manufacturing and fossil fuel combustion during the last 200 years, since the start of industrialization, have been absorbed by the seas. This demonstrates the vital role that oceans play in the "carbon cycle," which is the term for the natural processes that cycle carbon worldwide. This subject is beginning to get a lot of attention in various parts of the world's scientific community, including at the 2004 UNESCO conference on the Oceans in a High-CO₂ World. It is very well known what chemical processes occur when CO₂ is drawn from the atmosphere and dissolved in seawater. However, little is known about the chemical and biological processes that underpin marine life. Therefore, predicting the consequences of ocean acidification is a challenging yet crucial undertaking. Some marine species have weaker calcified skeletons and/or lower net calcification

rates as a result of a drop in the calcium carbonate saturation state, which has been linked to rising OA, according to several studies. Ocean acidification is expected to have an impact on consumer choices as well as the physiological, organoleptic, and nutritional traits of commercial species.

Effect in biodiversity

As a result of climate change's effects on biodiversity, native species are competing with them for resources and habitat, changing habitats, spreading pathogenic organisms, and causing genetic interactions through introgression and hybridization. Local biodiversity may be impacted as a result of fish species moving to other areas with better climatic conditions due to rising temperatures and changing ocean currents. Fish reproductive cycles are disrupted by climate change, which also modifies spawning habits and breeding seasons. Population dynamics and biodiversity may be impacted by warmer seas as certain species may develop more quickly while others may grow more slowly. Fish breeding, feeding, and nursery habitats are diminished by habitat loss, which lowers population variety and abundance. Furthermore, it is asserted that genetic drift and selective breeding methods have altered the genetic makeup of aquaculture populations, occasionally resulting in severe inbreeding. By means of genetic mutation between the wild equivalents and the fugitives, Such modifications may affect the gene pools of the natural animals and their equivalents in culture.

Climate change's effects on fish physiology, breeding and spawning

Variations in temperature, acidity, hypoxia, and pluviosity regimes brought on by global climate change are anticipated to have an impact on fish reproductive behavior. Due to thermal stress brought on by the anticipated 1.5 °C increase in global temperature this century, fish, particularly those from colder waters like the Atlantic halibut, salmon, and cod, as well as intertidal shellfish, are expected to die at higher rates. Thus, extended temperature stress may have a variety of effects on aquaculture production, with a particular emphasis on lower output. Chronic stress can alter the immune systems, cardiorespiratory systems, and aerobic capacity of a number of economically significant species. Climate change has long-term effects on aquatic creatures' physiology, development patterns, and behavior that reduce their geographic range and impair their capacity for reproduction. One of the most detrimental effects of climate change, the harm that high temperatures do to the gonads. Elevated temperatures can have irreversible effects on fish during sensitive early developmental stages, impacting sex differentiation/determination, larval growth, and the frequency of malformations. This can lead to functional masculinization in fish. Climate change is already having an impact on early life cycle events and reproduction in the majority of fish. In order to do this, many kinds of systems at different levels are involved, and as our knowledge of them grows, they become more complicated.

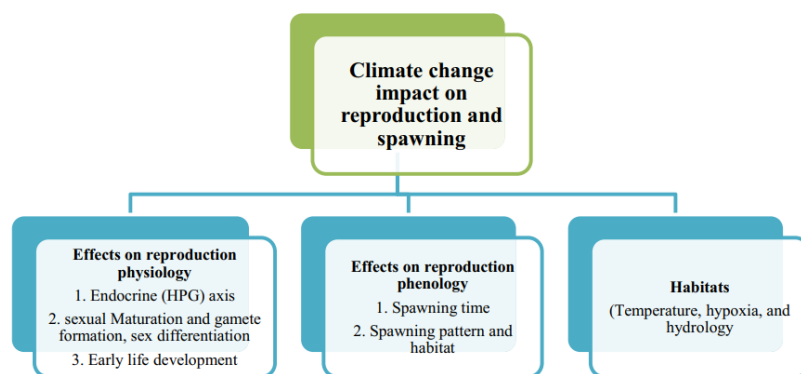


Fig.2 Climate change impact on spawning

The timing of spawning, the degree to which extreme temperature events cause physiological stress, the fish's energy reserves and reproductive maturity, its previous exposure to temperature fluctuations, and its ability to adapt are all important factors that can be impacted by thermal challenges during the reproductive cycle. In both freshwater and marine animals, the process of spawning and successful reproduction is essentially controlled by evolutionary mechanisms. In order to reproduce and complete their life cycle, organisms have evolved to take into consideration the circumstances in their environment and perhaps the unpredictability of these factors. In order to promote a larva's chances of surviving to become a reproducing adult or, at the very least, reduce the disturbance brought on by unpredictable climatic events (food), spawning times and locations have evolved to correspond with the current physical (temperature, salinity, currents) and biological conditions.

Conclusion

The many effects of climate change on aquaculture have been examined in this article, emphasizing the urgent need for sustainable management techniques. The data presented in this analysis highlights how aquaculture is vulnerable to climate change, which is shown in temperature fluctuations, ocean acidity, and an increase in the frequency of extreme weather events. The productivity, sustainability, and socioeconomic worth of aquaculture are seriously threatened by these changes. Additionally, the article emphasizes how well climate-resilient adaptation strategies work to mitigate these effects. Aquaculture can overcome the difficulties of climate change and thrive to improve global food security and livelihoods by adopting innovative techniques, technology, and policies.

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MICRONUTRIENT POWERHOUSES: THE CRITICAL ROLE OF VITAMINS IN THE HEALTH AND PRODUCTIVITY OF PIGS AND POULTRY

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Abstract

In modern intensive livestock production, vitamins are far more than just dietary supplements; they are essential regulators of life, growth, and immune resilience. While required in minute quantities, their absence can lead to devastating metabolic failures and economic losses. This article explores the classification, physiological functions, and clinical significance of fat-soluble (A, D, E, K) and water-soluble (B-complex and C) vitamins in pigs and poultry. By examining the impact of environmental stressors—such as heat stress and intensive stocking on vitamin requirements, this review highlights strategic supplementation as a cornerstone for optimizing animal welfare and production efficiency in a challenging global market.

Keywords: Animal Nutrition, Fat-soluble Vitamins, B-complex, Immune Function, Oxidative Stress, Poultry Management, Swine Health.

Introduction

Vitamins are organic nutrients that serve as the silent engines of metabolic machinery. In the fast-paced environment of modern pig and poultry farming, animals are pushed to their genetic limits, making them highly susceptible to nutritional imbalances. Unlike macronutrients that provide energy or structural building blocks, vitamins act primarily as cofactors for enzymes, antioxidants to combat cellular damage, and regulators of gene expression. As stressors—ranging from temperature fluctuations to social competition—become more prevalent, the traditional "minimum requirement" approach to vitamin nutrition is evolving into a strategy of "optimal supplementation" to safeguard animal health and ensure high-quality food products for human consumption.

Classification and Metabolic Pathways

Vitamins are broadly classified into two categories based on their solubility, which dictates how they are absorbed, stored, and excreted by the animal.

- **Fat-Soluble Vitamins (A, D, E, and K):** These are absorbed alongside dietary fats and stored in the liver and adipose tissues. Because they are stored, they can provide a reservoir during short-term deficiency, but they also carry a risk of toxicity if over-supplemented.
- **Water-Soluble Vitamins (B-complex and C):** These vitamins act in the cytosol or extracellular fluids. Because they are not significantly stored in the body (with the exception of B12), they must be supplied daily in the diet or through microbial synthesis in the gut.

The Pillars of Health: Fat-Soluble Vitamins

The fat-soluble group is primarily responsible for structural integrity and systemic regulation:

- **Vitamin A (Retinol):** Often called the "anti-infective" vitamin, it is crucial for maintaining mucosal integrity. In poultry, a deficiency leads to "nutritional roup," characterized by discharge from the eyes and nostrils.

- **Vitamin D (Calciferol):** Essential for Calcium and Phosphorus homeostasis. Without adequate Vitamin D, young birds and pigs develop rickets, characterized by soft, rubbery bones and poor growth.
- **Vitamin E (Tocopherol):** The primary biological antioxidant. It works synergistically with Selenium to protect cell membranes from oxidative damage, particularly in high-performing muscles and reproductive organs.
- **Vitamin K:** The "coagulation vitamin," essential for the synthesis of prothrombin. In commercial settings, supplemental Vitamin K is vital to prevent internal hemorrhaging, especially when anti-vitamin factors are present in the feed.

The Engine Room: Water-Soluble Vitamins

The B-complex vitamins and Vitamin C are the drivers of energy metabolism and stress resistance:

- **Energy Release:** Vitamins like B1 (Thiamine), B2 (Riboflavin), and B3 (Niacin) are fundamental to the Krebs cycle, converting carbohydrates and fats into usable energy for growth.
- **Neurological Health:** Pyridoxine (B6) and B12 are critical for nerve function. A deficiency in Riboflavin in chicks, for example, results in "curled-toe paralysis," a classic sign of peripheral nerve degeneration.
- **Folic Acid and Biotin:** These are essential for DNA synthesis and skin/feather integrity. In pigs, Biotin is the gold standard for preventing hoof lesions and maintaining reproductive longevity in sows.
- **The Vitamin C Paradox:** While pigs and poultry can synthesize Vitamin C endogenously, intensive production conditions often exhaust these stores. Supplemental Vitamin C is a proven intervention during heat stress, helping to lower cortisol levels and improve shell quality in laying hens.

Navigating Stress: Strategic Supplementation

Modern farming introduces stressors that "old" nutritional standards did not account for. Environmental heat, social stress during weaning in pigs, and the rapid growth rates of modern broiler genetics increase the production of free radicals.

- **Immune Strength:** Targeted levels of Vitamin E and C enhance the primary immune response to vaccinations, ensuring better flock and herd protection.
- **Reproductive Performance:** In boars and sows, high-level vitamin nutrition improves semen quality and fetal development, directly impacting the number of weaned pigs per sow per year.

Conclusion

Strategic vitamin nutrition is not merely a supportive measure; it is an essential foundation of modern animal management. While these nutrients are required in micro-amounts, their impact on macro-outcomes—growth, fertility, and disease resistance—is profound. By understanding the specific roles of fat- and water-soluble vitamins and adjusting supplementation to meet the demands of environmental stressors, producers can achieve a balance of animal welfare and economic profitability. In the future of "Precision Nutrition," vitamins will remain the key to unlocking the full genetic potential of livestock.

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