TABLE OF CONTENTS

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Dr. Priyanka A. Dahiwale

Dr. Dilip K. Deokar

ARTICLE ID: 01

CRYPTORCHIDISM AND INFERTILITY IN LIVESTOCK: CAUSES, IMPACTS AND MANAGEMENT

In animal husbandry, reproductive efficiency is the cornerstone of profitability and sustainability. Among the various reproductive disorders that challenge livestock producers, **cryptorchidism** stands out as a major, preventable cause of male infertility and sub-fertility.

Understanding the mechanics of this condition, its direct link to infertility, and effective management strategies is essential for maintaining a genetically sound and productive herd.

1. What is Cryptorchidism?

Cryptorchidism is a developmental defect characterized by the **failure of one or both testes to descend** into the scrotum.

- **Unilateral Cryptorchidism ("Monorchid"):** Only one testis descends, while the other remains retained in the abdominal cavity or inguinal canal.
- **Bilateral Cryptorchidism:** Both testes fail to descend.

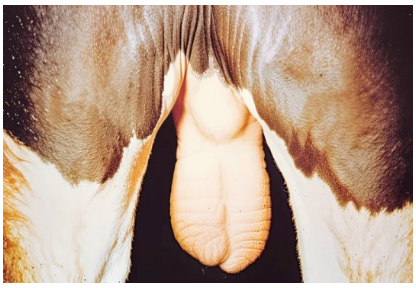
During fetal development, the testes form near the kidneys and must migrate down into the scrotum via a ligament called the *gubernaculum*. When this migration is interrupted, cryptorchidism occurs. This condition is frequently observed in stallions, boars, rams, and bulls.

2. The Link to Infertility: Why Retained Testes Fail

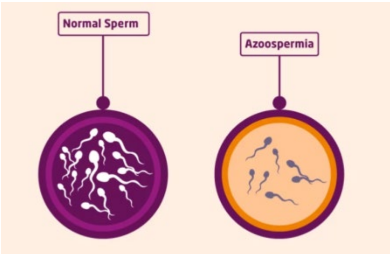
The primary function of the scrotum is **thermoregulation**. For normal spermatogenesis (sperm production) to occur, the testes must be maintained at a temperature roughly 2°C to 4°C cooler than the animal's core body temperature.

When a testis remains trapped inside the abdomen or inguinal canal, it is exposed to constant core body heat. This chronic high temperature leads to:

Degeneration of Seminiferous Tubules: The sperm-producing tissues fail to develop or undergo severe atrophy.



Azoospermia: In bilateral cryptorchids, sperm production is completely halted, rendering the animal completely **infertile**.



Subfertility: Unilateral cryptorchids can often still produce sperm from the single descended testis. However, their overall sperm count, motility, and quality are significantly reduced, leading to poor conception rates.

Note: While sperm production is compromised, testosterone production by the Leydig cells usually continues. Consequently, cryptorchid animals will still exhibit normal male libido and secondary sexual characteristics, often making them aggressive or difficult to handle.

3. Causes of Cryptorchidism

The exact cause is multifactorial, involving a combination of genetics, anatomy, and hormones.

Genetic Factors

Cryptorchidism is widely recognized as a **heritable trait**. It is generally considered a sex-limited, autosomal recessive characteristic. This means that while females do not express the condition, they can carry and pass the genes to their offspring.

Hormonal Imbalances

The descent of the testes relies heavily on hormones like testosterone and Insulin-Like Peptide 3 (INSL3), which are secreted by the fetal testes. Insufficient production of these hormones, or a lack of responsiveness from maternal hormones during pregnancy, can halt the descent.

Anatomical Abnormalities

Physical obstructions can physically block the path of descent. These include:

- An abnormally narrow inguinal canal.
- A short spermatic cord.
- Malformation of the gubernaculum ligament.

4. Measures and Management in Animal Husbandry

Because of its hereditary nature and impact on fertility, livestock managers must implement strict measures to control and mitigate cryptorchidism.

Action Item	Strategy & Implementation
Strict Culling	**Never use cryptorchid males for breeding.** Even if a unilateral cryptorchid is fertile, he will pass the genetic defect to his progeny, increasing the incidence in future generations.
Pedigree Tracking	Identify and phase out the mothers (dams) and fathers (sires) that consistently produce cryptorchid offspring, as they are carriers of the defective genes.
Surgical Castration	For meat-producing or working animals (like market hogs, market lambs, or geldings), surgical removal of both the descended and retained testes is highly recommended. This eliminates aggressive male behavior and prevents accidental, low-quality breeding.
Careful Screening	Perform thorough physical palpations of the scrotum on all young potential sires during Breeding Soundness Examinations (BSE) before purchase or selection.

Conclusion

Cryptorchidism is a costly reproductive defect that directly impairs fertility and threatens the genetic integrity of livestock herds. In animal husbandry, the most effective "treatment" is **prevention through rigorous selection**. By prioritizing sound breeding standards and culling affected animals, producers can safeguard their herd's reproductive performance and overall profitability.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Trupti Dodiya

Anand Agricultural University, Anand (Gujarat)

ARTICLE ID: 02

WEED MAT: AN EFFECTIVE TOOL FOR WEED PREVENTION

Introduction

Weeds can be a persistent challenge, as they compete with cultivated plants for nutrients, water, and light. This competition often results in reduced plant health and diminished yields. Adopting effective weed control methods is crucial to maintaining productive and thriving gardens or crops. Weed management involves a lot of manpower and cost. In many cases, plantations are overpowered by excessive weed growth. Weed mats offer an efficient solution for suppressing weed growth without relying on chemical herbicides.

What is Weed mat?

Weed mat is a specialized fabric that is made from polypropylene or a similar material. It works to spread over the soil to block the weed growth while also allowing the air, water, and nutrients to pass through.

Weed control mats are commonly used in:

- Vegetable farming
- Fruit cultivation
- Nurseries and polyhouses

Advantages of using weed mat

- Weed mat prevents weed growth in a natural way, without requiring no chemical
- This saves water and reduces evaporation by up to 40-50%
- By minimizing competition for nutrients and ensuring optimal growing conditions, weed mats can lead to healthier plants and increased crop yields.
- Using weed mats is an environmentally friendly and sustainable option
- Soil Health Maintenance
- Weed mats are simple to lay down and require minimal maintenance, making them an easy solution for long-term weed control

Selection of right weed mat

1. GSM Thickness:

Every crop requirement is different, so pick as per that. 90-100 GSM for short-term crops and 100-130 GSM for vegetables and fruits

2. UV Stabilization:

Make sure the weed mat is UV resist and capable to work in long outdoor use.

3. Climate:

Now check if the mat can handle hot climate. As it requires higher GSM and UV resistance.

4. Budget vs. Durability:

Always opt for quality over the price. Cheaper mats wear quickly, while better one comes with durability and reliability.

Tips for installing and maintaining weed mats

- **Prepare the Area**: Clear the garden area of existing weeds, rocks, and debris.
- **Cut the weed mat to size**: Lay the mat out flat and cut it according to the dimensions of your garden bed.
- **Secure the mat**: Use landscape pins or staples to secure the mat firmly into the soil.

Types of weed matting fabrics

1. Woven fabric weed mats:

These are highly durable and can be reused for multiple seasons. They allow water and air to penetrate while preventing weeds.

2. Non-Woven fabric weed mats:

These are lightweight and ideal for smaller gardens or flower beds.

3. Biodegradable weed mats:

Made from natural fibers, these mats decompose over time, offering an eco-friendly option for gardeners.

Tips for maximizing the longevity weed mats

1. Select Quality Mats:

Start with high-quality weed mats designed for longevity and durability. Consider UV-resistant options for outdoor settings.

2. Regular Maintenance:

Inspect mats for tears or displacements regularly. Promptly repair any damage to prevent weeds from finding a way through.

3. Adjust for Seasonality:

During heavy rains or strong winds, check mats more frequently. Adjust them as necessary to ensure they remain in place.

4. Compost and Debris Removal:

Clear fallen leaves or organic material from the mats to prevent decay that can weaken their structure.

5. Renew Mulch Layer:

Maintain a layer of mulch over the mats. This not only improves aesthetic appeal but also adds an extra layer of protection.

6. Monitor Plant Health:

Ensure the plants around the mats are not stressed or hindered by covered areas. Adjust if necessary to support optimal growth.

Conclusion

Weed mats provide a sustainable and effective solution for managing weeds, offering significant advantages such as reduced maintenance and healthier plant environments. Their ease of installation and long-term benefits make them an asset in both small-scale gardens and large agricultural ventures. By following appropriate installation techniques and regular maintenance practices, growers can harness the full potential of weed mats to protect crops and improve yields. Emphasizing durability and consistent care ensures these mats continue to deliver excellent results, supporting a thriving ecosystem that's beneficial for both cultivated plants and the surrounding environment.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

ARTICLE ID: 03

REVITALIZING INDIGENOUS CROPS THROUGH AGRICULTURAL EXTENSION: PATHWAYS TO SUSTAINABLE LIVELIHOODS

AUTHORS' DETAILS:

Mr. D. Lokeshwaran
Ph.D. Research Scholar
Department of agricultural Extension, Faculty of agriculture, Annamalai University, Chidambaram, Tamilnadu - 608002

Abstract

Farmers' varieties and indigenous crops represent valuable agricultural resources that contribute significantly to livelihood security, nutritional diversity, climate resilience, and sustainable agricultural development, particularly in rural, tribal, and marginal farming communities. These traditional crop varieties are often well adapted to local agro-climatic conditions and require fewer external inputs. Despite their importance, the potential of farmers' varieties and indigenous crops remains underutilized due to factors such as limited awareness, inadequate technical guidance, poor access to quality seed, weak market linkages, and lack of value addition and commercialization support. Agricultural extension plays a crucial role in addressing these constraints by designing and implementing suitable strategies that enhance farmers' knowledge, skills, and capacities. Extension strategies such as capacity building through training programmes, participatory extension approaches, on-farm demonstrations, promotion of farmer-led innovations, seed entrepreneurship, value addition, processing, branding, and establishment of market linkages are essential for improving the economic viability of farmers' varieties and indigenous crops. Institutional convergence among extension agencies, research institutions, self-help groups, farmer producer organizations, and local markets further strengthens livelihood opportunities. This paper highlights key extension strategies for enhancing livelihood opportunities through farmers' varieties and indigenous crops and emphasizes their role in increasing farm income, employment generation, and sustainable rural development.

Keywords: Agricultural Extension; Farmers' Varieties; Indigenous Crops; Livelihood Enhancement; Rural Development; Sustainable Agriculture

INTRODUCTION AND BACKGROUND

Agriculture remains the main source of income for a significant number of rural and tribal communities in India. Nevertheless, small and marginal farmers are increasingly confronted with challenges such as climate variability, decreasing soil fertility, escalating input costs, and fluctuating market prices. In this scenario, farmers' varieties and indigenous crops have received renewed focus due to their adaptability to local agro-climatic conditions, minimal input requirements, and resilience against biotic and abiotic stresses. These traditional crop resources, nurtured and preserved by farmers over generations, are vital for sustaining rural livelihoods, ensuring food and nutritional security, and maintaining agrobiodiversity.

Farmers' varieties and indigenous crops are intricately woven into local farming systems, cultural practices, and traditional knowledge. In contrast to modern high-yielding varieties, these crops often exhibit tolerance to drought, pests, and diseases, making them well-suited for marginal environments such as rainfed, hilly, and tribal regions.

They play a significant role in enhancing household food security, dietary diversity, and income generation, especially among resource-poor farmers. Despite their numerous advantages, the potential of these crops remains largely untapped due to limited awareness, insufficient extension support, inadequate seed systems, lack of value addition, and poor market integration. Agricultural extension serves a crucial function in connecting traditional knowledge systems with contemporary development processes. Extension agencies function as facilitators to improve farmers' skills, encourage farmer-led innovations, reinforce local seed systems, and connect producers with markets and institutions. By implementing suitable extension strategies such as participatory methods, capacity building, on-farm demonstrations, promotion of seed entrepreneurship, and the development of value chains, farmers' varieties and indigenous crops can be converted into sustainable livelihood options. Consequently, this paper aims to explore the significance of agricultural extension and to underscore essential extension strategies for improving livelihood opportunities through farmers' varieties and indigenous crops, with a particular focus on sustainable rural development.

FARMERS’ VARIETIES AND INDIGENOUS CROPS: CONCEPT AND LIVELIHOOD SIGNIFICANCE

Farmers’ varieties and indigenous crops denote traditional crop varieties that have been developed, selected, and preserved by farmers over generations through ongoing cultivation and informal selection methods. These varieties are specific to their locations and are closely linked to local agro-ecological conditions, cultural practices, and traditional knowledge systems. Farmers’ varieties often exhibit genetic diversity, allowing them to adapt to changing environmental conditions and endure climatic stresses such as drought, floods, and pest infestations. Indigenous crops, which include millets, pulses, oilseeds, tubers, and minor cereals, are essential components of traditional farming systems and local diets, particularly in tribal and marginal regions. The livelihood importance of farmers’ varieties and indigenous crops is rooted in their low-cost cultivation and risk-mitigating characteristics. These crops typically require fewer external inputs such as chemical fertilizers, pesticides, and irrigation, rendering them economically feasible for small and marginal farmers. Their resilience to adverse climatic conditions guarantees stable yields even in unpredictable environments, thereby minimizing production risks and income volatility. For resource-limited households, particularly in rainfed and tribal areas, these crops serve as a safety net by ensuring food security and supporting farm-based livelihoods.

In addition to generating income, farmers' varieties and indigenous crops are crucial for ensuring food and nutritional security. Numerous indigenous crops are abundant in essential nutrients such as proteins, minerals, dietary fiber, and micronutrients, thereby contributing to balanced diets. Crops like millets, indigenous pulses, and leafy vegetables are recognized for their high nutritional value and health advantages. Their consumption aids in combating malnutrition and health issues related to lifestyle, particularly among rural and tribal communities. Consequently, the promotion of these crops fosters both livelihood improvement and nutritional health. Farmers' varieties and indigenous crops also play a significant role in generating employment and diversifying livelihoods. Activities such as seed production, processing, storage, value addition, and marketing create further employment opportunities both on-farm and off-farm. Women and self-help groups are instrumental in these activities, particularly in seed conservation, processing, and the creation of value-added products. By incorporating these crops into local value chains, farming households can enhance their income streams and lessen reliance on single crops or external markets. Moreover, the conservation and promotion of farmers' varieties and indigenous crops bolster agrobiodiversity and ecological sustainability. These crops contribute to maintaining soil health, mitigating environmental degradation, and encouraging sustainable farming practices. From an extension viewpoint, acknowledging the livelihood potential of these crops presents an opportunity to formulate inclusive and farmer-centric development strategies. Therefore, farmers' varieties and indigenous crops are not merely remnants of tradition but are invaluable resources for establishing resilient, sustainable, and livelihood-focused agricultural systems.

CONSTRAINTS IN PROMOTION AND UTILIZATION OF FARMERS' VARIETIES AND INDIGENOUS CROPS

Despite the considerable livelihood, nutritional, and ecological advantages associated with farmers' varieties and indigenous crops, their widespread adoption and promotion encounter numerous obstacles. A primary challenge related to production is the restricted availability of quality seeds. Traditional seed systems are predominantly informal, and the lack of organized seed multiplication, certification, and distribution systems frequently hinders farmers' access to dependable planting materials. Consequently, farmers may face inconsistent yields, which discourages ongoing cultivation and restricts broader adoption. Another significant constraint is the insufficient technical knowledge and extension support. While many farmers have traditional knowledge concerning the cultivation and utilization of indigenous crops, this knowledge is often not scientifically validated, documented, or incorporated into formal extension programs. Additionally, extension personnel may have limited exposure or training regarding farmers' varieties and indigenous crops, resulting in inadequate dissemination of enhanced cultivation practices, post-harvest management techniques, and methods for value addition. This gap in knowledge diminishes productivity and curtails the economic potential of these crops.

Market-related limitations further impede the promotion of farmers' varieties and indigenous crops. These crops frequently experience poor market visibility, a lack of standardized grading, and the absence of organized marketing channels. Farmers often encounter challenges in accessing profitable markets and securing fair prices due to low consumer awareness, limited demand, and the prevalence of commercial crop varieties. Insufficient infrastructure for storage, processing, and transportation further limits market access, leading to distress sales and diminished profitability. Constraints related to value addition and commercialization also restrict livelihood opportunities. Numerous indigenous crops are sold in their raw state with minimal processing, resulting in low returns. Limited access to processing technologies, packaging facilities, branding assistance, and financial resources hinders farmers and rural entrepreneurs from creating value-added products. Furthermore, regulatory hurdles, a lack of quality standards, and inadequate institutional support dissuade small-scale enterprises focused on indigenous crops.

Socio-cultural and policy-related factors additionally present challenges in promoting farmers' varieties. Younger generations often view indigenous crops as inferior or outdated, favoring high-yielding or commercial varieties instead. At the policy level, investments in research and development, subsidies, and support programs are predominantly directed towards major commercial crops, leaving farmers' varieties underrepresented. These combined challenges highlight the necessity for targeted extension strategies, institutional collaboration, and supportive policies to fully realize the livelihood potential of farmers' varieties and indigenous crops.

STRATEGIES FOR EXTENSION TO ENHANCE LIVELIHOOD OPPORTUNITIES VIA FARMERS' VARIETIES AND INDIGENOUS CROPS

Agricultural extension is crucial in improving livelihood opportunities through farmers' varieties and indigenous crops by enabling knowledge transfer, skill enhancement, and institutional connections. Extension strategies must be tailored to specific contexts and participatory, taking into account the socio-economic realities of small, marginal, and tribal farmers. By merging traditional knowledge with scientific advancements, extension systems can foster sustainable production methods while enhancing the economic viability of these crops.

Capacity Building and Skill Enhancement

Capacity building serves as a fundamental extension strategy that empowers farmers to boost the productivity and profitability of farmers' varieties and indigenous crops. Training programs, field schools, and exposure visits equip farmers with skills related to advanced cultivation techniques, seed selection, pest and disease management, and post-harvest processing. Extension agencies can create training modules that are tailored to the needs and locations of farmers, building on their existing knowledge while introducing innovative technologies. A particular emphasis on women and rural youth enhances human resources and fosters inclusive livelihood development.

Participatory Extension Methods and Farmer-led Innovations

Participatory extension methods promote the active engagement of farmers in the planning, execution, and assessment of extension initiatives. Techniques such as participatory rural appraisal and farmer field schools empower farmers to exchange experiences, experiment with local varieties, and refine traditional methods. Innovations led by farmers in seed conservation, mixed cropping, and indigenous pest management can be documented and expanded through extension networks. These methods boost farmers' confidence, decision-making skills, and the long-term adoption of improved practices.

On-farm Demonstrations and Strengthening Local Seed Systems

On-farm demonstrations serve as effective extension tools that highlight the performance of farmers' varieties and indigenous crops in actual field conditions. Conducting demonstrations in farmers' fields fosters trust and promotes peer learning within farming communities. By strengthening local seed systems through community seed banks, seed villages, and farmer-managed seed production, the availability of quality seed is ensured. Additionally, the promotion of seed entrepreneurship generates extra income opportunities while preserving valuable genetic resources.

Value Addition, Processing, and Branding

Value addition increases the economic returns from farmers' varieties and indigenous crops by converting raw produce into market-ready products. Extension agencies can offer training on processing technologies, product diversification, packaging, and quality standards. The development of value-added products boosts consumer demand and market acceptance. Furthermore, branding and promoting indigenous products based on their nutritional and cultural importance enhances market visibility and price realization. Engaging self-help groups and rural enterprises in value addition activities bolsters livelihood diversification.

Market Linkages and Institutional Convergence

Robust market linkages are crucial for maintaining livelihood opportunities centered on farmers' varieties and indigenous crops. Extension services can facilitate direct marketing channels, connect farmers with farmer producer organizations, and advocate for collective marketing strategies. Institutional convergence among research institutions, extension agencies, financial institutions, non-governmental organizations, and local markets improves access to technical support, credit, and infrastructure. These coordinated efforts enhance commercialization prospects and ensure the long-term sustainability of livelihood initiatives.

CONCLUSION AND PATH AHEAD

The varieties cultivated by farmers and indigenous crops possess significant potential for improving livelihood opportunities, especially for small, marginal, and tribal farming communities. Their ability to adapt to local agro-climatic conditions, minimal input needs, nutritional value, and resilience to climate fluctuations render them essential assets for sustainable agricultural progress. Nevertheless, in spite of these benefits, their impact on livelihoods is not fully realized due to production challenges, insufficient extension support, fragile seed systems, and poor market integration. Agricultural extension is vital in unlocking the livelihood potential of farmers' varieties and indigenous crops. By focusing on capacity building, participatory methods, on-farm demonstrations, enhancement of local seed systems, value addition, and the establishment of market connections, extension strategies can improve farmers' skills, income, and resilience. Collaborative efforts among research institutions, extension services, farmer producer organizations, self-help groups, and market participants further bolster these initiatives by offering coordinated technical, financial, and marketing assistance. Moving forward necessitates a fundamental change in extension systems to acknowledge farmers as stewards of agrobiodiversity and active collaborators in innovation. Policy support for the conservation, promotion, and commercialization of farmers' varieties should be reinforced through targeted programs, incentives, and integration into mainstream agricultural development initiatives. Increased funding for research, documentation of indigenous knowledge, and the promotion of value chains centered on indigenous crops are crucial for scaling successful models. In summary, the incorporation of farmers' varieties and indigenous crops into extension-led livelihood strategies presents a sustainable approach to enhancing farm income, securing food and nutritional stability, and fostering inclusive rural development. A comprehensive and farmer-focused extension strategy will not only improve livelihood prospects but also aid in achieving long-term agricultural sustainability and resilience.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

ARTICLE ID: 04

BETTER SEEDS, BETTER YIELDS: THE SCIENCE OF COTTON IMPROVEMENT

AUTHORS' DETAILS:

K. Baghyalakshmi

ICAR-Central Institute for Cotton Research, Regional Station, Coimbatore

G. Sarathapriya

ICAR-Central Institute for Cotton Research, Regional Station, Coimbatore

AR Priyanka

ICAR-Central Institute for Cotton Research, Regional Station, Coimbatore

T. Radhamani

Dept. of Plant Biotechnology, Tamil Nadu Agricultural University, Coimbatore.

Cotton has earned its reputation as "white gold" not merely because of its economic value, but because of the millions of lives it supports. From farmers in rural fields to workers in textile mills, cotton connects agriculture and industry in a powerful chain of livelihood. In many developing countries, cotton is more than a crop—it is an engine of rural development. Yet behind every successful cotton harvest lies a quiet force driving progress: better seeds. The story of cotton improvement is, in essence, the story of how science has worked to produce stronger, more productive, and more resilient seeds. As farming faces increasing challenges—climate change, pest outbreaks, soil degradation, and rising production costs—the role of seed science has never been more critical.

The Foundation: Why Seeds Matter

In agriculture, the seed is the starting point of productivity. No matter how advanced irrigation systems or fertilizers may be, yield potential is largely determined by the genetic makeup of the seed. A high-performing seed contains the blueprint for desirable traits such as better fibre quality, pest resistance, drought tolerance, and efficient nutrient use. In cotton, where fibre quality determines market price and yield determines profitability, the genetic strength of the seed directly influences farmers' incomes. Better seeds are not accidental; they are the result of systematic breeding efforts designed to combine superior traits into a single variety or hybrid.

From Traditional Selection to Scientific Breeding

Cotton improvement began centuries ago when farmers saved seeds from the healthiest and most productive plants. This process, known as selection, gradually improved cultivated cotton over generations. Though simple, it laid the groundwork for organized plant breeding. With the discovery of genetic principles in the early 20th century, breeding became more scientific. Researchers began making deliberate crosses between selected parent plants to combine desirable characteristics. For example, one plant might have excellent fibre length but lower yield, while another might yield heavily but produce average fibre. Through controlled crossing and selection, breeders could combine these traits. Methods such as pedigree breeding and pure-line selection helped stabilize desirable characteristics over time. These approaches significantly improved yield and uniformity, but they required patience—often a decade or more to release a new variety.

Hybrid Cotton: Harnessing Hybrid Vigor

One of the most significant breakthroughs in cotton improvement was the development of hybrid cotton. Hybrids are created by crossing two genetically distinct parent lines. The first-generation offspring often display heterosis, or hybrid vigor, meaning they outperform both parents.

Hybrid cotton plants typically show:

- Higher yield potential
- More uniform growth
- Better adaptability to varying conditions
- Stronger early vigor

This technology transformed cotton production in several regions. Farmers adopting hybrid seeds observed substantial yield increases compared to traditional varieties. Hybrid systems also allowed breeders to combine multiple beneficial traits more effectively. However, hybrid seeds must be purchased each season, as saving seed reduces the vigor advantage. While this increases annual investment, the productivity gains often outweigh the additional cost.

Biotechnology and the Bt Revolution

Cotton cultivation has historically been threatened by insect pests, especially bollworms. Before the introduction of pest-resistant varieties, farmers relied heavily on chemical pesticides, increasing production costs and environmental risks. The introduction of Bt cotton marked a turning point. Bt cotton contains a gene derived from the bacterium *Bacillus thuringiensis*, which produces a protein toxic to certain insect pests. This innovation significantly reduced bollworm damage and decreased the need for repeated pesticide applications.

The impact was substantial:

- Higher effective yields
- Reduced pesticide expenses
- Improved environmental safety
- Lower health risks for farmers

Bt technology demonstrated how biotechnology could directly address major production constraints. Although resistance management and integrated pest management remain important, the Bt revolution highlighted the power of science in crop improvement.

Molecular Tools: Precision in Breeding

While traditional breeding relies on visible traits, modern science has moved deeper—into the plant's DNA. Molecular breeding tools allow scientists to identify specific genes associated with desirable characteristics. Marker-assisted selection (MAS) is one such tool. It uses DNA markers linked to important traits, enabling breeders to screen young seedlings in laboratories rather than waiting for full plant development in the field. This speeds up breeding cycles and increases selection accuracy.

With advances in genomics, breeders can now analyze thousands of genetic markers simultaneously. This approach, known as genomic selection, predicts a plant's performance based on its DNA profile. Such techniques shorten the time required to develop improved varieties and enhance precision in combining complex traits like drought tolerance and fibre quality.

Improving Fibre Quality alongside Yield

Cotton improvement is not only about producing more bolls per plant. Fibre quality—length, strength, fineness, and uniformity—is equally important. Textile industries demand consistent, high-quality fibre for efficient spinning and weaving. Modern breeding programs therefore focus on balancing yield and fibre quality. High yield without acceptable fibre standards does not benefit farmers if market prices decline. By combining genetic improvement with quality testing, breeders ensure that new varieties meet both productivity and industry requirements.

This dual focus strengthens the entire cotton value chain—from farm to fabric.

Climate Resilience: The New Frontier

Agriculture today operates under the shadow of climate variability. Irregular rainfall, rising temperatures, and extreme weather events threaten crop stability. Cotton, being sensitive to moisture stress and heat, is particularly vulnerable.

Seed improvement programs now prioritize:

- Drought tolerance
- Heat tolerance
- Early maturity
- Efficient water use

Developing climate-resilient varieties ensures stable yields even under stress conditions. These improvements not only protect farmer incomes but also enhance national production stability.

Better seeds, in this context, are a form of insurance against climatic uncertainty.

Sustainability Through Seed Innovation

Sustainable agriculture requires producing more with fewer resources. Improved cotton seeds contribute to this goal in multiple ways. Higher-yielding varieties reduce the need to expand cultivated area. Pest-resistant varieties lower chemical pesticide usage. Efficient nutrient uptake reduces fertilizer waste. Early-maturing varieties save water and energy. By embedding efficiency into the genetic structure of the plant, breeding supports environmentally responsible farming practices. Seed improvement thus becomes a central component of sustainable agriculture.

Challenges in Cotton Improvement

Despite remarkable progress, cotton breeding faces ongoing challenges. Genetic diversity in cultivated cotton is relatively narrow, making it important to continuously introduce new genetic sources. Emerging pests and diseases require constant vigilance and innovation. Another challenge is ensuring that improved seeds reach smallholder farmers. Access to quality seed, extension services, and proper agronomic guidance is essential for realizing the full benefits of scientific advances. Moreover, public perception and regulatory frameworks influence the adoption of biotechnology-based innovations. Transparent communication and evidence-based policies are necessary to sustain progress.

The Road Ahead

The future of cotton improvement lies in integration. Traditional breeding knowledge, molecular genetics, biotechnology, and digital agriculture tools must work together. Emerging technologies such as gene editing offer precise ways to enhance specific traits without altering the entire genome. At the same time, data analytics and remote sensing allow breeders and agronomists to monitor crop performance in real time. This feedback accelerates improvement cycles and ensures that varieties meet practical field conditions. Ultimately, better seeds are not just products of laboratories; they are the result of collaboration among scientists, farmers, policymakers, and industry stakeholders.

Conclusion

The journey of cotton improvement reflects the remarkable progress of agricultural science. From farmer-led selection to genomic precision, each stage has contributed to stronger, more productive seeds. These improved seeds have enhanced yields, strengthened resilience, improved fibre quality, and supported millions of livelihoods. In a world where demand for sustainable fibre continues to grow and environmental challenges intensify, the importance of scientific seed improvement cannot be overstated. Better seeds truly mean better yields—but they also mean better incomes, better resource use, and a more secure future for cotton farming. As innovation continues, the science of cotton improvement will remain central to shaping a resilient and productive agricultural landscape—ensuring that white gold continues to shine for generations to come.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Dr. NITIN VASANTRAO PARJANE
Assistant Professor, Mahatma Phule Krishi Vidyapeeth, Vrindavan College of Agriculture, Gunjalwadi Pathar, Sangamner.

Dr. MAHADEV POPAT KHATAL
Assistant Professor, Mahatma Phule Krishi Vidyapeeth, Government College of Agriculture Pune

Dr. AVINASH SHIVAJI MAHALE
Assistant Professor, Mahatma Phule Krishi Vidyapeeth, Government College of Agriculture, Dhule.

ARTICLE ID: 05

TRICHODERMA VIRIDE: NATURE'S GREEN SHIELD

INTRODUCTION

Agriculture forms the foundation of global food security, yet crop productivity continues to be severely constrained by a wide range of fungal diseases. These challenges have intensified the need for safer, eco-friendly and sustainable alternatives for crop protection (Zin & Badaluddin, 2020; Asghar *et al*., 2024). Biological control has emerged as one of the most promising approaches for sustainable disease management, and among the numerous beneficial microorganisms available, *T. viride* (Persoon) has earned a distinguished place as one of the world's most successful biocontrol agent (Poveda, 2021; Harman *et al*., 2021).

Unlike chemical fungicides that generally target pathogens through a single mode of action, *T. viride* employs multiple biological mechanisms. (Medeiros *et al*., 2024; Gutierrez-Moreno *et al*., 2025). In recent years, the increasing adoption of organic farming, Integrated Disease Management (IDM), and climate-smart agricultural practices has further enhanced the importance of *T. viride* (Woo & Pepe, 2023; Singh *et al*., 2025).

HISTORY OF TRICHODERMA VIRIDE

The scientific journey of *Trichoderma* began over two centuries ago.

- ✓ **1794:** The fungal genus *Trichoderma* was first described by the German mycologist **Christiaan Hendrik Persoon**.
- ✓ **1927:** Gilman and Abbott classified different species of *Trichoderma* based on colony morphology.
- ✓ **1932:** Scientist **R. Weindling** discovered that *Trichoderma* attacks and destroys plant pathogenic fungi through a process called **mycoparasitism**, laying the foundation for biological disease control.
- ✓ **1934:** Researchers isolated **gliotoxin**, an antimicrobial compound responsible for suppressing several plant pathogens.
- ✓ During **World War II**, *Trichoderma* gained attention for its remarkable ability to produce cellulase enzymes useful in industrial applications.
- ✓ Today, *Trichoderma viride* is commercially produced worldwide and is extensively used in sustainable agriculture as a biofungicide and plant growth promoter.

TAXONOMIC POSITION

Category	Classification
Kingdom	Fungi
Division	Ascomycota
Class	Sordariomycetes
Order	Hypocreales
Family	Hypocreaceae
Genus	*Trichoderma*
Species	*Trichoderma viride*

MORPHOLOGICAL CHARACTERISTICS

The fungus can easily be recognized under laboratory conditions.

- ✓ Colonies initially appear **white** and gradually turn **bright green** due to abundant spore formation.
- ✓ It possesses rapidly growing branched mycelium.
- ✓ Conidiophores are highly branched with flask-shaped phialides.
- ✓ Conidia are small, spherical, smooth, and green.
- ✓ The fungus grows rapidly on culture media and can colonize the rhizosphere within a few days.
- ✓ Optimum temperature for growth ranges from **25–30°C**.
- ✓ It performs well under slightly acidic to neutral soil conditions (pH **5.5–7.5**). (Kumar *et al*., 2023)

NATURAL HABITAT

Trichoderma viride naturally inhabits:

- ✓ Agricultural soils
- ✓ Forest soils
- ✓ Compost heaps
- ✓ Farmyard manure
- ✓ Vermicompost
- ✓ Decaying crop residues
- ✓ Plant rhizosphere

Because of its excellent survival ability, it establishes itself rapidly around plant roots and suppresses disease-causing fungi

HOW DOES TRICHODERMA VIRIDE WORK

Unlike chemical fungicides, *T. viride* employs several biological mechanisms simultaneously to protect plants.

1. Competition for Nutrients and Space

The fungus grows rapidly around plant roots, utilizing available nutrients before harmful fungi can establish themselves. This deprives pathogens of food and space, preventing infection.

2. Mycoparasitism

This is one of the most remarkable characteristics of *Trichoderma*.

The fungus detects pathogenic fungi, coils around their hyphae, penetrates their cell walls, and digests them using specialized enzymes such as:

- ✓ Chitinase
- ✓ β-1,3-glucanase
- ✓ Cellulase
- ✓ Protease

Ultimately, the pathogen dies due to destruction of its cell wall. (Medeiros *et al*., 2024)

3. Antibiosis

Trichoderma secretes several antibiotics and toxic metabolites including:

- ✓ Gliotoxin
- ✓ Viridin
- ✓ Peptaibols
- ✓ Volatile organic compounds

These compounds inhibit the growth and multiplication of plant pathogens. (Yao *et al*., 2023).

4. Induced Systemic Resistance (ISR)

Once roots are colonized, *Trichoderma* activates the plant's natural immune system. As a result, plants become more resistant to future fungal attacks.

(Guzman-Guzman et al., 2023: (Gutierrez-Moreno *et al*., 2025)

MAJOR BENEFITS OF TRICHODERMA VIRIDE

Disease Management

It effectively controls many destructive diseases including:

- ✓ Damping-off, Collar rot, Root rot, Wilt, Charcoal rot, Seedling blight, Rhizome rot, Stem rot, Leaf spot etc.

Improves Root Growth

Research has shown that treated plants often develop **25–50% larger root systems**, enabling better water and nutrient uptake.

Enhances Nutrient Availability

The fungus solubilizes phosphorus and micronutrients, making them readily available to plants. (Sharma et al., 2024)

Improves Soil Health

It accelerates decomposition of organic matter and improves microbial diversity in soil.

Increases Crop Yield

Healthier plants with stronger root systems produce higher yields and better-quality produce. (Asghar *et al*., 2024; Kumar *et al*., 2023).

PLANT DISEASES CONTROLLED BY TRICHODERMA VIRIDE

Crop	Disease	Pathogen
Tomato	Damping-off	*Pythium* spp.
Chilli	Wilt	*Fusarium oxysporum*
Cotton	Root rot	*Rhizoctonia solani*
Groundnut	Collar rot	*Sclerotium rolfsii*
Soybean	Charcoal rot	*Macrophomina phaseolina*
Vegetables	Seedling blight	Various soil-borne fungi
Pulses	Root rot	*Fusarium* spp.
Fruits	Root diseases	Multiple fungi

METHODS OF APPLICATION

1. Seed Treatment

- ✓ **Dose:** 6–10 g/kg seed
- ✓ Mix the formulation thoroughly with seeds.
- ✓ Dry in shade for 30 minutes before sowing.

Benefits

- ✓ Protects seeds from soil-borne pathogens.
- ✓ Improves germination.
- ✓ Enhances seedling vigour.

2. Soil Application

Mix:

- ✓ 1 kg Trichoderma formulation
- ✓ 100 kg well-decomposed FYM or compost

Incubate the mixture for about a week under moist conditions before broadcasting in the field.

This method effectively controls root diseases and enriches soil microbial activity.

3. Root Dip Treatment

Before transplanting:

- Prepare a suspension containing **10 g Trichoderma + 100 g FYM per litre of water**.
- Dip seedling roots for **10 minutes** before transplanting.

This ensures rapid root colonization and protection from soil pathogens.

4. Drip Irrigation and Soil Drenching

Use: 3–5 ml liquid formulation/L water or 5–10 g powder/L water

Apply near the root zone for effective disease suppression.

5. Foliar Spray

Prepare 5 g powder per litre of water

Spray both upper and lower leaf surfaces to suppress foliar fungal pathogens.

(Zin & Badaluddin, 2020; Kumar *et al*., 2023).

ADVANTAGES

- ✓ Eco-friendly
- ✓ Safe for humans and animals
- ✓ Residue-free crop production
- ✓ Compatible with organic farming
- ✓ Reduces dependence on chemical fungicides
- ✓ Improves soil fertility
- ✓ Promotes healthy root development
- ✓ Increases nutrient uptake
- ✓ Enhances crop productivity
- ✓ Cost-effective and sustainable

LIMITATIONS

Although highly beneficial, *T. viride* has some limitations:

- ✓ Sensitive to prolonged exposure to direct sunlight.
- ✓ Performance decreases in extremely dry soils.
- ✓ Cannot cure severe infections once disease is well established.
- ✓ Should not be mixed directly with strong chemical fungicides.
- ✓ Requires proper storage to maintain viability. (Gutierrez-Moreno *et al*., 2025)

PRECAUTIONS DURING USE

- ✓ Always use fresh, quality-certified formulations.
- ✓ Store in a cool, dry place away from sunlight.
- ✓ Do not mix with fungicides during seed treatment.
- ✓ Apply in moist soil for better establishment.
- ✓ Use well-decomposed FYM or compost.
- ✓ Follow the recommended dose only.

ROLE IN SUSTAINABLE AGRICULTURE

The future of agriculture lies in reducing dependence on synthetic chemicals while maintaining productivity. *T. viride* plays a vital role by:

- Reducing chemical fungicide use.
- Conserving beneficial soil microorganisms.
- Improving soil fertility.
- Supporting climate-smart agriculture.
- Promoting organic and natural farming.
- Enhancing long-term sustainability of crop production. (Singh *et al.,* 2025)

FARMER TIPS

- Apply *T. viride* before disease appears rather than after severe infection.
- Combine it with organic manures for better performance.
- Maintain adequate soil moisture after application.
- Use certified formulations from reliable manufacturers.
- Integrate it with good agronomic practices and crop rotation for maximum benefits.

CONCLUSION

T. viride is one of the most effective and environmentally friendly biological control agents available today. Beyond suppressing a wide range of soil-borne fungal pathogens, it enhances root growth, improves nutrient availability, stimulates plant immunity, and contributes to healthier soils. Its compatibility with integrated disease management and organic farming makes it an indispensable tool for sustainable agriculture. By adopting *T. viride* in routine crop management, farmers can reduce dependence on chemical fungicides, lower production costs, and produce healthier, residue-free crops while protecting the environment. This multifunctional fungus truly represents a "green shield" for modern agriculture and a key component of future climate-resilient farming systems.

REFERENCES

- Asghar, W., Khan, M. I., & colleagues. (2024). The application of *Trichoderma* spp., an old but new useful fungus, in sustainable agriculture: A comprehensive review. *Soil Security,* 16, 100178.
- Gutierrez-Moreno, K., Olguin-Martinez, A. I., Montoya-Martínez, A. C., & de los Santos-Villalobos, S. (2025). Trichoderma in Sustainable Agriculture and the Challenges Related to Its Effectiveness. *Diversity*, 17(10), 734.
- Harman G.Khadka R.Doni F. Uphoff N. (2021). Benefits to plant health and productivity from enhancing plant microbial symbionts. *Front. Plant Sci.*11:610065.
- Kumar, V., Kumar, P., Singh, R., & colleagues. (2023). Journey of *Trichoderma* from pilot scale to mass production: Challenges and future prospects. *Agriculture,* 13(10), 2022.
- Medeiros, F. H. V., Silva, R. N., & Harman, G. E. (2024). Mechanisms involved in Trichoderma–plant–pathogen interactions and biological control. *Frontiers in Microbiology*, 15, 1387654.
- Poveda, J. (2021). *Trichoderma* as biocontrol agent against pests: New uses for a mycoparasite. *Biological Control,* 159, 104634.
- Sharma, S., Kumar, A., Singh, R., & Patel, P. (2024). Role of *Trichoderma* species in plant growth promotion and nutrient mobilization under sustainable agriculture. *Journal of Fungi,* 10(2), 131.
- Singh, R., Verma, P., Kumar, V., & Sharma, N. (2025). *Trichoderma*-based bioformulations for climate-resilient and sustainable crop production. *Agriculture*, 15(2), 198.
- Woo, S. L., & Pepe, O. (2023). Microbial consortia and Trichoderma-based biostimulants for sustainable agriculture. *Microorganisms,* 11(3), 734.
- Zin, N. A., & Badaluddin, N. A. (2020). Biological functions of *Trichoderma* spp. for agriculture applications. *Annals of Agricultural Sciences*, 65(2), 168–178.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Manga Tharaka
M.Sc., Department of Genetics and Plant Breeding, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan

Kallagunta Navyasree
Ph.D. Scholar, Department of Plant Pathology, Advanced Post Graduate Centre, ANGRAU, Lam, Guntur

ARTICLE ID: 06

GENE PYRAMIDING: A STRATEGIC APPROACH TO CROP IMPROVEMENT

Abstract
Climate variability, emerging pests, and evolving pathogens challenge conventional breeding. Gene pyramiding provides an effective solution by combining multiple desirable genes into a single genotype. It enhances resistance, yield, and stress tolerance. This review covers its historical background, rationale, objectives, and determinants of success. It explains conventional and molecular approaches such as MAS, MABC, MARS, and transgenic pyramiding. It also highlights achievements in major crops and commercial transgenic products. Despite limitations like cost and technical complexity, gene pyramiding remains essential for sustainable agriculture and food security.
Keywords Gene pyramiding, marker-assisted selection, crop improvement, molecular breeding, resistance breeding

1. Introduction
Climate volatility, emerging pests, and rapidly evolving pathogens limit the effectiveness of traditional breeding. These methods often fail to provide durable resistance. Gene pyramiding overcomes this by stacking multiple resistance or tolerance genes into a single genotype. This improves the crop's ability to withstand biotic and abiotic stresses.

2. Historical Background
Gene pyramiding began with Biffen (1905), who showed that disease resistance in wheat follows Mendelian inheritance. He identified the role of recessive genes in rust resistance. Later, H.H. Flor proposed the gene-for-gene hypothesis. This explained interactions between plant resistance (R) genes and pathogen avirulence (Avr) genes. Watson and Singh (1953) introduced the term "gene pyramiding" and proposed combining multiple genes into one genotype. With the development of molecular tools like marker-assisted selection (MAS), this concept became precise and efficient.

3. Rationale for Gene Pyramiding
Gene pyramiding combines multiple beneficial genes into a single elite genotype. It provides durable resistance to pests and diseases. It improves yield and tolerance to stresses like drought and salinity. It reduces chemical usage and supports sustainable agriculture. It also enhances elite cultivars through targeted genetic improvement.

4. Objectives
1. Enhance trait performance
2. Remedy genetic deficits through introgression
3. Increase durability of resistance
4. Broaden genetic base for long-term stability

5. Determinants of Success of Gene Pyramiding
Success depends on several factors. The number of genes affects complexity. Genetic distance between genes and markers influences selection efficiency. The number of genotypes selected affects success rate. Germplasm diversity is important for strong traits.

Linkage and pleiotropic effects can complicate selection. Accurate phenotyping at the plant level is essential for proper expression of traits.

6. Methodological Approaches

6.1 Conventional Techniques or Serial Gene Pyramiding

Conventional gene pyramiding uses traditional breeding methods to combine genes step by step across generations. This approach is known as serial gene pyramiding.

- **Backcross Method**

A donor parent with a desirable gene is crossed with an elite parent. The progeny are repeatedly backcrossed with the elite parent. This helps transfer the target gene while maintaining the elite background.

- **Pedigree Breeding**

Two parents with desirable traits are crossed. The F_1 generation is selfed to create variation. Superior plants are selected across generations. These are advanced and stabilized for uniform performance.

- **Recurrent Selection**

This method involves repeated cycles of selection and intermating. It increases the frequency of favorable alleles in the population over time.

Advantages of Conventional Methods

These methods are simple, cost-effective, and widely applicable. They rely on phenotypic traits and do not require special equipment. They are suitable for complex traits and free from regulatory issues.

Disadvantages of Conventional Methods

They require extensive phenotyping. They are effective mainly for traits with major effects. Linkage and pleiotropy can affect results. Linkage drag may occur. The process is time-consuming and less efficient for complex traits.

6.2 Molecular Techniques

Molecular tools like MAS improve the efficiency and accuracy of gene pyramiding. They allow precise gene selection at early stages.

- **Marker-Assisted Selection (MAS)**

MAS uses molecular markers linked to traits for selection. It enables precise and early identification of desirable genes.

A key example is the wheat cultivar “Madsen” (1986), developed using isozyme marker EpD1b. This helped incorporate resistance to eyespot disease caused by *Tapesia yallundae* (Allan et al., 1989).

MAS enables:

- Early and non-destructive selection
- Selection of complex traits
- Faster breeding cycles
- Reduction of linkage drag
- Stacking of multiple genes without phenotyping

- **Marker-Assisted Backcrossing (MABC)**

Nelson (1978) introduced MABC for gene pyramiding. It combines multiple resistance genes into a recurrent parent.

If genes come from one donor, the process is simple. If from multiple donors, it becomes complex.

- **Separate Backcross Program**

Each donor is crossed separately with the recurrent parent. Resulting lines are intercrossed. Through selfing and selection, a pyramided genotype is developed.

- **Single Backcross Program**

All donor parents are included in one program using mating schemes.

  - **Symmetrical Mating Scheme**

    F_1 plants from different crosses are intercrossed in pairs. A complex hybrid is formed. It is backcrossed with the recurrent parent to recover the background.

  - **Tandem Mating Scheme**

    The recurrent parent is crossed with one donor first. The progeny are then crossed sequentially with other donors. The final hybrid is backcrossed to recover the recurrent parent with all genes.

- **Marker-Assisted Recurrent Selection (MARS)**

MARS uses markers to select multiple genomic regions linked to traits. Selected individuals are intercrossed within the same season. This speeds up selection cycles and increases favorable alleles. It is useful for improving complex traits and multi-parent populations.

- **Transgenic Pyramiding**

This involves stacking multiple transgenes into a plant. It improves traits like disease resistance, stress tolerance, and nutrition.

Notable Achievements in Crop Improvement through Gene Pyramiding

Crop	Trait	Pyramided genes	Reference
Rice	BLB BPH Blast, BLB, BPH, drought and gall midge resistance BLB	Xa4, Xa5, Xa7, xa13 and Xa21 Bph3+Bph14+ Bph15+Bph18+ Bph20 +Bph21 Pi9+Xa4+xa5+Xa21+ Bph17+Bph3+Gm4+ Gm8+qDTY1.1 + qDTY3.1 Xa4+Xa5+Xa13 +Xa21	Hsu et al. (2020) Jiang et al. (2018) Dixit et al. (2020) Dokku et al.(2013)
Cotton	Insect pest resistance Bacterial blight and Sheeth blight	Cry 1Ac, Cry 2Ac chi11, tlp and Xa21	Gahan et al. (2005) Maruthasalam et al. (2007)
Wheat	Leaf rust resistance	Lr41, Lr42, Lr43	Cox et al. (1993)
Barley	Yellow mosaic virus resistance	rym4, rym5, rym9, rym11	Werner et al. (2005)
Chickpea	Lepidopteran resistance	Cry1Ac + cry1c	Meenakshi et al. (2011)
Soybean	Soybean mosaic virus resistance	Rsv1, Rsv3, Rsv4	Zhu et al. (2002)

Methods include:

- Co-transformation
- Crossing transgenic lines
- Multi-gene constructs
- CRISPR/Cas9 gene editing

Advantages of Molecular Techniques

They provide high precision and efficiency. Selection can be done at early stages. They are useful for complex traits. They reduce breeding time and linkage drag. They enable efficient gene stacking.

Disadvantages of Molecular Techniques

They are costly and require skilled personnel. Advanced equipment is needed. Suitable markers may not be available for all traits. Over-reliance may reduce genetic diversity.

Conclusion

Gene pyramiding is a powerful strategy for developing crop varieties with durable resistance and improved performance by combining multiple beneficial genes. Advances in molecular tools like MAS have greatly enhanced its precision and efficiency compared to conventional methods. Despite challenges such as cost and technical complexity, its benefits in overcoming biotic and abiotic stresses are significant. Overall, gene pyramiding plays a crucial role in ensuring sustainable agriculture and future food security.

Reference

- Dormatey, R., Sun, C., Ali, K., Coulter, J. A., Bi, Z., & Bai, J. (2020). Gene pyramiding for sustainable crop improvement against biotic and abiotic stresses. *Agronomy*, *10*(9), 1255.
- Marker-Assisted Plant Breeding: Principles and Practices by B.D. Singh and A.K. Singh.
- Molecular techniques in crop improvement by S.Mohan Jain and D.S.Brar.
- Kaur, B., Bhatia, D., & Mavi, G. S. (2021). Eighty years of gene-for-gene relationship and its applications in identification and utilization of R genes. Journal of genetics, 100(2), 50.
- Rajput, R., Naik, J., Misra, P., Trivedi, P. K., & Pandey, A. (2023). Gene pyramiding in transgenic plant development: approaches and challenges. Journal of Plant Growth Regulation, 42(10), 6038-6056.
- Hsu, Y. C., Chiu, C. H., Yap, R., Tseng, Y. C., & Wu, Y. P. (2020). Pyramiding bacterial blight resistance genes in Tainung82 for broad-spectrum resistance using marker-assisted selection. *International Journal of Molecular Sciences*, *21*(4), 1281.

Some of the transgenic products with molecularly stacked trait genes currently available in the market

Source/ Trait developer	Crop	Product name	Transgenic event	Trait genes	Trait targets
Bayer Crop Science	Cotton	FiberMax LibertyLink Bolllgar ll	LLCotton25, MON15985	bar, Cry1Ac, Cry2Ab	Lepidopteran pests, weeds
Dow AgroSciences	Cotton	Wide5trike'/Roundup Ready' Flex	DAS-21023-5, DAS-24236-5, MON-88913-8	*pat,* CrylAc, CrylFa, CP4 EPSPS	Lepidopteran pests, weeds
Monsanto	Cotton	Bollgard II/Roundup Ready' Flex	MON88913-8, MON15985	CP4 EPSPS, CrylAc, Cry2Ab	lepidopteran pests, weeds
Dow AgroSciences and Poineer Hi-Bred	Maize	Herculex XTRA	TC1507, DAS-59122-7	Cry 1Fa, Cry34Ab1, Cry35Ab1, pat	Lepidopteran and coleopteran pests, Weeds
Monsanto	Maize	Yieldgard VT Pro	MON89034	Cry1A105, Cry2Ab2	Lepidopteran pests
Syngenta	Maize	Agrisure GT/CB/LL	Bt11, GA21	Cry1Ab, pat, mutant maize EPSPS	Lepidopteran pests (European corn borer), weeds

- Jiang, H., Hu, J., Li, Z., Liu, J., Gao, G., Zhang, Q., ... & He, Y. (2018). Evaluation and breeding application of six brown planthopper resistance genes in rice maintainer line Jin 23B. *Rice*, *11*(1), 22.
- Dixit, S., Singh, U. M., Singh, A. K., Alam, S., Venkateshwarlu, C., Nachimuthu, V. V., ... & Kumar, A. (2020). Marker assisted forward breeding to combine multiple biotic-abiotic stress resistance/tolerance in rice. *Rice*, *13*(1), 29.
- Dokku, P., Das, K. M., & Rao, G. J. N. (2013). Pyramiding of four resistance genes of bacterial blight in Tapaswini, an elite rice cultivar, through marker-assisted selection. *Euphytica*, *192*(1), 87-96.
- Gahan, L. J., Ma, Y. T., MacgregorCoble, M. L., Gould, F., Moar, W. J., & Heckel, D. G. (2005). Genetic basis of resistance to Cry1Ac and Cry2Aa in Heliothis virescens (Lepidoptera: Noctuidae). *Journal of economic entomology*, *98*(4), 1357-1368.
- Maruthasalam, S., Kalpana, K., Kumar, K. K., Loganathan, M., Poovannan, K., Raja, J. A. J, & Balasubramanian, P. (2007). Pyramiding transgenic resistance in elite indica rice cultivars against the sheath blight and bacterial blight. *Plant cell reports*, *26*(6), 791-804.
- Cox, T.S, Raupp, W.J &Gill, B.S (1993). Leaf rust resistance gene Lr41, Lr42 and Lr43 transferred from Triticum tauschii to common wheat. Crop Science, 121: 295-309.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Dr. S. P. Khedkar
Assistant Professor
College of Agriculture, Ahilyanagar

Miss. Anushka Santosh Tupe
UG Scholar,
College of Agriculture, Ahilyanagar

Dr. I. D. Ghatul
Assistant Professor
College of Agriculture, Ahilyanagar

ARTICLE ID: 07

APPLICATION OF BIOSTIMULANTS IN SOLANACEOUS VEGETABLES

Abstract

The increasing demand for sustainable and resource-efficient agricultural production has accelerated the adoption of Biostimulants as an innovative strategy to improve crop productivity and resilience. In solanaceous vegetable crops, including tomato (*Solanum lycopersicum L*.), brinjal (*Solanum melongena L*.), chilli (*Capsicum annuum L*.), potato (*Solanum tuberosum L*.), and bell pepper (*Capsicum annuum var. grossum*), biostimulants have emerged as valuable inputs that enhance physiological performance without functioning as conventional fertilizers or pesticides. These products, derived from natural sources such as seaweed extracts, humic and fulvic substances, protein hydrolysates, beneficial microorganisms, amino acids, and plant-derived bioactive compounds, regulate key metabolic pathways involved in nutrient acquisition, photosynthesis, antioxidant defense, and hormonal signaling. Biostimulants encompass a diverse range of materials, including humic and fulvic substances, seaweed extracts, protein hydrolysates, amino acids, microbial inoculants such as plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), as well as emerging formulations based on organic metabolites and microbial derivatives. Their multifunctional nature contributes not only to improved crop performance but also to restoration of soil biological activity, enhancement of soil carbon dynamics, and increased resilience of agroecosystems under changing climatic conditions. Unlike conventional agrochemicals, their effectiveness depends on complex interactions among plant genotype, soil characteristics, environmental conditions, and application strategies. As research continues to uncover their diverse mechanisms of action, biostimulants are becoming an essential component of sustainable crop management and a promising strategy for meeting future global food security challenges.

Keywords: Biostimulants , , Abiotic stress, Rhizosphere, Soil health , Bioactive compounds.

1. Introduction

Global agriculture is facing unprecedented challenges due to climate change, environmental degradation, declining soil fertility, and the increasing occurrence of abiotic stresses such as drought, salinity, heat, and nutrient deficiencies. These factors negatively influence plant growth, productivity, and food quality, posing a significant threat to global food and nutritional security. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), climate-induced stresses are expected to intensify in the coming decades, while the global population is projected to reach approximately 9.7 billion by 2050, increasing the demand for sustainable and resource-efficient agricultural production (United Nations, 2022).Solanaceous vegetables, including tomato (*Solanum lycopersicum* L.), eggplant (*Solanum melongena* L.), chilli and sweet pepper (*Capsicum spp*.), are among the most important vegetable crops worldwide because of their high economic value, nutritional significance, and wide consumer acceptance.

However, these crops require intensive nutrient management and are highly susceptible to environmental stresses, soil degradation, and emerging pest and disease pressures, resulting in considerable yield and quality losses (Rouphael & Colla, 2020). Plant biostimulants have emerged as an innovative and environmentally sustainable approach to improve crop performance without acting as direct nutrient sources. They include humic and fulvic substances, seaweed extracts, protein hydrolysates, beneficial microorganisms, silicon-based compounds, amino acids, and plant growth-promoting rhizobacteria (PGPR). These products enhance nutrient uptake, stimulate root development, improve photosynthetic efficiency, activate antioxidant defense mechanisms, regulate phytohormonal balance, and increase plant tolerance to abiotic stresses, thereby improving yield, fruit quality, and resource-use efficiency (Rouphael *et al*., 2021; Yakhin et al., 2017). cconsidering the increasing pressure to produce more food with fewer resources and reduced environmental impact, biostimulants are becoming an integral component of sustainable horticulture. This review summarizes the classification, mechanisms of action, and recent advances in the application of biostimulants for improving growth, productivity, stress tolerance, and fruit quality in solanaceous vegetable crops, while highlighting future research priorities for climate-resilient vegetable production.

2. Importance and Need of Biofortification

Solanaceous vegetable crops, including tomato (Solanum lycopersicum L.), brinjal (Solanum melongena L.), chilli and sweet pepper (Capsicum spp.), constitute one of the most economically valuable groups of horticultural crops worldwide. These crops require intensive nutrient management and are frequently exposed to environmental constraints such as drought, heat stress, salinity, nutrient imbalance, and soil degradation, all of which adversely affect plant growth, flowering, fruit set, yield, and quality. The increasing demand for sustainable food production, coupled with the adverse effects of excessive chemical fertilizer use, has created a need for environmentally friendly crop management strategies. In this context, plant biostimulants have emerged as an innovative and sustainable approach to enhance crop productivity while reducing dependence on synthetic agricultural inputs. Unlike fertilizers, biostimulants do not primarily act by supplying nutrients; instead, they stimulate the plant's natural physiological and biochemical processes. They improve nutrient acquisition, root architecture, photosynthetic efficiency, antioxidant activity, and stress tolerance, thereby increasing nutrient use efficiency and overall plant performance. Their application has become particularly important in solanaceous vegetables because these crops possess high nutrient requirements and exhibit considerable sensitivity to abiotic stresses during critical growth stages such as transplant establishment, flowering, and fruit development. The intensive cultivation of solanaceous vegetables often results in depletion of soil organic matter, deterioration of soil microbial diversity, and reduced nutrient availability.

Biostimulants such as humic substances, seaweed extracts, protein hydrolysates, beneficial microorganisms, silicon, and amino acid formulations contribute to restoring soil biological activity, enhancing root-soil interactions, and improving nutrient mobilization. Consequently, they promote vigorous root development, greater water uptake, and efficient absorption of macro- and micronutrients, ultimately improving plant vigor and productivity under diverse cultivation systems. Climate change has intensified the occurrence of drought, heat waves, irregular rainfall, and salinity, posing major challenges to vegetable production. Biostimulants activate antioxidant defense systems, regulate osmotic balance, stabilize cellular membranes, and stimulate the synthesis of protective metabolites, enabling plants to withstand environmental stresses more effectively. Enhanced tolerance to abiotic stress minimizes physiological damage, maintains photosynthetic activity, and reduces yield losses, making biostimulants an important component of climate-resilient horticulture. Besides increasing yield, biostimulants significantly improve fruit quality by enhancing size, firmness, colour development, soluble solids, vitamin C content, antioxidant compounds, and shelf life. These improvements increase the commercial value and consumer acceptability of tomato, chilli, pepper, and brinjal fruits while reducing post-harvest losses. Improved quality attributes are particularly important for export-oriented production systems where premium quality standards are essential. Furthermore, the integration of biostimulants with integrated nutrient management programme

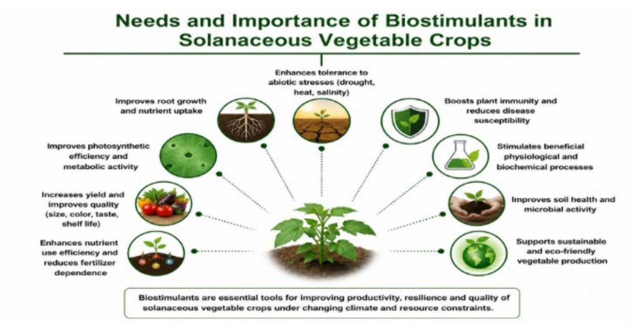


Figure 1 : Needs and importance of biostimulants in solanaceous vegetable crops

3.Categories of Plant Bio- stimulants

Plant biostimulants comprise a heterogeneous group of natural substances, beneficial microorganisms, and bioactive compounds that stimulate plant physiological processes independently of their direct nutrient content. According to Regulation (EU) 2019/1009, a plant biostimulant is defined as a product that enhances plant nutrition processes with the primary objective of improving nutrient use efficiency, tolerance to abiotic stress, crop quality, or nutrient availability in the rhizosphere, irrespective of its nutrient concentration. Unlike fertilizers and pesticides, biostimulants function by modulating biochemical, physiological, and molecular mechanisms that improve plant performance under both optimal and stressful environmental conditions. Based on their origin, composition, and mode of action, plant biostimulants are broadly classified into the following categories.

3.1 Humic and Fulvic Substances:-

Humic substances represent one of the oldest and most extensively studied classes of plant biostimulants. They are naturally formed during the microbial decomposition and humification of plant and animal residues and mainly consist of humic acid, fulvic acid, and humin. Commercial formulations are generally extracted from leonardite, lignite, peat, vermicompost, or composted organic matter. Humic substances exert their biostimulant activity by improving both soil properties and plant metabolism. They enhance cation exchange capacity, increase nutrient solubility, stimulate plasma membrane H^+-ATPase activity, promote lateral root formation, and increase root hair density. At the physiological level, they regulate auxin-like responses, enhance nitrate uptake, improve photosynthetic efficiency, and activate antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD).In solanaceous vegetable crops, humic substances have been reported to improve seedling establishment, vegetative growth, flowering, fruit set, nutrient uptake, and fruit yield while simultaneously enhancing soil microbial activity and nutrient availability. Their role becomes particularly important under drought, salinity, and nutrient-deficient conditions where root growth determines crop productivity.

3.2 Seaweed and Algal Extracts:-

Seaweed extracts are among the most commercially successful plant biostimulants worldwide. They are primarily derived from brown algae such as Ascophyllum nodosum, Ecklonia maxima, Sargassum spp., and Laminaria spp., although green and red algae are also utilized. Seaweed extracts contain a complex mixture of naturally occurring phytohormones (auxins, cytokinins, gibberellins and brassinosteroids), betaines, mannitol, alginates, laminarin, fucoidans, amino acids, vitamins, polyphenols, and essential mineral nutrients. Rather than acting as fertilizers, these bioactive compounds regulate cellular metabolism and signaling pathways. Their application enhances chlorophyll biosynthesis, photosynthetic efficiency, osmotic adjustment, antioxidant metabolism, carbohydrate translocation, and hormonal balance. They also stimulate root architecture, increase nutrient acquisition, improve pollen viability, enhance fruit development, and delay senescence. In tomato, chilli, eggplant, and sweet pepper, seaweed extracts consistently improve flowering, fruit set, fruit size, vitamin C content, lycopene concentration, total soluble solids, antioxidant capacity, and post-harvest shelf life while increasing tolerance to drought, heat, and salinity stress.

3.3 Protein Hydrolysates and Amino Acid-Based Biostimulants

Protein hydrolysates are mixtures of peptides, oligopeptides, and free amino acids produced through enzymatic or chemical hydrolysis of plant proteins (soybean, alfalfa, legume biomass) or animal proteins (collagen and gelatin).These compounds serve as signaling molecules that regulate carbon and nitrogen metabolism. Protein hydrolysates stimulate nitrate reductase activity, chlorophyll synthesis, Rubisco activity, amino acid metabolism, and the biosynthesis of endogenous phytohormones. They also improve membrane stability and activate antioxidant defense systems during stress conditions. Their application promotes vigorous root growth, increases nutrient uptake efficiency, accelerates vegetative development, enhances flowering, and improves fruit quality characteristics such as soluble solids, sugars, pigments, and antioxidants. In solanaceous vegetables, protein hydrolysates have been shown to reduce oxidative damage caused by drought and salinity while significantly increasing marketable fruit yield.

3.4 Beneficial Microorganisms

Microbial biostimulants consist of beneficial bacteria and fungi that colonize the rhizosphere or plant tissues and improve plant growth through multiple biological mechanisms. Major groups include Plant Growth-Promoting Rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), Trichoderma spp., Bacillus spp., Pseudomonas spp., Azospirillum spp., and Rhizobium species. These microorganisms stimulate biological nitrogen fixation, phosphorus and potassium solubilization, siderophore production, phytohormone synthesis, ACC-deaminase activity, induced systemic resistance, and beneficial rhizosphere interactions. They improve nutrient acquisition, root morphology, soil microbial diversity, and plant resilience against abiotic and biotic stresses. In tomato, chilli, and eggplant, microbial biostimulants enhance transplant establishment, nutrient uptake, flowering, fruit production, disease suppression, and nutrient use efficiency while reducing dependence on synthetic fertilizers.

3.5 Silicon-Based Biostimulants

Although silicon is not considered an essential nutrient for most dicotyledonous plants, it functions as an important beneficial element. Silicon biostimulants are commonly applied as potassium silicate, sodium silicate, silicic acid, calcium silicate, or nano-silicon formulations.Silicon is deposited beneath the cuticle and within cell walls, increasing tissue rigidity and reducing transpiration losses. It enhances antioxidant enzyme activity, regulates osmotic adjustment, improves water-use efficiency, stabilizes photosynthetic pigments, and decreases reactive oxygen species accumulation during environmental stress.In solanaceous vegetables, silicon significantly improves tolerance to drought, salinity, high temperature, and heavy metal toxicity while enhancing fruit firmness, shelf life, and resistance to fungal diseases.

3.6 Chitosan and Other Biopolymers

Chitosan is a biodegradable polysaccharide obtained by deacetylation of chitin, which is naturally present in crustacean shells, insects, and fungal cell walls.It functions as an elicitor molecule capable of activating plant innate immunity through induction of defence-related genes and secondary metabolite synthesis. Chitosan stimulates antioxidant enzymes, phenylalanine ammonia-lyase (PAL), phytoalexin production, lignification, and callose deposition while enhancing membrane stability.Foliar application of chitosan improves seed germination, vegetative growth, flowering, fruit development, disease resistance, and post-harvest quality in tomato, chilli, and eggplant.

3.7 Inorganic Beneficial Elements

Certain mineral elements, including silicon, selenium, cobalt, titanium, and rare earth elements, exhibit biostimulatory effects when supplied at low concentrations. These elements participate in antioxidant metabolism, osmotic regulation, chloroplast protection, enzyme activation, and redox homeostasis. Selenium enhances glutathione metabolism, while cobalt improves nitrogen metabolism and biological nitrogen fixation in associated microorganisms. Appropriate application of beneficial elements improves photosynthesis, nutrient use efficiency, stress tolerance, and fruit quality in vegetable crops.

3.8 Botanical Extracts and Plant-Derived Biostimulants

Plant-derived biostimulants are produced from medicinal plants, crop residues, herbs, moringa leaves, aloe vera, garlic, neem, and numerous other botanical sources. These extracts contain flavonoids, phenolic acids, terpenoids, alkaloids, vitamins, polysaccharides, natural antioxidants, and phytohormone-like compounds that regulate plant metabolism. They stimulate chlorophyll synthesis, nutrient transport, antioxidant defence, osmotic adjustment, and secondary metabolite production.In solanaceous vegetables, botanical extracts improve seed germination, root development, flowering, fruit yield, fruit nutritional quality, and tolerance to abiotic stresses while supporting environmentally sustainable crop production.

4. Mechanism of Action of Plant Biostimulant

Biostimulants comprise diverse substances and microorganisms, their mechanisms of action differ; however, they ultimately converge toward improving plant growth, resource-use efficiency, and resilience under both optimal and adverse environmental conditions .

4.1 Modulation of Root Growth and Architecture

Biostimulants stimulate the formation of lateral roots, root hairs, and overall root biomass through auxin-like and cytokinin-mediated signalling pathways. A larger and more active root system increases soil exploration, water absorption, and nutrient uptake. Humic substances, seaweed extracts, and protein hydrolysates activate plasma membrane H^+-ATPase, facilitating proton extrusion and enhancing nutrient transport across root membranes. In solanaceous vegetables, improved root architecture results in better transplant establishment, enhanced nutrient acquisition, and increased tolerance to drought and nutrient-deficient soils .

4.2. Improvement of Nutrient Uptake and Nutrient Use Efficiency

Plant biostimulants enhance the absorption, translocation, and assimilation of essential macro- and micronutrients by stimulating root membrane transporters and increasing nutrient availability in the rhizosphere. Beneficial microorganisms solubilize phosphorus, mobilize potassium, fix atmospheric nitrogen, and produce siderophores that improve iron acquisition. Enhanced nutrient assimilation increases nitrogen metabolism, chlorophyll biosynthesis, amino acid synthesis, and protein accumulation, resulting in improved nutrient use efficiency (NUE) and reduced fertilizer requirements (Calvo et al., 2014; Rouphael & Colla, 2020).

4.3. Regulation of Photosynthesis and Primary Metabolism

Biostimulants enhance photosynthetic performance by increasing chlorophyll concentration, improving chloroplast development, maintaining stomatal conductance, and stimulating carbon fixation. Protein hydrolysates and seaweed extracts increase Rubisco activity, ATP synthesis, and carbohydrate metabolism, thereby promoting biomass accumulation and reproductive growth. Enhanced photosynthetic efficiency contributes directly to improved fruit yield and quality in tomato, chilli, pepper, and eggplant (Colla et al., 2017).

4.4. Activation of Antioxidant Defense System

Environmental stresses induce excessive production of reactive oxygen species (ROS), which damage cellular membranes, proteins, lipids, and nucleic acids. Biostimulants enhance both enzymatic and non-enzymatic antioxidant defence mechanisms by increasing the activity of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), glutathione reductase (GR), and antioxidants such as ascorbic acid, glutathione, carotenoids, and phenolic compounds. These protective systems minimize oxidative damage, preserve membrane integrity, and maintain cellular homeostasis during stress (Rouphael et al., 2021; Yakhin et al., 2017).

4.5. Regulation of Phytohormonal Balance

Many biostimulants influence endogenous phytohormone biosynthesis and signalling. Seaweed extracts contain hormone-like compounds, while beneficial microorganisms synthesize auxins (IAA), cytokinins, gibberellins, and abscisic acid modulators. These hormones regulate cell division, elongation, flowering, fruit development, and senescence. Balanced hormonal regulation enhances reproductive success, fruit set, and overall plant productivity in solanaceous crops (du Jardin, 2015).

4.6. Enhancement of Abiotic Stress Tolerance

One of the most important mechanisms of plant biostimulants is the enhancement of tolerance to drought, salinity, heat, cold, and heavy metal stress. Biostimulants stimulate osmotic adjustment by increasing the accumulation of compatible osmolytes such as proline, glycine betaine, soluble sugars, and polyamines. They also regulate aquaporin expression, maintain cellular water potential, stabilize membranes, and protect the photosynthetic apparatus under stress conditions. Consequently, plants maintain higher physiological activity and experience lower yield losses under adverse environments (Rouphael & Colla, 2020).

4.7. Improvement of Soil Health and Rhizosphere Activity

Microbial biostimulants enhance rhizosphere biodiversity by promoting beneficial microbial populations and suppressing pathogenic organisms. They stimulate extracellular enzyme production, organic matter decomposition, nutrient mineralization, and biological nitrogen fixation while improving soil aggregation and structure. Enhanced microbial interactions improve nutrient cycling and long-term soil fertility, which are particularly important in intensive vegetable production systems (Backer et al., 2018).

4.8. Induction of Plant Defence Responses

Several biostimulants function as elicitors that activate induced systemic resistance (ISR) and systemic acquired resistance (SAR). Chitosan, beneficial microbes, and seaweed polysaccharides stimulate defence-related genes, phenylpropanoid metabolism, lignin deposition, phytoalexin production, and pathogenesis-related proteins. These responses strengthen natural defence mechanisms and reduce disease severity without directly acting as pesticides (Van Oosten et al., 2017).

4.9. Improvement of Fruit Quality and Post-harvest Performance

Biostimulants increase carbohydrate partitioning towards fruits and stimulate the synthesis of secondary metabolites such as lycopene, carotenoids, vitamin C, flavonoids, anthocyanins, and phenolic compounds. These changes improve fruit colour, flavour, nutritional quality, antioxidant capacity, firmness, and shelf life while reducing post-harvest deterioration in tomato, chilli, sweet pepper, and eggplant (Rouphael et al., 2021).

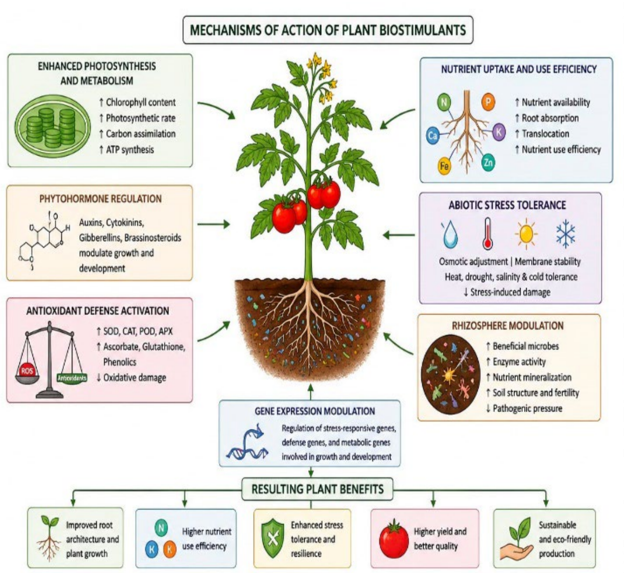


Figure 2: mechanisms of action of plant biostimulants

5.Application Methods of Plant Biostimulants

The effectiveness of plant biostimulants depends not only on their chemical or biological composition but also on the method of application, crop growth stage, environmental conditions, and dosage. Appropriate application techniques ensure efficient absorption of bioactive compounds, maximize physiological responses, and improve nutrient use efficiency. In solanaceous vegetable crops such as tomato, eggplant, chilli, and sweet pepper, biostimulants are commonly applied through foliar spraying, soil application, seed treatment, root dipping, fertigation, and protected cultivation systems.

5.1. Foliar Application

Foliar spraying is the most widely adopted method for applying plant biostimulants because bioactive molecules are rapidly absorbed through the leaf cuticle and stomata. This method bypasses soil-related limitations such as nutrient fixation and poor microbial activity, resulting in faster physiological responses. Seaweed extracts, protein hydrolysates, amino acids, humic substances, silicon formulations, and chitosan are frequently applied as foliar sprays. Foliar application enhances chlorophyll synthesis, photosynthetic efficiency, antioxidant enzyme activity, phytohormone regulation, flowering, fruit set, and fruit quality. It is particularly effective during flowering, fruit development, and periods of abiotic stress.

Advantages

- Rapid absorption and plant response
- Lower application rates
- Improved stress tolerance
- Enhanced fruit quality and marketable yield

5.2. Soil Application

Soil application delivers biostimulants directly to the rhizosphere, where they interact with plant roots and beneficial microorganisms. Humic substances, fulvic acids, microbial inoculants, compost extracts, and biochar-based formulations are commonly applied through soil incorporation or drenching. This method improves soil aggregation, organic matter decomposition, microbial diversity, nutrient mineralization, root proliferation, and nutrient availability. Soil application is especially beneficial during transplant establishment and throughout vegetative growth.

Advantages

- Improved soil fertility
- Enhanced root development
- Increased microbial activity
- Better nutrient cycling

5.3. Seed Treatment (Seed Priming or Seed Coating)

Seed treatment involves soaking or coating seeds with biostimulants before sowing. Protein hydrolysates, seaweed extracts, humic acids, microbial inoculants, silicon, and chitosan are widely used for seed priming. Seed treatment accelerates germination, improves seedling vigour, increases root growth, enhances antioxidant defense, and improves tolerance to drought and salinity during early growth.

Advantages

- Uniform germination
- Vigorous seedlings
- Better field establishment
- Improved stress tolerance

5.4. Root Dipping Before Transplanting

Root dipping is commonly practiced in transplanted vegetable crops. Seedling roots are immersed in a suspension containing microbial inoculants, seaweed extracts, humic substances, or amino acid formulations before transplanting. This technique enhances root colonization by beneficial microorganisms, stimulates root regeneration, reduces transplant shock, and improves nutrient uptake during early establishment.

Advantages

- Reduced transplant stress
- Faster root establishment
- Improved survival rate
- Enhanced nutrient absorption

5.5. Fertigation

Fertigation combines irrigation with the application of soluble biostimulants through drip or sprinkler irrigation systems. Humic substances, amino acids, seaweed extracts, and microbial products compatible with irrigation systems are commonly used.This method ensures uniform distribution in the root zone while improving nutrient availability, water-use efficiency, and crop productivity. Fertigation is particularly suitable for greenhouse and protected cultivation of solanaceous vegetables.

Advantages

- Uniform application
- Efficient water and nutrient management
- Reduced nutrient losses
- Higher nutrient use efficiency

5.6. Hydroponic and Protected Cultivation

In hydroponic and greenhouse production systems, biostimulants are incorporated directly into nutrient solutions or applied as foliar sprays. Seaweed extracts, amino acids, microbial inoculants, and protein hydrolysates improve nutrient uptake, photosynthesis, fruit quality, and tolerance to environmental stress under intensive cultivation.Their use is increasing because of the need for high productivity with efficient resource utilization in controlled environments.

• Enhanced nutrient solution efficiency
• Improved crop quality
• Better stress management
• Increased productivity.

Application method	Common Biostimulants	Major benefits
1.Foliar spray	Seaweed extracts, protein hydrolysates, amino acids, silicon, chitosan	Improved photosynthesis, flowering,fruit quality, stress tolerance.
2. Soil application	Humic substances, fulvic acids, microbial inoculants	Root growth, nutrient uptake, soil health
3. Seed treatment	Seaweed extracts, humic acids, PGPR, chitosan	Germination, seedling vigour, early stress tolerance
4. Root dipping	PGPR, AMF, seaweed extracts, humic substances	Transplant establishment, root regeneration
5. Fertigation	Humic acids, amino acids, seaweed extracts	Uniform nutrient delivery, water-use efficiency

6.Factors Influencing the Efficiency of Biostimulant Application

The success of biostimulant application depends on several
interacting factors:

• Type and composition of the biostimulant
• Concentration and dosage
• Crop species and cultivar
• Growth stage of the plant
• Method and frequency of application
• Soil properties and microbial activity
• Temperature, humidity, and irrigation conditions
• Compatibility with fertilizers and crop protection products

Optimizing these factors maximizes physiological responses and ensures consistent improvements in crop growth, yield, and quality.

7.Global Contribution of Biostimulants in Solanaceous Vegetable Crops

The increasing global demand for sustainable agricultural production has accelerated the adoption of plant biostimulants across horticultural systems, particularly in solanaceous vegetable crops such as tomato (Solanum lycopersicum L.), eggplant (Solanum melongena L.), chilli (Capsicum annuum L.), and sweet pepper (Capsicum annuum var. grossum). These crops contribute substantially to global vegetable production but are highly susceptible to abiotic stresses, nutrient deficiencies, and soil degradation. Consequently, plant biostimulants have become an integral component of sustainable crop management by improving productivity, resource-use efficiency, and environmental sustainability (du Jardin, 2015; Rouphael & Colla, 2020). Globally, commercial biostimulant products derived from seaweed extracts, humic substances, protein hydrolysates, beneficial microorganisms, silicon, and amino acids are increasingly incorporated into integrated nutrient management programmes. Their application has demonstrated significant improvements in seed germination, root development, nutrient uptake, photosynthetic efficiency, flowering, fruit set, yield, and fruit quality while simultaneously reducing dependence on synthetic fertilizers. These benefits have contributed to increased profitability and improved sustainability in intensive vegetable production systems (Calvo et al., 2014; Rouphael et al., 2021).

7.1 Contribution in Tomato

Tomato is the most extensively studied solanaceous vegetable with respect to biostimulant application. Research conducted in Europe, North America, Asia, and the Mediterranean region has consistently demonstrated that seaweed extracts, protein hydrolysates, humic substances, and microbial biostimulants increase vegetative growth, chlorophyll concentration, nutrient uptake, flowering, fruit set, marketable yield, and fruit nutritional quality. Improvements in vitamin C, lycopene, carotenoids, phenolic compounds, and antioxidant activity have also been widely reported. Under drought and salinity stress, biostimulants reduce oxidative damage and improve water-use efficiency, resulting in higher yield stability (Colla et al., 2017; Rouphael et al., 2021).

7.2 Contribution in Chilli and Sweet Pepper

Biostimulants have become increasingly important in chilli and sweet pepper cultivation because these crops are highly sensitive to temperature fluctuations and water deficits during flowering and fruit development. Foliar application of seaweed extracts, amino acids, silicon, and microbial inoculants has been shown to improve pollen viability, fruit retention, nutrient uptake, chlorophyll synthesis, and antioxidant metabolism. Consequently, significant improvements in fruit number, fruit size, capsaicin concentration, vitamin C content, colour development, and shelf life have been reported under both open-field and protected cultivation systems (Van Oosten et al., 2017; Rouphael et al., 2021).

7.3 Contribution in Eggplant

In eggplant cultivation, biostimulants improve root architecture, nutrient acquisition, vegetative growth, flowering, and fruit production. Beneficial microorganisms such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) enhance phosphorus solubilization, biological nitrogen fixation, and beneficial root–microbe interactions, thereby improving nutrient use efficiency. Seaweed extracts and humic substances also increase antioxidant activity and improve fruit quality under drought and salinity stress (Backer et al., 2018).

7.4 Contribution to Climate-Resilient Vegetable Production

Climate change has intensified the frequency of drought, salinity, heat stress, and irregular rainfall, significantly affecting vegetable production worldwide. Plant biostimulants contribute to climate resilience by enhancing antioxidant defence systems, osmotic adjustment, phytohormonal regulation, membrane stability, and photosynthetic efficiency. These mechanisms reduce stress-induced cellular damage and enable plants to maintain growth and productivity under adverse environmental conditions. Consequently, biostimulants are increasingly recognized as an essential component of climate-smart horticulture (Rouphael & Colla, 2020).

7.5 Contribution to Sustainable Agriculture

Beyond improving crop productivity, biostimulants contribute substantially to environmental sustainability. They increase nutrient use efficiency, reduce fertilizer losses through leaching and volatilization, improve soil organic matter turnover, stimulate beneficial microbial diversity, and enhance soil health. Their integration into precision nutrient management programmes reduces the environmental footprint of vegetable production while supporting long-term agricultural sustainability. These characteristics align with the United Nations Sustainable Development Goals (SDGs), particularly those related to food security, sustainable agriculture, and responsible resource management (United Nations, 2022).

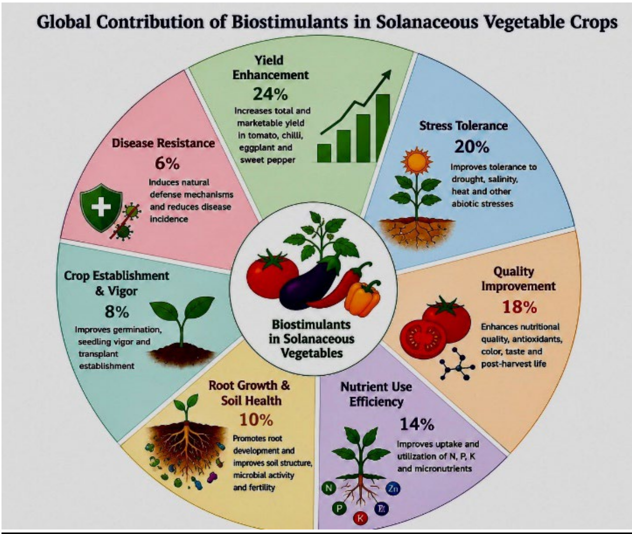


Figure 3: global contribution of biostimulants

7.6 Future Perspectives

The global biostimulant industry is expanding rapidly owing to increasing awareness of sustainable crop production and stricter environmental regulations regarding fertilizer and pesticide use. Future research should focus on elucidating molecular mechanisms, optimizing crop-specific application strategies, integrating biostimulants with precision agriculture technologies, and developing next-generation formulations that combine bioactive compounds with beneficial microorganisms. Such innovations will further strengthen the role of biostimulants in enhancing the productivity, quality, and resilience of solanaceous vegetable crops under changing climatic conditions.

8.Conclusion

The increasing demand for sustainable food production, coupled with the challenges imposed by climate change, soil degradation, and the excessive use of synthetic agrochemicals, has accelerated the adoption of plant biostimulants as an integral component of modern horticulture. In solanaceous vegetable crops, including tomato (Solanum lycopersicum L.), chilli and sweet pepper (Capsicum annuum L.), and eggplant (Solanum melongena L.), biostimulants have demonstrated significant potential to enhance plant growth, nutrient use efficiency, stress tolerance, fruit quality, and overall productivity through the regulation of physiological, biochemical, and molecular processes rather than by serving as direct nutrient sources. The diverse categories of biostimulants—including humic and fulvic substances, seaweed extracts, protein hydrolysates, beneficial microorganisms, silicon-based products, chitosan, and botanical extracts—operate through complementary mechanisms that improve root architecture, activate nutrient transport systems, optimize photosynthesis, regulate phytohormonal signalling, strengthen antioxidant defence, and promote beneficial rhizosphere interactions.. Future research integrating multi-omics approaches, precision agriculture technologies, artificial intelligence-based decision support systems, and advanced formulation technologies will facilitate the development of next-generation biostimulants with improved consistency and efficacy. Overall, plant biostimulants represent a promising and environmentally sustainable strategy for enhancing the productivity, nutritional quality, and climate resilience of solanaceous vegetable crops. Their integration into integrated nutrient management and climate-smart agricultural practices will play an increasingly important role in achieving global food security while minimizing the environmental footprint of intensive vegetable production.

9. Referances

- Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., Subramanian, S., & Smith, D. L. (2018). Plant biostimulants: A review of the science and technology behind their use. Frontiers in Plant Science, 9, 1473.
- Calvo, P., Nelson, L., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. Plant and Soil, 383(1–2), 3–41.
- Canellas, L. P., Olivares, F. L., Aguiar, N. O., Jones, D. L., Nebbioso, A., Mazzei, P., & Piccolo, A. (2015). Humic and fulvic acids as biostimulants in horticulture. Chemical and Biological Technologies in Agriculture, 2, 15.
- Colla, G., Hoagland, L., Ruzzi, M., Cardarelli, M., Bonini, P., Canaguier, R., & Rouphael, Y. (2017). Biostimulant action of protein hydrolysates: Unraveling their effects on plant physiology and crop performance. Scientia Horticulturae, 196, 28–38.
- du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. Scientia Horticulturae, 196, 3–14.
- European Parliament and Council. (2019). Regulation (EU) 2019/1009 laying down rules on the making available on the market of EU fertilising products. Official Journal of the European Union.
- Halpern, M., Bar-Tal, A., Ofek, M., Minz, D., Muller, T., & Yermiyahu, U. (2015). The use of biostimulants for enhancing nutrient uptake. Journal of Experimental Botany, 66(21), 6637–6648.
- Khan, W., Rayirath, U. P., Subramanian, S., Jithesh, M. N., Rayorath, P., Hodges, D. M., Critchley, A. T., Craigie, J. S., Norrie, J., & Prithiviraj, B. (2009). Seaweed extracts as biostimulants of plant growth and

development. Journal of Plant Growth Regulation, 28, 386–399.

- Rouphael, Y., & Colla, G. (2020). Toward a sustainable agriculture through plant biostimulants: From experimental data to practical applications. Biology, 9(12), 431.
- Rouphael, Y., Colla, G., Giordano, M., El-Nakhel, C., Kyriacou, M. C., & De Pascale, S. (2021). Biostimulant substances for sustainable agriculture: Main categories, mechanisms and applications. Agronomy, 11, 1419.
- Van Oosten, M. J., Pepe, O., De Pascale, S., Silletti, S., & Maggio, A. (2017). The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. Frontiers in Plant Science, 8, 1229.
- Yakhin, O. I., Lubyanov, A. A., Yakhin, I. A., & Brown, P. H. (2017). Biostimulants in Plant Science: A global perspective. Frontiers in Plant Science, 7, 2049.
- Bulgari, R., Franzoni, G., & Ferrante, A. (2019). Biostimulants application in horticultural crops under abiotic stress conditions. Agronomy, 9(6), 306.
- Sharma, H. S. S., Fleming, C., Selby, C., Rao, J. R., & Martin, T. (2014). Plant biostimulants: A review on the processing of macroalgae and the use of extracts for crop management. Journal of Applied Phycology, 26, 465–490.
- Parađiković, N., Teklić, T., Zeljković, S., Lisjak, M., & Špoljarević, M. (2019). Biostimulants research in some horticultural plant species—A review. Food and Energy Security, 8(2), e00162.
- Mądry, W., et al. (2022). Plant biostimulants in sustainable vegetable production. Horticulturae, 8, 1047.
- Canellas, L. P., & Olivares, F. L. (2014). Physiological responses to humic substances as plant growth promoters. Chemical and Biological Technologies in Agriculture, 1, 3.
- Nardi, S., Pizzeghello, D., Schiavon, M., & Ertani, A. (2016). Plant biostimulants: Physiological responses induced by protein hydrolyzed-based products and humic substances. Frontiers in Plant Science, 7, 435.
- Ertani, A., Pizzeghello, D., Altissimo, A., & Nardi, S. (2013). Use of biostimulants to improve crop quality and nutritional value. Journal of Food, Agriculture & Environment, 11, 1094–1100.
- Craigie, J. S. (2011). Seaweed extract stimuli in plant science and agriculture. Journal of Applied Phycology, 23, 371–393.
- Colla, G., Rouphael, Y., Bonini, P., & Cardarelli, M. (2015). Co-application of protein hydrolysates and plant biostimulants in tomato.
- Rouphael, Y., Kyriacou, M. C., Petropoulos, S. A., De Pascale, S., & Colla, G. (2018). Improving vegetable quality through biostimulants. Scientia Horticulturae.
- Sestili, F., Rouphael, Y., Cardarelli, M., et al. (2018). Protein hydrolysate biostimulants improve tomato growth under greenhouse conditions.
- Bulgari, R., Cocetta, G., Trivellini, A., Vernieri, P., & Ferrante, A. (2015). Biostimulants and crop responses in horticultural plants.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Ravi Dupdal
ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Ballari-583104

B.S. Naik
ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Ballari-583104

M.N. Ramesha
ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Ballari-583104

K.N. Ravi
ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Ballari-583104

B.K. Rao
ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Ballari-583104

ARTICLE ID: 08

Climate-Resilient Agriculture through Farm Pond Intervention: A Success Story of a Dryland Farmer in the Semi-Arid Region

Farmer Details

Shri. Rajshekar Reddy, a 45 year-old farmer from K. Veerapura village in Ballari taluk of Ballari district of Karnataka, owns five acres of rainfed agricultural land. Traditionally he cultivated crops such as redgram, jowar and chickpea under rainfed conditions relying entirely on monsoon rainfall for agricultural production. His farming system was largely subsistence-oriented with limited scope for crop diversification due to the absence of assured irrigation facilities. However, in recent years the region has experienced low and erratic rainfall along with frequent occurrences of drought including both mid-season and terminal droughts. These adverse climatic conditions significantly affected crop growth and yields leading to instability in production. As a result, the farmer experienced declining productivity, increased vulnerability to crop failure and reduced farm profitability making it difficult to sustain his livelihood solely through agriculture.

Background

Prior to the adoption of the farm pond, Shri. Rajshekar Reddy was entirely dependent on monsoon rainfall for crop cultivation. Frequent rainfall failures, including both mid-season and terminal droughts adversely affected crop growth resulting in poor crop performance and significantly reduced yields. These climatic uncertainties not only increased the risk of crop failure but also led to instability in farm income. Consequently, despite incurring relatively high cultivation costs on inputs such as seeds, fertilizers and labor the returns remained minimal and often insufficient to cover his expenditure. The absence of assured irrigation facilities further constrained his ability to diversify into high-value crops or adopt improved agricultural technologies and practices. This limited resilience of his farming system made him highly vulnerable to climatic variability. As a result, he was compelled to supplement his income through non-farm employment activities to sustain his household livelihood.

Farm pond technology intervention

During 2014-15, the Government of Karnataka introduced the Krishi Bhagya Scheme with the objective of promoting rainwater harvesting and enhancing agricultural productivity in rainfed regions. Under this initiative, Shri. Rajshekar Reddy approached the Agriculture Department and availed himself of the scheme benefits for the construction of a farm pond in his field during 2016-17. A farm pond measuring 30 × 30 × 3 meters was constructed to facilitate the collection and storage of rainwater. This intervention enabled the farmer to access a reliable source of water for providing supplemental irrigation during critical stages of crop growth, thereby reducing dependence on erratic rainfall. The availability of stored water significantly improved soil moisture conditions and enhanced crop survival during dry spells. With improved water availability from the farm pond, the farmer gradually diversified his cropping system by integrating horticultural crops with traditional field crops on his five-acre farm.

He established a mixed dryland fruit orchard comprising sapota, lemon, and guava with technical guidance and financial assistance from the Department of Horticulture for orchard establishment and management. During the *rabi* season, chickpea was cultivated as an intercrop between the fruit trees. This integrated farming approach ensured efficient utilization of land and harvested rainwater stored in the farm pond while providing an additional source of income during the gestation period of the fruit orchard. The shift towards horticultural diversification enhanced farm resilience, improved water and land use efficiency, reduced production risks under rainfed conditions, and strengthened the long-term sustainability and profitability of the farming system.

Table 1: Impact of Farm pond on cropping pattern, crop yields and income

Crop	Area (Acre)	Yields (q acre^{1})	COC (₹ acre^{1})	Gross returns (₹ acre^{1})	Net returns (₹ acre^{1})	B:C Ratio
Before farm pond intervention						
Redgram	2.0	6.5	26825	46800	19975	1.74
Chickpea	1.5	4.30	14766	24940	10174	1.68
After farm pond intervention						
Sapota + lemon guava +Chickpea* (intercrop)	5.0	50q (sapota) + 35q (lemon) + 15q (guava)+ 13q (chickpea)	154300	283411	125700	1.83

Note: * Chickpea is grown as an intercrop with mixed horticulture orchard after the farm pond intervention.

Impact of farm pond intervention

The farm pond intervention resulted in a significant improvement in farm productivity and income by enabling a shift from rainfed field crops to a diversified horticulture-based farming system. Prior to the intervention, the farmer cultivated redgram (2.0 acres) and chickpea (1.5 acres) without farm pond water source under rainfed conditions. Crop productivity and profitability were constrained by erratic rainfall, resulting in modest net returns of ₹19,975 acre^{-1} from redgram and ₹10,174 acre^{-1} from chickpea, with benefit-cost ratios of 1.74 and 1.68, respectively. After adoption of the farm pond, the availability of assured supplemental irrigation enabled the farmer to diversify the entire five-acre farm by establishing a mixed orchard of sapota, lemon, and guava with chickpea grown as an intercrop during the *rabi* season. The diversified production system yielded 50q of sapota, 35q of lemon, 15q of guava, and 13q of chickpea. Although the cost of cultivation increased to ₹1,54,300 due to investments in orchard establishment and improved crop management, the gross returns increased substantially to ₹2,83,411, generating a net return of approximately ₹1,25,700 with a benefit-cost ratio of 1.83. Overall, the farm pond intervention facilitated crop diversification, enhanced the efficient use of harvested rainwater and land resources, increased farm profitability, and reduced the production risks associated with rainfall variability, thereby improving the long-term sustainability and resilience of the farming system.

Conclusion

The farm pond intervention demonstrated that assured supplemental irrigation through harvested rainwater can effectively transform traditional rainfed farming into a diversified and resilient production system. By facilitating the integration of horticultural crops with field crops, the farm pond enhanced agricultural productivity, improved water and land use efficiency, and increased overall farm profitability. Crop diversification not only generated higher and more stable farm income but also contributed to improved household nutritional security through the production of diverse fruits and pulses. Furthermore, the availability of supplemental irrigation reduced the risks associated with rainfall variability and enabled sustainable utilization of available natural resources. Overall, farm ponds represent an effective climate-resilient water management intervention that strengthens diversified farming systems, enhances farmers' livelihoods, and promotes sustainable agricultural development in semi-arid dryland regions.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Subrot Bhattacharyya
M.Sc. Scholar, Department of Tea Husbandry & Technology, Assam Agricultural University, Jorhat, Assam

Manuranjan Gogoi
Assistant Professor, Department of Tea Husbandry & Technology, Assam Agricultural University, Jorhat, Assam

Manish Upadhyaya
M.Sc. Scholar, Department of Tea Husbandry & Technology, College of Agriculture, Assam Agricultural University, Jorhat, Assam

Anubhab Dhadumia
M.Sc. Scholar, Department of Horticulture, Biswanath College of Agriculture, Assam Agricultural University, Jorhat, Assam

Pragyan Gogoi
B.Sc. Scholar, Assam Agricultural University, Jorhat, Assam

ARTICLE ID: 9

TEA ECOPHYSIOLOGY: HOW CLIMATE, SOIL, AND LIGHT SHAPE THE FLAVOUR, YIELD, AND RESILIENCE OF TEA

Abstract

Tea (*Camellia sinensis* L.) is one of the most widely consumed beverages in the world. It represents a major commercial crop supporting the livelihoods of millions of people across Asia, Africa and Latin America. The growth, productivity, quality and resilience of tea plants are profoundly influenced by environmental factors, particularly climate, soil, and light. The interaction among these ecological variables determines physiological processes such as photosynthesis, respiration, nutrient uptake, water relations, secondary metabolite synthesis, and stress tolerance. These physiological responses ultimately influence tea yield and the accumulation of quality-determining compounds, including catechins, caffeine, theanine, polyphenols, flavonoids, and volatile aroma compounds. Understanding tea ecophysiology has become increasingly important because climate change, unpredictable rainfall, increasing temperatures, and soil degradation pose significant challenges to sustainable tea production worldwide. Modern tea cultivation therefore requires an integrated understanding of environmental physiology, precision nutrient management, and climate-adaptive cultivation practices. This review discusses the ecophysiological principles governing tea growth with emphasis on the influence of climate, soil, and environmental interactions. It also highlights recent scientific findings that improve tea productivity while maintaining beverage quality and ecological sustainability.

Keywords: *Camellia sinensis*, ecophysiology, climate, soil, tea quality, photosynthesis, secondary metabolites, sustainable tea production

1. Introduction

Tea is grown in tropical and subtropical countries where the climate supports its perpetual development, making it the second most popular beverage in the world after water. India, China, Sri Lanka, Kenya, Japan, Vietnam, Indonesia, and a number of developing nations are among the many agroecological zones where tea is commercially grown. Assam, Darjeeling, Nilgiri, Kangra, and Dooars are significant tea-growing regions that produce different teas known for their distinct flavour and aroma, making India one of the world's top producers of tea.

In addition to genetic considerations, the environment in which the plant develops affects the quality of the tea. Understanding how environmental conditions affect plant physiological processes that govern yield, quality, and resilience is the main goal of the idea of tea ecophysiology. Seasonal flush development, transpiration, respiration, and photosynthesis are all regulated by climate. The availability of nutrients, root development, microbial activity, and water retention are all influenced by the soil. Carbon fixation, leaf development, chlorophyll generation, and the manufacture of secondary metabolites that give tea its flavour are all influenced by light.

The main reason tea is picked is for its young shoots, which are made up of two leaves and a bud. The sensory quality of the beverage is determined by the high amounts of catechins, amino acids, caffeine, volatile compounds, and other phytochemicals found in these delicate shoots. Through the regulation of metabolic pathways within the tea plant, environmental circumstances have a significant impact on the concentration of these chemicals.

One of the biggest issues affecting tea production in recent decades has been climate change. Extreme weather events, lengthy droughts, rising temperatures, and erratic rainfall all have an impact on tea productivity and change the biochemical makeup of harvested leaves. Sustainable production is further threatened by soil degradation brought on by heavy farming. As a result, enhancing crop management and creating climate-resilient tea production systems require an understanding of tea ecophysiology.

2. Tea Plant and Its Ecophysiology

Tea belongs to the family Theaceae and is scientifically known as *Camellia sinensis*. Two principal botanical varieties are recognized: *Camellia sinensis* var. *sinensis*, which is adapted to relatively cooler environments and produces small leaves, and *Camellia sinensis* var. *assamica*, which grows vigorously under warm, humid conditions and bears larger leaves with higher productivity. Tea is an evergreen perennial shrub with a deep and extensive root system that enables efficient absorption of water and nutrients. Continuous harvesting stimulates the production of young vegetative shoots, making leaf physiology the primary determinant of crop productivity and commercial quality.

Tea ecophysiology studies how environmental conditions control physiological processes that affect shoot growth, leaf quality, and long-term productivity. These activities include photosynthesis, respiration, transpiration, mineral nutrition, hormone regulation, and stress responses. Because of their higher chlorophyll concentration, stomatal conductance, mesophyll efficiency, and enzymatic activity, young growing leaves have better photosynthetic activity than mature leaves, which leads to improved carbon assimilation. In addition to supporting plant growth and development, the carbohydrates generated by photosynthesis act as precursors for secondary metabolites, such as catechins, caffeine, theanine, and aromatic chemicals that affect the quality of tea.

3. Influence of Climate on Tea Growth and Development

Climate is the most influential ecological factor governing tea production. Temperature, rainfall, humidity, wind, and atmospheric carbon dioxide interact continuously to regulate plant physiology.

Temperature

Nearly all of the metabolic processes in tea plants are impacted by temperature. Enzyme activity, photosynthesis, leaf expansion, and cell division are all facilitated by ideal temperatures. In general, strong vegetative development is supported by temperatures between 18°C and 30°C. High temperatures decrease the stability of chlorophyll, speed up respiration, increase water loss, and inhibit the beginning of shoots. On the other hand, cold temperatures postpone leaf emergence and slow metabolic activities. While prolonged heat stress results in leaf burning and decreased photosynthetic efficiency, frost injury destroys vulnerable shoots by rupturing cellular membranes.

Rainfall

Throughout the growing season, tea needs a lot of evenly spaced rainfall. When combined with adequate drainage, annual precipitation between 1500 and 2500 mm promotes continuous shoot production. Carbon absorption, stomatal conductance, nutrient transport, and leaf turgor are all directly impacted by water availability. Drought increases oxidative stress in plant tissues while decreasing shoot density, leaf size, and harvest frequency. By encouraging waterlogging, nitrogen leaching, and fungal infections that damage roots and plants, excessive rainfall can also be detrimental.

Relative Humidity

Tea performs best under humid atmospheric conditions. Relative humidity between 70 and 90 percent minimizes excessive transpiration and maintains favourable water balance within leaves.

Low humidity increases evaporative demand, resulting in stomatal closure and reduced photosynthesis. High humidity supports continuous shoot growth but may also encourage certain foliar diseases if air circulation is poor.

Wind

Moderate air movement improves gas exchange and reduces disease incidence. Strong winds increase transpiration, break young shoots, and reduce leaf quality. Wind also alters canopy temperature and influences pollination in seed-producing tea gardens.

Atmospheric Carbon Dioxide

Increasing atmospheric carbon dioxide can stimulate photosynthesis and biomass accumulation under favourable nutrient and water conditions. However, the beneficial effects may be offset by rising temperatures and moisture stress associated with climate change.

Table 1. Optimum Environmental Requirements for Tea Cultivation

Environmental factor	Optimum range	Physiological significance
Temperature	18 to 30°C	Supports photosynthesis, shoot growth, and enzyme activity
Annual rainfall	1500 to 2500 mm	Maintains continuous vegetative growth
Relative humidity	70 to 90 per cent	Reduces transpiration and improves leaf development
Soil pH	4.5 to 5.5	Maximizes nutrient availability
Altitude	600 to 2200 m	Influences flavour, aroma, and growth rate
Light intensity	Moderate diffused light	Enhances photosynthesis while reducing heat stress

4. Influence of Soil on Tea Productivity and Quality

Because it provides water, nutrients, oxygen, and mechanical support for root development, soil is the cornerstone of sustainable tea cultivation.

Deep, well-drained acidic soils that are high in organic matter are ideal for growing tea. The crop is naturally suited to acidic conditions where hazardous calcium concentrations are prevented and vital nutrients are nevertheless easily accessible.

Soil Texture

Loamy soils containing balanced proportions of sand, silt, and clay provide ideal conditions for tea cultivation. Such soils combine adequate drainage with sufficient water retention. Heavy clay soils often suffer from poor aeration, whereas excessively sandy soils retain insufficient moisture during dry periods.

Soil Organic Matter

It enriches soil structure, stimulates microbial activity, improves nutrient retention and increases water-holding capacity. As organic residues decompose, they release nitrogen, phosphorus, sulphur, and micronutrients that are needed for strong shoot production. Associated microbial activity of organic materials also drives nutrient cycling and suppresses some soil-borne diseases.

Soil Acidity

Tea is unusual among cultivated crops because it thrives under acidic conditions. A soil pH between 4.5 and 5.5 promotes efficient absorption of nitrogen, phosphorus, iron, manganese, zinc, and other micronutrients. Excessively alkaline soils reduce nutrient availability and often induce deficiencies that impair leaf development.

Nutrient Management

Nitrogen is the most significant limiting nutrient for tea productivity due to its direct involvement in chlorophyll generation, photosynthesis and vegetative growth. Phosphorus aids root growth and energy metabolism. Potassium affects enzyme activity, water balance and stress tolerance. Calcium, magnesium, sulfur, iron, zinc, manganese, boron, copper and molybdenum have physiological functions and are also involved in determining tea quality. Balanced fertilization boosts yield and biochemical composition of harvested shoots.

Soil Moisture

Adequate soil moisture is essential for nutrient transport, root respiration, and maintenance of cellular turgor. Water deficits reduce leaf expansion, inhibit photosynthesis, and increase accumulation of reactive oxygen species that damage cellular components. Proper irrigation scheduling therefore represents an important management strategy in regions experiencing irregular rainfall.

5. Interactions Between Climate and Soil

Soil and climate work together rather than separately. Temperature affects the microbial degradation of organic matter and therefore the release of nutrients into the soil solution. Rainfall impacts the mobility of nutrients, leaching loss and the availability of soil moisture. Too much rain can take important nutrients away, and dry soils limit the dispersion of nutrients to roots. Healthy soils with high organic matter content can better withstand climatic stress by holding more water, supporting beneficial micro-organisms and buffering temperature changes. Tea plantations with high levels of soil organic carbon are generally thought to have greater drought tolerance. This is because a better soil structure improves water retention and root penetration. Likewise, organic mulches help to control the temperature of the soil, minimize evaporation, inhibit weeds and stimulate biological activity.

6. Altitude and Microclimate

The altitude generates special microclimatic conditions that greatly affect the quality of the tea. Higher elevations tend to have cooler temperatures, more cloud cover, slower shoot growth and greater change in temperature between the day and the night. The reduced yields of high-altitude tea are often compensated by a slower development rate, which allows for larger buildup of amino acids, aromatic compounds and flavour precursors. This is one of the reasons why Darjeeling and other mountain teas are widely famous for their delicate aroma and nuanced taste. At relatively low elevations, tea gardens recorded more biomass because of the warmer temperatures and rapid growth of shoots. However, if the environmental management is not optimized, rapid development can dilute some of the quality components. The unique features of teas from various geographic areas are ultimately caused by the combination of height, temperature, rainfall, and sun radiation.

7. Role of Light in Tea Growth, Photosynthesis, and Flavour Development

Light is one of the most important environmental factors that regulate the growth, productivity and quality of tea. It is the primary energy source for photosynthesis, and directly influences carbon assimilation, biomass production, shoot development and the synthesis of secondary metabolites responsible for tea flavour and aroma. The intensity, duration, spectral quality and seasonal change of light determine the efficiency with which tea plants convert solar energy to chemical power. Tea is commonly classified as a shade-tolerant crop however, its requirement of light varies with cultivar, altitude and climatic circumstances. Young tea plants benefit from partial shade, as too much sun radiation damages chloroplasts, reduces chlorophyll content, increases leaf temperature, and decreases photosynthetic efficiency. Mature tea bushes, in contrast, need sufficient light for rapid shoot growth and good yields. Chlorophyll pigments absorb solar light during photosynthesis and convert carbon dioxide and water into carbohydrates, which supply the energy needed for cell division, root and shoot development and for secondary metabolite production, which determines tea quality. Moderate light intensity upregulates chlorophyll production and photosynthetic capacity. Excess light results in photoinhibition, which damages the photosynthetic machinery, reduces carbon fixation, accelerates leaf senescence and reduces shoot yield.

Light intensity is not the only factor; the spectrum composition of light also has a strong effect on tea physiology. Blue wavelengths trigger stomatal opening, chlorophyll production and compact vegetative growth. Red wavelengths stimulate photosynthetic activity and biomass buildup. The ratio of red and blue light determines the plant morphology and biochemical composition. Recently, it has been established that the use of light-emitting diode technology to modulate light spectra can boost the concentration of beneficial phytochemicals in tea leaves. Seasonal fluctuations in photoperiod also affect shoot development and flushing cycles, in combination with temperature and rainfall, with longer daylight hours generally favouring the ongoing formation of tender shoots for harvest. Shade control is therefore an important aspect of sustainable tea cultivation. Shade trees in the tea plantations reduce canopy temperature, excessive sun radiation, save soil moisture and improve biodiversity

8. Ecophysiological Responses to Abiotic Stress

Tea plants are frequently exposed to environmental stresses that alter physiological and biochemical processes. Abiotic stresses such as drought, high temperature, low temperature, salinity, and nutrient deficiency reduce plant growth and affect tea quality.

Drought Stress

Drought is one of the most important restrictions on tea production globally. A water deficiency decreases the leaf water potential, leading to stomatal closure and a reduction in transpiration. This saves water but restricts carbon dioxide uptake and lowers photosynthesis due to stomatal closure. Reduced photosynthesis results in reduced carbohydrate production, leading to slower shoot growth and lower frequency of harvest. Drought also speeds up leaf ageing and lowers chlorophyll content. Excess water stress affects cellular membranes through oxidative stress from reactive oxygen species.

Heat Stress

Increasing temperatures associated with global climate change expose tea plants to heat stress. High temperatures accelerate respiration, reducing the amount of carbohydrates available for growth. Protein denaturation, membrane instability, and chlorophyll degradation further reduce photosynthetic efficiency.

Heat stress alters hormone balance by increasing ethylene production and reducing cytokinin activity. Consequently, shoot development declines and leaf quality deteriorates. Tea plants respond by synthesizing heat shock proteins that stabilize cellular proteins and maintain membrane integrity under elevated temperatures.

Cold Stress

Tea plants growing in subtropical and temperate regions occasionally experience chilling injury or frost damage. Low temperatures reduce membrane fluidity, inhibit enzyme activity, and impair photosynthesis.

Cold acclimation involves increased synthesis of protective proteins, soluble sugars, and antioxidants that improve freezing tolerance. Nevertheless, prolonged frost can destroy young shoots and significantly reduce annual yield.

Nutrient Stress

Physiological processes needed for tea growth are impaired by deficiencies of nitrogen, phosphorus, potassium, magnesium, or micronutrients. Chlorosis and poor shoot development are observed due to decreased chlorophyll synthesis in the case of nitrogen deficit. Potassium deficit reduces stress tolerance and water-use efficiency. Therefore, balanced nutrient management is still crucial for maintaining productivity.

Oxidative Stress

Almost all environmental stresses generate reactive oxygen species within plant cells. Excessive accumulation of these molecules damages lipids, proteins, and nucleic acids.

Tea plants possess sophisticated antioxidant defence systems consisting of enzymatic antioxidants and nonenzymatic compounds including ascorbic acid, glutathione, carotenoids, and polyphenols. These protective mechanisms contribute significantly to stress tolerance.

Table 2. Major Environmental Factors and Their Ecophysiological Effects on Tea

Environmental factor	Physiological response	Effect on yield	Effect on tea quality
High temperature	Increased respiration and reduced photosynthesis	Decreases	Reduces aroma and catechin balance
Drought	Stomatal closure and reduced carbon assimilation	Decreases	Alters polyphenol concentration
Adequate rainfall	Improved water status and nutrient transport	Increases	Enhances flavor development
Moderate	Efficient	Increase	Improves

Environmental factor	Physiological response	Effect on yield	Effect on tea quality
light	photosynthesis	s	amino acid and chlorophyll content
Excessive light	Photoinhibition and oxidative stress	Decreases	Causes leaf scorching and quality loss
Acidic fertile soil	Efficient nutrient uptake	Increases	Improves biochemical composition
High organic matter	Better microbial activity and moisture retention	Increases	Enhances resilience and shoot quality

9. Climate Change and Tea Production

Climate change is dramatically changing the way tea is produced around the world by altering the climatic variables that govern plant growth, productivity and quality. The physiology of tea is being affected by rising temperatures, changing patterns of precipitation, increasing amounts of carbon dioxide in the atmosphere and the increased frequency of extreme weather events and this is altering the geographic distribution of appropriate land for tea production. Areas that have traditionally been good for growing high-quality tea may become less suitable because there will be too much heat, but higher-elevation areas may become more suitable.

Higher temperatures may promote the plant's vegetative growth and leaf yield, but they tend to decrease the content of key flavour-enhancing metabolites such as catechins, theanine and volatile aromatic compounds. This often leads to a decline in sensory quality despite the increase in biomass production. Warmer circumstances also lead to changes in the population dynamics of insect pests and pathogens; many species are able to produce additional generations per year, which increases pest pressure, crop losses and control costs. Some of the suggested adaptation solutions to overcome these issues are rainwater gathering, mulching, precision irrigation, shade tree management, conservation agriculture and generation of stress-tolerant tea cultivars through current breeding programs. Moreover, advances in remote sensing, weather prediction, geographic information systems and precision agriculture technologies are providing tea growers with valuable tools to monitor in real time and make informed decisions, thereby improving the resilience and sustainability of tea production under changing climate conditions.

10. Influence of Ecophysiology on Tea Flavour and Biochemical Composition

The quality of tea is mostly influenced by the concentration and balance of secondary metabolites produced during leaf development, and environmental circumstances are of immense importance in regulating the metabolic pathways of secondary metabolite formation. The principal polyphenols in green tea are catechins, which contribute to bitterness, astringency and antioxidant activity. The accumulation of polyphenols is affected by light intensity, temperature, nutrient availability and plant water status. Theanine is an amino acid unique to premium teas, providing them with their characteristic sweet and umami taste, and tends to build up in larger amounts under cool temperatures and moderate shading. Caffeine is a natural defence molecule against herbivores and pathogens and is responsible for the stimulating effects of tea. Caffeine production is controlled by environmental stress and nitrogen availability.

11. Sustainable Ecophysiological Management Practices

The way to sustainable tea production is through integrated management practices that promote environmental health, constant productivity and excellent leaf quality. The application of compost, farmyard manure and green manures increases the organic matter in the soil; it boosts soil fertility, improves the microbial variety, increases the water-holding capacity and gradually builds up the soil structure and nutrient availability. Mulching also helps sustainable farming by conserving soil moisture, controlling weed development, moderating soil temperature and preventing soil erosion. Integrated nutrient management (INM) using organic and inorganic fertilizers provides balanced plant nutrition with less environmental pollution and enhanced nutrient usage efficiency. Shade tree management gives favourable microclimatic conditions, reduces heat stress, saves soil moisture and increases biodiversity in the tea plantations, whereas nitrogen-fixing shade trees provide additional nutrients and organic matter to the soil. Efficient irrigation systems such as drip systems increase water use efficiency and minimize drought stress by maximizing the use of water during restricted rainfall periods. Integrated pest management calls for the employment of biological control agents, habitat conservation, resistant cultivars, and judicious pesticide administration to reduce pest damage while protecting beneficial creatures and ecological balance. Modern precision agriculture technologies such as soil sensors, weather monitoring stations, drone-based imaging and geographic information systems further allow for site-specific management, enabling tea growers to optimize resource use, improve production efficiency and enhance the long-term viability of tea cultivation.

12. Future Perspectives

Rapid advances in plant physiology, genomics, artificial intelligence, and precision agriculture are transforming tea research. Molecular breeding techniques are facilitating the development of cultivars with improved tolerance to heat, drought, and emerging diseases.

Genome sequencing has identified genes involved in photosynthesis, stress tolerance, flavonoid biosynthesis, and aroma formation. These discoveries provide opportunities for marker-assisted breeding and gene editing.

Artificial intelligence can integrate weather data, soil information, and crop physiology to predict yield, optimize irrigation schedules, and forecast pest outbreaks.

13. Conclusion

Tea ecophysiology is the science that reveals the impact of environmental conditions on the growth, production, quality and resilience of Camellia sinensis. Climate controls physiological activities such as photosynthesis, respiration, transpiration and seasonal shoot development, whereas soil impacts nutrient availability, root health, microbial activity and water retention. Light regulates carbon assimilation and synthesis of chlorophyll and secondary metabolites that influence tea flavour and aroma. Finally, the combination of these environmental factors affects both the yield and quality of the beverage. Climate change has resulted in higher temperatures, unpredictable rainfall and greater environmental stress, and hence requires adaptive management approaches for sustainable tea cultivation. By integrating ecophysiological knowledge, current technologies, precision agriculture and ecologically responsible management, productivity can be increased while maintaining soil health and tea quality. Further study into plant physiology, climate adaptation and sustainable farming practices will be important to ensure the long-term resilience and worldwide competitiveness of the tea business.

References

- Ahmed, S., Griffin, T. S., Kraner, D., Schaffner, M. K., Sharma, D., Hazel, M., Leitch, A. R., Orians, C. M., Han, W., & Stepp, J. R. (2014). Environmental factors variably impact tea secondary metabolites in the context of climate change. *Frontiers in Plant Science, 5*, 1–15.
- Barua, D. N. (2008). *Science and Practice in Tea Culture*. Tea Research Association.
- Chen, L., Apostolides, Z., & Chen, Z. M. (2012). *Global Tea Breeding: Achievements, Challenges and Perspectives*. Springer.
- FAO. (2022). *World Tea Production and Trade: Current and Future Development*. Food and Agriculture Organization of the United Nations.
- Harbowy, M. E., & Balentine, D. A. (1997). Tea chemistry. *Critical Reviews in Plant Sciences, 16*(5), 415–480.
- Hilton, J. (1973). Tea cultivation and climate relationships. *Experimental Agriculture, 9*, 65–72.

- Mondal, T. K. (2014). *Tea: Cultivation to Consumption*. Springer.
- Ruan, J., Gerendás, J., Härdter, R., & Sattelmacher, B. (2007). Effect of nitrogen form and root zone pH on tea plants. *Annals of Botany, 99*, 301–310.
- Sana, D. L. (1989). *Tea Cultivation to Consumption*. Kalyani Publishers.
- TRI. (2021). *Tea Research Institute Annual Report*. Tea Research Institute.
- Wang, Y., Gao, L., Shan, Y., Liu, Y., Tian, Y., & Xia, T. (2012). Influence of environmental factors on catechin accumulation in tea plants. *Plant Physiology and Biochemistry, 60*, 205–210.
- Willson, K. C., & Clifford, M. N. (1992). *Tea: Cultivation to Consumption*. Chapman & Hall.
- Yamamoto, T., Juneja, L. R., Chu, D. C., & Kim, M. (1997). *Chemistry and Applications of Green Tea*. CRC Press.
- Zhang, Q., Li, N., & Chen, L. (2020). Climate change impacts on tea production and quality. *Agricultural and Forest Meteorology, 291*, 108066.
- Zhao, J., Liu, S., & Chen, L. (2021). Ecophysiological adaptation of tea plants under abiotic stress. *Frontiers in Plant Science, 12*, 673421.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

R. Raman
Professor & Head, Department of Agronomy and Director, Centre for Natural Farming and Sustainable Agriculture

S. Seenikkannaiyan
Research Scholar, Department of Agronomy, Faculty of Agriculture, Annamalai University, Tamil Nadu, India

D. Suresh
Research Scholar, Department of Agronomy, Faculty of Agriculture, Annamalai University, Tamil Nadu, India

ARTICLE ID: 10

THE RISE OF INVASIVE WEEDS IN A WARMING WORLD

Abstract

Climate change is increasingly recognized as a major driver influencing the distribution, establishment and invasiveness of weed species across agricultural and natural ecosystems. Rising temperatures, elevated atmospheric carbon dioxide (CO_2) concentrations, altered precipitation patterns and more frequent extreme weather events create favourable conditions for invasive weeds to expand into previously unsuitable habitats. Many invasive weed species possess adaptive traits such as rapid growth, prolific seed production, phenotypic plasticity, efficient dispersal and broad environmental tolerance, enabling them to respond more effectively to changing climatic conditions than native vegetation and cultivated crops. Consequently, climate change enhances weed competitiveness, accelerates geographic range expansion, alters phenology, and increases reproductive success, intensifying ecological and agricultural impacts. In cropping systems, invasive weeds reduce productivity through increased competition for water, nutrients, light and space while contributing to herbicide resistance and higher management costs. In natural ecosystems, they disrupt biodiversity, nutrient cycling, habitat structure and ecosystem resilience. This review synthesizes current knowledge on the interactions between climate change and invasive weed species by examining key climatic drivers, mechanisms promoting invasion success, impacts on agriculture and ecosystems, representative case studies and climate-smart management strategies. It also highlights research priorities to improve prediction, early detection and sustainable weed management for resilient agricultural systems under changing climatic conditions.

Keywords: Climate change, Climate-smart management strategies, Invasive weed species

Introduction

Climate change is reshaping global environments through altered temperature and precipitation patterns, elevated atmospheric CO_2 and more frequent extreme events, producing profound implications for agriculture, biodiversity and ecosystem functioning (Yang *et al*., 2024). Concurrently, invasive weed species, plants that establish rapidly, spread aggressively, and cause significant ecological or economic damage, are emerging as a major concern. Their success is driven by characteristics such as high reproductive capacity, broad environmental adaptability, efficient dispersal mechanisms, phenotypic plasticity, and rapid evolutionary potential, enabling them to capitalize on changing climatic conditions, expand into new habitats, and outcompete native vegetation and agricultural crops (Clements and Jones, 2021). Climatic changes are expanding the geographic range and extending the growing seasons of many invasive weed species, enhancing their ability to establish and spread in previously unsuitable areas (Gharde *et al*., 2023).

Simultaneously, land-use changes and human-mediated dispersal pathways further accelerate their introduction and expansion, creating complex interactions that intensify threats to agricultural productivity, food security, biodiversity, and ecosystem services (Deeksha *et al*., 2024). Consequently, understanding the interplay between climate change and invasion biology has become increasingly important. Integrating climate projections with knowledge of species biology, dispersal mechanisms, and adaptive management approaches is essential for predicting future invasion dynamics, strengthening surveillance and early detection systems, and developing resilient and sustainable agricultural systems capable of minimizing ecological and economic impacts (Kathiresan and Gualbert, 2016).

Invasive Weed Species and Their Adaptive Traits

Invasive weed species are plants that establish, spread rapidly, and cause significant ecological, agricultural, or economic damage beyond their native range. Their invasion success is largely attributed to a suite of adaptive traits, including high reproductive capacity, rapid growth rates, efficient dispersal mechanisms, broad environmental tolerance, phenotypic plasticity, and the ability to evolve quickly under changing environmental conditions (DiTomaso, 2000). These characteristics enable invasive weeds to exploit disturbed habitats and emerging ecological niches more effectively than native species (Van Kleunen *et al*., 2010). As climate change alters temperature regimes, precipitation patterns, and atmospheric carbon dioxide concentrations, many invasive weeds are expected to gain a competitive advantage, facilitating their establishment and expansion across diverse ecosystems (Clements and Jones, 2021).

Climate Change as a Driver of Weed Invasions

Climate change is increasingly recognized as a major factor influencing the distribution, abundance, and invasiveness of weed species. Rising temperatures, altered rainfall patterns, elevated atmospheric CO_2 concentrations, and an increased frequency of extreme weather events create favourable conditions for the introduction and proliferation of invasive weeds (Bhowmik, 2014). Warmer climates can extend growing seasons and enable species to expand into higher latitudes and elevations that were previously unsuitable. Simultaneously, disturbances associated with droughts, floods, wildfires, and land-use changes reduce ecosystem resilience and create opportunities for invasive weeds to establish and spread. Human activities, including global trade, transportation, and agricultural intensification, further accelerate the movement of invasive species across geographical boundaries, amplifying invasion risks under changing climatic conditions (Deeksha *et al*., 2024).

Ecological and Agricultural Consequences

The interaction between climate change and invasive weeds poses significant challenges to agricultural productivity, biodiversity conservation, and ecosystem functioning. In agricultural systems, invasive weeds compete aggressively with crops for light, water, nutrients, and space, leading to yield reductions and increased production costs (Gharde *et al*., 2023). Many invasive species also exhibit enhanced growth and reproductive performance under elevated CO_2 conditions, further intensifying crop-weed competition. Ecologically, invasive weeds can alter habitat structure, disrupt nutrient cycling, modify fire regimes, reduce native plant diversity, and negatively affect associated fauna (Bhowmik, 2014). The combined impacts of climate change and biological invasions threaten ecosystem services, food security, and rural livelihoods, highlighting the need for proactive monitoring, early detection, and climate-smart weed management strategies.

Climate Change: Key Drivers Affecting Weed Dynamics

Climate change affects weed dynamics through several major drivers that strengthen weed establishment, spread, and persistence. Elevated atmospheric CO_2 can stimulate photosynthesis, water-use efficiency, and biomass production in many weeds, often giving invasive species a competitive advantage over crops and native plants (Singh *et al*., 2011). Rising temperature can speed germination, growth, and reproduction, extend growing seasons, and allow weed species to shift into new geographical regions as climate suitability changes (Redowan *et al*., 2025). Altered rainfall patterns can favor drought-tolerant weeds under moisture stress and also aid dispersal by moving seeds and propagules through floods, irrigation channels, and runoff. Extreme weather events such as storms, floods, and droughts create disturbed habitats, reduce competition from established vegetation, and open new niches that are highly vulnerable to invasion (Ramesh *et al*., 2017). Together, these drivers make climate change a key force reshaping weed distribution, abundance, and management risk in agricultural and natural ecosystems.

Mechanisms Linking Climate Change and Invasive Weed Success

Climate change strengthens invasive weed success through linked processes that affect where weeds can grow, how fast they reproduce, and how well they compete with other plants. Rising temperatures, elevated CO_2, and irregular rainfall can expand weed ranges, improve seed germination and survival, shift flowering and emergence earlier, and give invasive species a stronger advantage over native plants (Singh *et al*., 2011).

Climate-driven **range expansion** allows many invasive weeds to move into new regions, higher latitudes, and greater elevations where they were previously limited by cold temperatures or short growing seasons (Redowan *et al*., 2025). At the same time, favorable conditions can increase **reproductive capacity**, leading to more flowers, seeds, and vegetative propagules that support faster spread and long-term persistence. Changes in temperature and moisture also enhance **seed germination and survival**, especially for species that tolerate drought, heat, or flooding during early establishment (Deeksha *et al*., 2024). In addition, climate change can trigger **phenological shifts** such as earlier emergence and flowering, which help weeds capture light, water, and nutrients before crops or native species fully develop **(Invasive Species Council, n.d.).** Together, these changes increase the **competitive superiority** of invasive weeds over native plants, reducing biodiversity and intensifying weed pressure in agricultural and natural ecosystems.

Impacts on Agricultural Systems

Invasive weeds can substantially reduce crop productivity by competing with crops for water, nutrients, and light, especially under climate-stressed conditions (Ziska and George, 2004). They also raise production costs, contribute to herbicide resistance, and threaten food security by lowering yields and weakening farm resilience.

Crop Yield Reduction

Invasive weeds reduce crop yield by competing with cultivated plants throughout the growing season and by interfering with crop establishment, growth, and harvest. Yield losses become more severe when weeds grow aggressively under elevated CO_2, warming, and variable rainfall, conditions that can favour faster weed growth than crop growth (Redowan *et al*., 2025).

Increased Competition for Resources

Weeds compete with crops for water, nutrients, and light, often becoming more aggressive in warming and CO_2-enriched environments.

- Water: Weeds can absorb soil moisture rapidly, reducing water availability during critical crop stages.
- Nutrients: Fast-growing weeds can deplete nitrogen and other nutrients before crops can use them.
- Light: Dense weed canopies shade crop plants, reducing photosynthesis and slowing development.

Herbicide Resistance Development

Repeated herbicide use creates strong selection pressure, allowing resistant weed biotypes to survive and multiply. Climate change can intensify this challenge by favoring weeds with rapid adaptation and by making control more difficult under stressful field conditions (Clements and Jones, 2021).

Increased Cost of Weed Management

Managing invasive weeds requires more labor, herbicides, machinery, and repeated field operations, which increases production costs. Farmers often need integrated weed management approaches such as crop rotation, manual removal, mulching, and close monitoring to reduce infestation pressure.

Threats to Food Security

When invasive weeds reduce yields and raise management costs, they directly undermine food availability, farm income, and system resilience. This is especially serious for smallholder farmers, who often have fewer resources for effective weed control and are more exposed to climate variability

Impacts on Natural Ecosystems

Invasive weeds can seriously damage natural ecosystems by reducing native biodiversity and disrupting ecological balance. They often spread rapidly in disturbed habitats, where they outcompete native species for space, light, water, and nutrients, causing a decline in species richness and abundance. As native plant communities shrink, animals that depend on them for food and shelter are also affected, leading to broader biodiversity loss and weaker ecosystem stability (Deeksha *et al*., 2024). In addition, invasive weeds can alter ecosystem functions by changing productivity, decomposition, and competition patterns, which reduces resilience and slows natural recovery after disturbance. They may also influence soil health and nutrient cycling through changes in litter quality, root activity, and decomposition rates, sometimes depleting key nutrients or altering microbial processes (Clements and Jones, 2021). Many invasive weeds further change fire regimes and habitat structure by forming dense thickets or continuous fuel layers, which can increase fire intensity or frequency and make habitats less suitable for native species.

Case Studies of Climate-Driven Weed Invasions

Climate change has influenced the spread and dominance of several major invasive weeds across different ecosystems. In South Asia, ***Parthenium hysterophorus*** has expanded rapidly in disturbed landscapes, roadsides, croplands, and grazing areas because warmer conditions and variable rainfall favor its establishment and persistence (Shabhir *et al*., 2023). In tropical forests and forest edges, ***Lantana camara*** has become highly invasive by forming dense thickets that suppress native regeneration and alter habitat structure, with climate variability often strengthening its spread (Ramaswami and Sukumar, 2013). In aquatic systems, **water hyacinth (*Eichhornia crassipes*)** proliferates quickly in nutrient-rich, warm-water environments, where it clogs waterways, reduces oxygen, and disrupts fisheries and irrigation. In arid and semi-arid regions, ***Prosopis juliflora*** spreads aggressively by tolerating drought and poor soils, forming dense stands that reduce pasture availability and alter ecosystem functioning (Deeksha *et al*., 2024). Together, these show how climate-sensitive traits help invasive weeds expand across terrestrial and aquatic environments, increasing their ecological and economic impacts.

Conclusion

Climate change is reshaping weed dynamics by favouring faster growth, broader range expansion, altered germination and phenology, and stronger competition with crops and native plants. Rising CO_2, higher temperatures, shifting rainfall, and more frequent extreme events are together making invasive weeds more persistent and more difficult to manage in agricultural and natural ecosystems. As a result, weeds are contributing to lower crop productivity, greater management costs, biodiversity decline, and reduced ecosystem services such as habitat quality, water regulation, and soil functioning. These combined pressures show that weed problems are no longer only a farm-level issue but a climate-linked challenge affecting food security, conservation, and ecosystem resilience. Proactive management is therefore essential, including early detection, integrated weed management, climate-informed risk assessment, and stronger policy support for prevention and adaptation.

References

Bhowmik, P. C. (2014). Invasive weeds and climate change: past, present and future. *Journal of crop and weed*, *10*(2), 345-349.

Clements, D. R., & Jones, V. L. (2021). Rapid evolution of invasive weeds under climate change: present evidence and future research needs. *Frontiers in Agronomy*, *3*, 664034.

Deeksha, M. G., Jadhav, M. M., Guleria, N., Barman, M., Srinivas, K., Kaur, P., & Anokhe, A. (2024). Impact of climate change on invasive weeds affecting biodiversity and natural ecosystems. *Indian Journal of Weed Science*, *56*(4), 349-357.

DiTomaso, J. M. (2000). Invasive weeds in rangelands: species, impacts, and management. *Weed science*, *48*(2), 255-265.

Gharde, Y., Dubey, R. P., Singh, P. K., Kumar, S., Jamaludheen, A., Mishra, J. S., & Gupta, P. K. (2023). Bibliographic analysis of modelling weed distribution and invasion with global perspective. Indian Journal of Weed Science (2023) 55(1): 1–12

Invasive Species Council. (n.d.). *Weeds and climate change*. https://invasives.org.au/wp-content/uploads/2014/02/fs_weedsandclimatechange.pdfinvasives.org

Kathiresan, R., & Gualbert, G. (2016). Impact of climate change on the invasive traits of weeds. *Weed biology and management*, *16*(2), 59-66.

Ramaswami, G., & Sukumar, R. (2013). Long-term environmental correlates of invasion by Lantana camara (Verbenaceae) in a seasonally dry tropical forest. *PLoS One*, *8*(10), e76995.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S. K., & Chauhan, B. S. (2017). Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. *Frontiers in plant science*, *8*, 95.

Shabhir, A., Zalucki, M. P., Dhileepan, K., Khan, N., & Adkins, S. W. (2023). The current and potential distribution of parthenium weed and its biological control agent in Pakistan. *Plants*, *12*(6), 1381.

Singh, R. P., Singh, R. K., & Singh, M. K. (2011). Impact of climate and carbon dioxide change on weeds and their management-a review. *Indian J. Weed Sci*, *43*(1), 1-11.

Van Kleunen, M., Weber, E., & Fischer, M. (2010). A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology letters*, *13*(2), 235-245.

Yang, Y., Tilman, D., Jin, Z., Smith, P., Barrett, C. B., Zhu, Y. G., Burney, J., Odorico, P., Fantke, P., Fargione,J., Rulli, M, C., Sloat, L., Groenigen, K. J. V., West, P.C., Ziska, L., Michalak, A. M., & Zhuang, M. (2024). Climate change exacerbates the environmental impacts of agriculture. *Science*, *385*(6713), 3747.

Ziska, L. H., & George, K. A. T. E. (2004). Rising carbon dioxide and invasive, noxious plants: potential threats and consequences. *World Resource Review*, *16*(4), 427-447.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

ARTICLE ID: 11

NET ZERO AGRICULTURE: CULTIVATING A CLIMATE SMART FUTURE

AUTHORS' DETAILS:

Ekta Kumari
Ph.D. student, Department of Extension Education and Communication Management, I.C. College of Community Science

Dr. Shakshi Bisht
Assistant Professor, Department of Extension Education and Communication Management, I.C. College of Community Science

Abstract
Net zero agriculture is a sustainable farming approach that seeks to balance greenhouse gas emissions with carbon removal while ensuring food security. As agriculture is both affected by and contributes to climate change, adopting climate-smart and low-carbon practices is essential. This article discusses the concept of net zero agriculture, major emission sources, and key practices such as efficient nutrient management, Alternate Wetting and Drying (AWD), agroforestry, conservation agriculture, renewable energy, and regenerative farming. It also highlights emerging technologies like AI-based precision agriculture, biochar, and agrivoltaics. Despite challenges such as high costs, limited awareness, and weak incentives, collaborative efforts can make agriculture more climate-resilient and sustainable.

Introduction
What if the farms that feed the world could also help cool the planet? This is the promise of net zero agriculture, an approach that aims to produce food while minimizing agriculture's contribution to climate change. Although carbon is essential for life, excessive greenhouse gas emissions have disrupted the Earth's climate, leading to rising temperatures, erratic rainfall, declining soil health, and increasing threats to food security. Net zero refers to balancing greenhouse gas emissions with their removal or absorption so that the overall emissions are effectively zero. India has recognized this challenge by committing to achieve net zero emissions by 2070, placing agriculture at the heart of its climate strategy.

What is Net Zero Agriculture?
As climate change increasingly affects agricultural productivity and farmers' livelihoods, the need for sustainable farming has never been greater. As both a victim of climate change and a significant source of greenhouse gas emissions, the agricultural sector has a unique opportunity to become part of the solution. Adopting climate-smart and low-carbon farming practices can help ensure food security while contributing to a more sustainable and climate-resilient future.

Net zero agriculture means a farming system where the climate impact of agriculture is balanced out by practices that absorb carbon, such as healthier soils, trees on farms, and better land management. It does not mean zero emissions in every activity, but rather a net balance between emissions released and emissions captured or avoided. This concept covers the whole food system, including crops, livestock, soil, water, energy use, storage, and transport. It also recognizes that agriculture can help solve the climate problem, not just contribute to it.

Agriculture contributes to carbon emissions through Crop Residue, Rice Cultivation, Enteric Fermentation, Manure Management, Synthetic Fertilizers and On farm energy use.

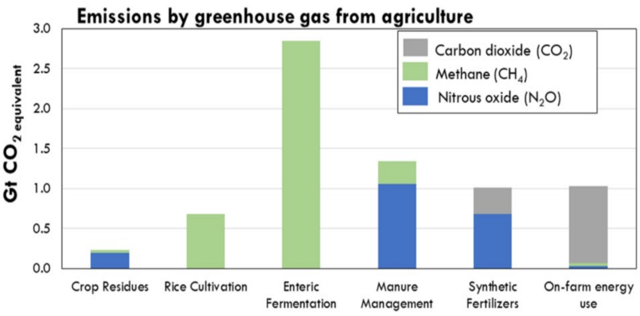


Fig 1: Sources of greenhouse gas emission from agriculture

Key Practices for Achieving Net Zero Agriculture

1. Efficient fertilizer and nutrient management

Efficient fertilizer use through soil testing, site-specific nutrient application, split nitrogen application, and integrated nutrient management reduces nutrient losses and nitrous oxide emissions while improving nutrient use efficiency and crop productivity.

2. Alternate Wetting and Drying (AWD) in rice cultivation

AWD involves periodic drying of paddy fields instead of continuous flooding. This practice lowers methane emissions, saves irrigation water, and maintains rice yields.

3. Sustainable livestock management

Improving feed quality, animal health, breeding, and manure management reduces methane emissions from livestock. Converting manure into biogas further captures methane and produces renewable energy.

4. Agroforestry systems

Integrating trees with crops and livestock enhances carbon sequestration, improves soil health, reduces erosion, supports biodiversity, and provides additional income through timber, fodder, fruits, and fuelwood.

5. Conservation agriculture and soil carbon enhancement

Practices such as minimum tillage, crop rotation, residue retention, and cover cropping increase soil organic carbon, improve soil fertility and moisture retention, and reduce fuel use, thereby lowering agriculture's carbon footprint.

6. Renewable energy in farming

The use of solar pumps, biogas plants, and energy-efficient machinery replaces fossil fuels, reducing greenhouse gas emissions while lowering long-term farm operating costs.

7. Minimizing post-harvest losses

Improved storage, cold-chain facilities, processing, and transportation reduce food losses, enhance resource-use efficiency, and decrease emissions throughout the agricultural value chain.

8. Carbon sequestration through regenerative agriculture

Practices such as composting, cover cropping, crop diversification, and improved grazing increase carbon storage in soils, improve soil health, and strengthen resilience to climate change, supporting low-emission farming systems.

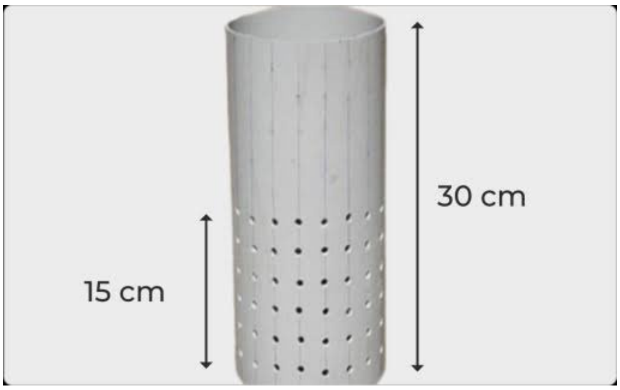


Fig 2: The AWD field pipe: A 30 cm perforated tube inserted 15 cm into the soil to check water levels below the surface.

One successful example is the adoption of **Alternate Wetting and Drying (AWD)** in rice cultivation. Instead of keeping paddy fields continuously submerged, irrigation is applied only after the water level drops to a specified threshold. This simple change in water management reduces methane emissions from flooded soils while conserving irrigation water, making AWD an effective climate-smart practice for rice-growing regions, particularly in India.

Innovative Technologies Driving Net Zero Agriculture

Achieving net zero agriculture depends on the integration of advanced technologies, biological innovations, and renewable energy solutions. These emerging approaches are transforming conventional farming into a more climate-resilient and low-carbon production system.

AI-enabled applications and Sensors: Using satellite imagery, multispectral sensors, GPS, and AI-based decision support systems, modern farm machinery can apply fertilizers and other inputs only where they are needed and in the required amounts. This site-specific application improves nutrient-use efficiency while reducing fertilizer losses, runoff, and greenhouse gas emissions by approximately 25 to 40 percent.

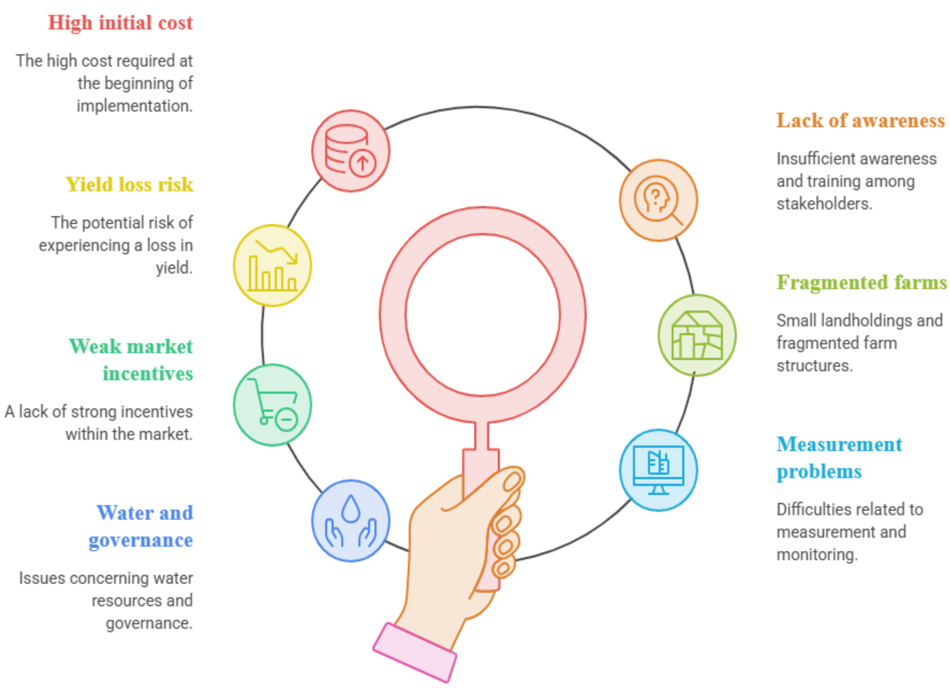
Battery-powered robotic equipment for planting, weeding, and other field operations offers a cleaner alternative to conventional diesel-powered machines. Besides eliminating direct fossil fuel emissions, lightweight autonomous machines reduce soil compaction, helping maintain healthy soil structure and productivity.

Biochar technology: Agricultural residues and other organic biomass can be converted into biochar through a process known as pyrolysis. When incorporated into the soil, biochar acts as a stable form of carbon that can remain stored for centuries. In addition to sequestering carbon, it enhances soil moisture retention, improves nutrient availability, and supports better soil health.

Agrivoltaics System

Agrivoltaics is an innovative land-use system that combines crop cultivation with solar power generation on the same piece of land. In this approach, elevated or semi-

Challenges in Implementation



transparent solar panels are installed above agricultural fields or grazing areas. While the panels produce renewable electricity, they also provide partial shade that lowers soil moisture loss through evaporation by about 20 to 30 percent and protects crops from excessive heat stress. This dual-purpose system increases land-use efficiency by simultaneously supporting food production and clean energy generation.

Moving Forward

Achieving net zero agriculture requires coordinated efforts from governments, researchers, extension agencies, agribusinesses, financial institutions, and farmers. Investments in research, climate-smart technologies, digital extension, carbon finance, and farmer capacity building are essential. Ensuring affordable technologies and financial support for smallholders is equally important. By integrating sustainable practices with improved productivity, net zero agriculture can strengthen food security, enhance farmers' livelihoods, and contribute significantly to climate change mitigation.

Conclusion

Net zero agriculture offers a sustainable pathway to address climate change while ensuring food and livelihood security. Although challenges such as high costs, limited awareness, and policy gaps remain, adopting climate-smart practices, innovative technologies, and supportive policies can transform agriculture into a resilient, low-carbon sector that benefits both farmers and the environment.

References:

I. Bluebird Solar. (2025, January 16). Agrivoltaics: Combining solar power and agriculture. *Bluebird Solar Blog*. https://bluebirdsolar.com/blogs/all/agrivoltaics-combining-solar-power-and-agriculture

II. **Op-***Electronics For You.* https://www.electronicsforu.com/technology-trends/precision-agriculture-enabling-farming-drones

III. **https://www.magnific.com/free-photos-vectors/biochar#uuid=2d9e9208-ca9d-4916-8959-a8b3189ed8bb**

IV. Hussain, M. M., Zhou, G., Yang, W., Liu, L., Zhao, C., Huang, Y., & Wang, S. (2026). Biochar towards soil carbon neutrality: a critical review. *Biochar X, 2*(1).

V. Khalil, M. I., Osborne, B. A., & Wingler, A. (2024). Towards net zero emissions without compromising agricultural sustainability: What is achievable?. *Nutrient Cycling in Agroecosystems*, *128*(3), 283-291.

VI. Kumar, S., Meena, R. S., & Ghosh, S. (2025). Agriculture toward net zero emissions: An overview. *Agriculture Toward Net Zero Emissions*, 1-9.

VII. Mose Solar. (2025, January 27). *How agrivoltaics transforms farmland into dual-purpose energy powerhouses*. https://www.moserbaersolar.com/specialized-applications/how-agrivoltaics-transforms-farmland-into-dual-purpose-energy-powerhouses/

VIII. Peramaiyan, P., Reddy, K. S., Kumar, S., Srivastava, A. K., Nath, D., Kumar, V., & Saikia, K. (2026). Assessing the scope for nano-urea to reduce nitrogen inputs while maintaining rice yields in India. *Frontiers in Sustainable Food Systems, 10,* 1759447.

IX. Priya, M., et al. (2026). Connecting agriculture and renewable energy: Insights into microclimatic changes, physiological, biochemical, and yield responses under agrivoltaics: A review. *Frontiers in Horticulture, 5,* 1645374

X. Rosa, L., & Gabrielli, P. (2023). Achieving net-zero emissions in agriculture: a review. *Environmental Research Letters, 18*(6), 063002

XI. The Policy Edge. (2026, February 11). *NITI Aayog: Agriculture's path to Viksit Bharat and Net Zero 2070.* https://www.policyedge.in/p/niti-aayog-agricultures-path-to-viksit-bharat-and-net-zero-2070

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Dr. T. Bharath
Senior Scientist & Head
Krishi Vigyan Kendra, Bhadradri Kothagudem (PJTAU), Telangana

ARTICLE ID: 12

El Niño and Contingency Crop Planning: Helping Farmers Reduce Climate Risks

Introduction

Agriculture depends heavily on timely and adequate rainfall. In recent years, climate variability has become one of the greatest challenges facing farmers. Among the major climate phenomena affecting Indian agriculture is **El Niño**, which often results in below-normal rainfall, prolonged dry spells, delayed monsoon onset, and higher temperatures. Although El Niño cannot be prevented, its adverse effects can be minimized through **scientific contingency crop planning**, efficient water management, and timely advisory services. With proper planning, farmers can reduce crop losses and improve resilience against climate uncertainty.

What is El Niño?

El Niño is a naturally occurring climate phenomenon characterized by the warming of sea surface temperatures in the central and eastern Pacific Ocean. This warming alters global weather patterns and often weakens the southwest monsoon over India.

Major impacts of El Niño include:

- Delayed onset of monsoon
- Reduced and erratic rainfall
- Long dry spells during crop growth
- Increased daytime temperatures
- Moisture stress in crops
- Reduced reservoir and groundwater recharge
- Lower agricultural productivity

Impact of El Niño on Agriculture

1. Delayed Sowing

Insufficient early-season rainfall delays land preparation and sowing operations, shortening the effective growing period.

2. Poor Germination

Lack of soil moisture affects seed germination, resulting in poor plant population and uneven crop establishment.

3. Moisture Stress

Dry spells during vegetative and reproductive stages reduce flowering, grain formation, and final yields.

4. Increased Pest and Disease Incidence

High temperatures and fluctuating humidity often favor pests such as:

- Fall Armyworm in maize
- Stem borers
- Aphids and whiteflies
- Sucking pests in cotton

5. Livestock Challenges

Reduced availability of green fodder and drinking water affects animal health and milk production.

Importance of Contingency Crop Planning

Contingency crop planning means selecting suitable crops and management practices according to the prevailing rainfall situation. It helps farmers utilize available moisture efficiently while reducing production risks.

Objectives

- Minimize crop failure
- Improve water use efficiency
- Ensure stable farm income
- Promote climate-resilient agriculture
- Sustain food and fodder production

Contingency Crop Planning for Climate-Resilient Agriculture

Climate variability, delayed monsoon, dry spells, and erratic rainfall have become common challenges for farmers. These conditions, often associated with **El Niño**, affect crop establishment, growth, and yield. **Contingency Crop Planning (CCP)** helps farmers reduce losses by selecting suitable crops, adopting timely sowing, conserving soil moisture, and using improved management practices.

What is Contingency Crop Planning?

Contingency crop planning is an alternative crop production strategy adopted when normal cropping is disrupted due to:

- Delayed onset of monsoon
- Early withdrawal of monsoon
- Prolonged dry spells
- Excess rainfall or floods
- Drought conditions

The objective is to ensure stable crop production, conserve natural resources, and maintain farmers' income under adverse weather conditions.

Why is Contingency Crop Planning Important?

- Minimizes crop losses during drought and erratic rainfall.
- Promotes efficient use of available rainfall.
- Improves soil moisture conservation.
- Enhances cropping intensity.
- Increases resilience to climate change.
- Ensures food and nutritional security.

Recommended Crops Under Delayed Monsoon

Time of Sowing	Recommended Crops	Suitable Varieties
Up to 15 June	Cotton, Maize, Paddy	Normal duration
16–30 June	Cotton, Maize, Redgram, Soybean	Medium duration
1–15 July	Redgram, Greengram, Blackgram, Sesame	Early maturing
16–31 July	Greengram, Blackgram, Cowpea, Foxtail Millet	Short duration
1–15 August	Cowpea (fodder), Horsegram, Sesame	Extra short duration

Recommended Sowing Windows

<u>Cotton</u>

- **Normal sowing:** 10 June – 10 July
- **Delayed sowing:** Up to 20 July
- Use drought-tolerant Bt hybrids recommended by the State Agricultural University.

<u>Maize</u>

- **Normal sowing:** 10 June – 30 June
- **Delayed sowing:** Up to 15 July
- Prefer early-duration hybrids under delayed conditions.

<u>Paddy</u>

- **Nursery:** Mid June
- **Transplanting:** Early July
- Under delayed rainfall, adopt:
  - Direct Seeded Rice (DSR)
  - Short-duration varieties (120–130 days)

<u>Redgram</u>

- **Best sowing:** 20 June – 15 July
- Intercrop with cotton or millets.

Greengram

- **Best sowing:** July
- Short-duration varieties (60–70 days)

Blackgram

- **Best sowing:** July
- Suitable after delayed rainfall.

Sesame

- **Best sowing:** July
- Performs well under limited moisture.

Millets

- Foxtail millet
- Little millet
- Browntop millet

Ideal sowing: **July–August**

Soil and Moisture Conservation Measures

Successful contingency crop planning depends on conserving every drop of rainfall.

In Rainfed Fields

- Construct compartment bunds.
- Follow contour farming on sloping lands.
- Prepare conservation furrows.
- Open dead furrows after every 8–10 rows.
- Create broad-bed and furrow systems in heavy soils.

Mulching

Use:

- Crop residues
- Paddy straw
- Cotton stalks
- Dry leaves

Benefits:

- Conserves soil moisture
- Suppresses weeds
- Improves soil organic matter
- Reduces evaporation by 30–40%

Rainwater Harvesting

Farmers should establish:

- Farm ponds
- Percolation tanks
- Check dams
- Recharge pits

Stored water can be used for lifesaving irrigation during dry spells.

Conservation Tillage

- Minimum tillage
- Zero tillage where feasible
- Residue retention

These practices reduce runoff and improve infiltration.

Vegetative Measures

Plant:

- Vetiver grass
- Napier grass
- Glyricidia
- Subabul

Along field bunds to reduce erosion.

Nutrient Management Under Moisture Stress

- Apply fertilizers based on soil test.
- Split nitrogen application.
- Foliar spray of **2% Urea** during drought.
- Spray **1% Potassium Nitrate (KNO_3)** to reduce moisture stress.
- Apply organic manures and compost.
- Use biofertilizers like **Azospirillum**, **Azotobacter**, **PSB**, and **Trichoderma**.

Weed Management

timely weed control conserves soil moisture.

Recommended practices:

- One intercultivation at 20–25 DAS.
- Mulching after weeding.
- Use recommended herbicides depending on the crop.

Dry Spell Management

If rainfall stops for 10–15 days:

- Thin excess plant population.
- Weed immediately.
- Apply mulch.
- Provide lifesaving irrigation if possible.
- Spray anti-stress nutrients.
- Avoid excess nitrogen application.

Crop Diversification

Instead of depending only on paddy or maize, farmers should diversify with:

- Millets
- Pulses
- Oilseeds
- Fodder crops

Diversification reduces climatic risk and improves farm income.

Recommended Contingency Crop Planning

If monsoon is delayed by 2–3 weeks

Farmers should prefer short-duration and drought-tolerant crops such as:

- Maize

- Redgram (Pigeonpea)
- Greengram
- Blackgram
- Sesame
- Foxtail millet
- Little millet

Under Low Rainfall Conditions

- Reduce seed rate only where recommended.
- Select early maturing varieties.
- Adopt line sowing for better moisture conservation.
- Practice timely intercultivation to reduce weed competition.
- Apply fertilizers based on soil moisture availability.

During Mid-Season Dry Spell

- Perform intercultivation to conserve moisture.
- Apply mulch using crop residues.
- Use foliar nutrient sprays (2% Urea or 1% Potassium Nitrate where recommended).
- Irrigate protective life-saving irrigation if water is available.
- Avoid unnecessary nitrogen application during severe drought.

Water Conservation Measures

- Construct farm ponds.
- Repair field bunds.
- Harvest rainwater.
- Promote drip and sprinkler irrigation.
- Recharge groundwater through check dams and percolation tanks.

Crop Diversification

Replacing water-intensive crops with drought-tolerant alternatives reduces production risks.

Instead of	Consider Growing
Long-duration Paddy	Short-duration Paddy (where irrigation is available)
Continuous Maize	Maize + Redgram Intercropping
Sole Cotton	Cotton + Redgram
Fallow Areas	Pulses and Millets

Integrated Nutrient Management

Healthy soils improve resilience during drought. Farmers are advised to:

- Apply Farm Yard Manure (FYM)
- Use Vermicompost
- Apply Biofertilizers
- Maintain balanced fertilizer application
- Improve soil organic carbon

Healthy soils retain more moisture during dry periods.

Integrated Pest Management

El Niño conditions may increase pest incidence. Farmers should:

- Monitor fields regularly.
- Install pheromone traps.
- Use yellow sticky traps.
- Encourage beneficial insects.
- Follow economic threshold levels before spraying pesticides.

Role of Krishi Vigyan Kendra (KVK)

Krishi Vigyan Kendras play an important role by providing:

- Weather-based agro-advisories
- Climate-smart technologies
- Contingency crop planning guidance
- Demonstrations on drought-resilient farming
- Farmer training programmes
- Soil and water management technologies

Regular advisories help farmers make timely decisions based on changing weather conditions.

Key Messages for Farmers

- Do not sow immediately after isolated rainfall; wait for adequate soil moisture.
- Choose short-duration and drought-tolerant crop varieties.
- Diversify cropping systems.
- Harvest every drop of rainwater.
- Maintain soil organic matter.
- Follow weather forecasts before field operations.
- Seek timely technical guidance from Krishi Vigyan Kendra and the Department of Agriculture.

Conclusion

El Niño poses serious challenges to agriculture by affecting rainfall distribution and increasing drought risk. However, timely contingency crop planning, scientific crop management, efficient water conservation, and climate-resilient farming practices can significantly reduce crop losses. Preparedness is the key to successful farming under changing climatic conditions. By adopting suitable technologies and following weather-based advisories, farmers can safeguard their crops, improve productivity, and build resilience against future climate uncertainties.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Hareesh, D
School of Natural Resources Management, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya – 793 103

Patra, T.
School of Natural Resources Management, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya – 793 103

Narayanan, M
School of Crop Improvement, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya – 793 103

ARTICLE ID: 13

The Secret Architects of Soil: How the Right Crop Variety Supercharges Natural Farming

Abstract:
Plant roots are the soil ecosystem's master architects underneath the surface. Different crop varieties actively create and nourish the microbial populations around them through differences in root architecture and the ongoing release of chemical exudates. By directing essential organic energy into the rhizosphere, genotypes with better belowground carbon allocation speed up nutrient cycling and strengthen soil biological health. The benefits of combining these genetically better cultivars with natural farming methods are enhanced, increasing soil microbial biomass, improving critical enzyme activities, and promoting sustainable fertility from the ground up. A strong, resource-efficient route to climate-resilient agriculture and long-term agricultural productivity is provided by combining smart crop genetics with ecological soil management.
Keywords: Crop genotype, Natural farming, Nutrient cycling, Rhizosphere, Root exudates and Soil biological health

1. Introduction

For generations, we've looked at soil through a chemical lens-focusing on how much NPK fertilizer we can drive into it. But soil is a living, breathing ecosystem that provides the foundation for sustainable agriculture by supporting plant growth and regulating essential ecosystem functions. Beyond serving as a medium for root anchorage, soil governs nutrient cycling, water retention, carbon sequestration, and biodiversity through the interactions of microorganisms, plant roots, and organic matter (Lehman et al., 2015). Increasing evidence also highlights that soil functions arise from complex interactions between plants and their surrounding environment, making soil biology an integral component of agricultural sustainability (Hongbo et al., 2015).

The rhizosphere, the narrow region surrounding plant roots, represents one of the most biologically active zones of the soil. Root exudates continuously supply carbon-rich compounds that stimulate diverse microbial communities responsible for organic matter decomposition, nutrient transformations, and enzyme production. These plant–soil interactions regulate soil fertility and influence crop productivity, particularly in biologically managed production systems (Junaidi et al., 2018; Lehman et al., 2015). Recent advances in soil microbiome research have further strengthened our understanding of these biological interactions and their significance for sustainable land management (Tarnowski et al., 2023).

Research has shifted from treating soil as a simple chemical system viewing it as a living, breathing ecosystem that thrives on biological activity. Today, we know that fostering strong relationships between plants and microbes is key to keeping soil fertile, resilient, and productive. Because of this, learning how different crop varieties influence soil microbial life has become a vital step in making natural farming more efficient and sustainable (Lehman et al., 2015; Todd-Brown et al., 2021).

2. Natural Farming: Building Soil Health Through Biological Processes

Natural farming is a biologically driven production system that minimizes dependence on synthetic fertilizers and pesticides while promoting ecological processes to sustain soil fertility and crop productivity. It relies on the application of indigenous microbial formulations such as *Jeevamrutha*, *Beejamrutha*, mulching, and organic residues to stimulate beneficial soil microorganisms and enhance nutrient cycling. These practices increase soil organic matter, improve microbial activity, and create favourable conditions for biologically mediated nutrient transformations, thereby restoring soil biological health and improving the resilience of agricultural ecosystems (Lehman et al., 2015). The growing emphasis on biological soil management reflects a broader shift towards sustainable agricultural systems that integrate plant, soil, and microbial interactions for long-term productivity (Hongbo et al., 2015).

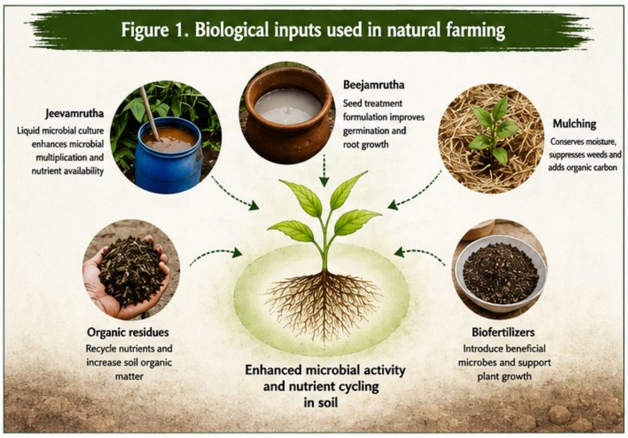


Figure 1. *Major biological inputs employed in natural farming, including Jeevamrutha, Beejamrutha, mulching, and biofertilizers, which stimulate soil microbial activity and nutrient cycling.*

The success of natural farming largely depends on the activity of rhizosphere microorganisms that decompose organic residues, release nutrients, and produce extracellular enzymes essential for soil functioning. Organic amendments and biological inputs provide carbon substrates that stimulate microbial proliferation, improve nutrient mineralization, and strengthen soil ecosystem services (Junaidi et al., 2018). Furthermore, healthy soils support diverse microbial communities that enhance nutrient-use efficiency, suppress soil-borne pathogens, and improve plant resilience (Lehman et al., 2015). Consequently, natural farming provides an ideal biological environment in which crop genotypes with efficient root systems and favourable rhizosphere interactions can maximize soil microbial biomass and enzyme activity, ultimately contributing to sustainable crop production.

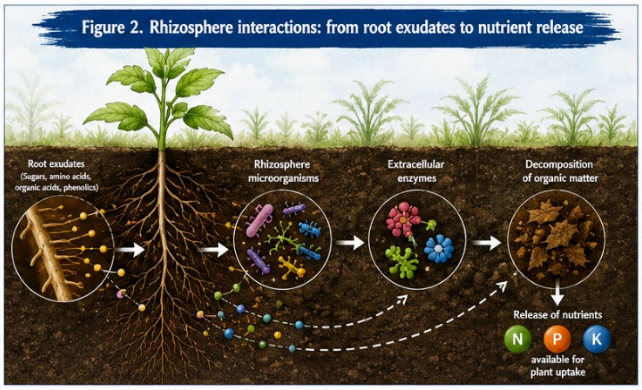
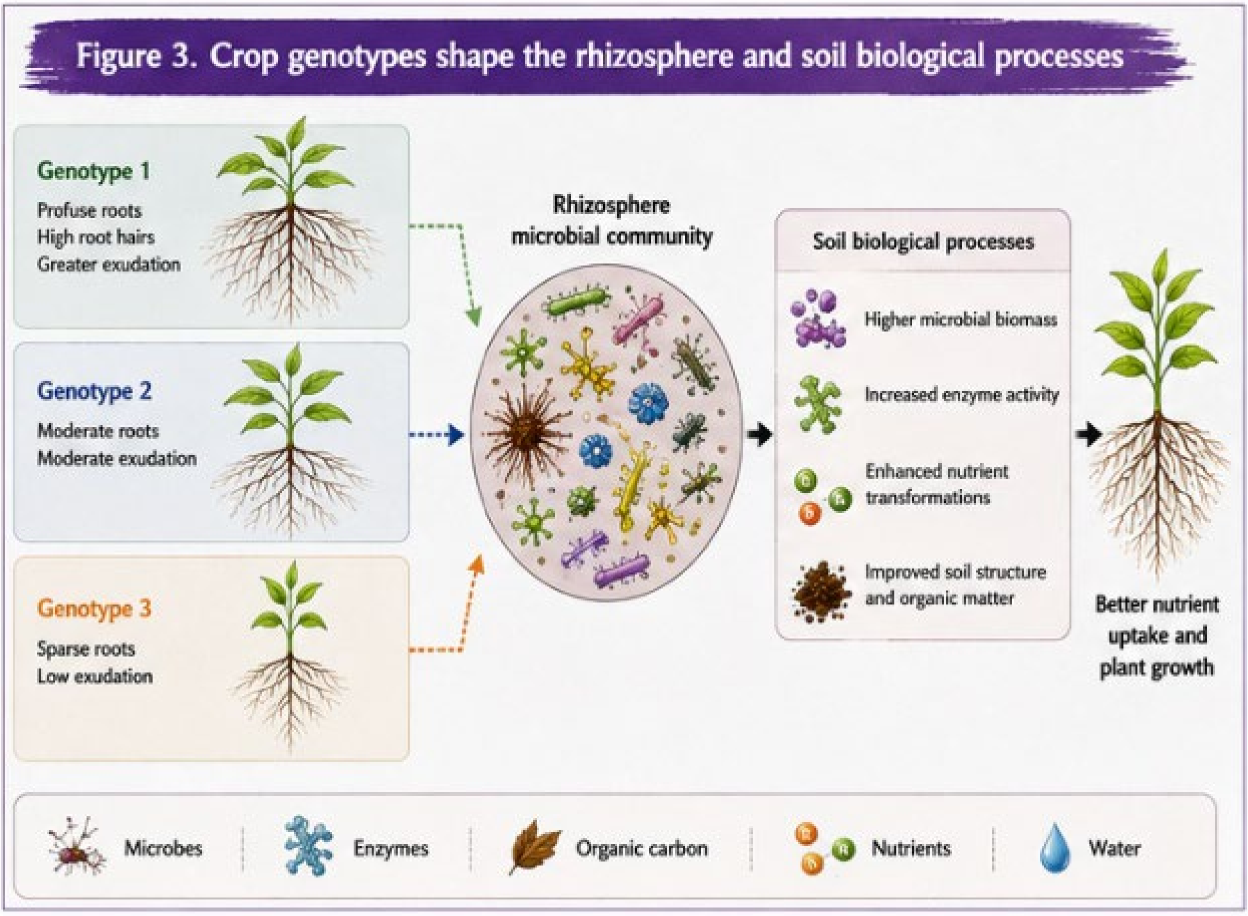


Figure 2. *Root exudates released by plant roots stimulate rhizosphere microorganisms, which produce extracellular enzymes responsible for organic matter decomposition and nutrient release.*

3. Crop Genotypes: The Hidden Architects of the Rhizosphere

Just as people have unique traits, different crop varieties have distinct "underground personalities." A plant's genotype-its genetic makeup-determines its physical and biological characteristics. These genetic differences influence root structure, growth depth, and the substances roots release into the soil. Because these factors shape the microbial life around the roots and affect nutrient recycling, choosing the right crop variety is a key factor in promoting soil health in natural and low-input farming systems (Junaidi et al., 2018). Similar genotype-specific effects on soil chemical properties and belowground processes have also been demonstrated in Populus, highlighting the broader role of plant genetics in regulating soil ecosystems (Craig et al., 2024).

Root exudates-a mix of sugars, amino acids, organic acids, and other small compounds-act as the primary energy source for the microorganisms living in the rhizosphere. When crop varieties direct more carbon



belowground, they generally foster more vibrant microbial communities, which boosts nutrient cycling and strengthens the helpful, mutually beneficial partnerships between plants and their soil-dwelling allies. Junaidi et al. (2018) demonstrated that wheat genotypes with higher root-to-shoot ratios exhibited greater microbial biomass nitrogen, improved nitrogen cycling, and enhanced nutrient uptake following compost application, emphasizing the importance of root phenotypic plasticity in biologically managed systems. Crop genetics do more than just influence microbial numbers; they essentially determine how the entire soil ecosystem functions. Differences in root characteristics and the quality of plant remains regulate how carbon enters the soil and how microbes process nutrients, which supports soil fertility and resilience. By choosing crop varieties with beneficial belowground traits alongside natural farming practices, we can effectively support the root zone and keep our farms sustainable for the long run (Lehman et al., 2015; Craig et al., 2024).

Figure 3. *Crop genotypes influence rhizosphere processes through variations in root architecture and root exudation. These genotype-specific traits regulate microbial colonization, nutrient transformations, and soil biological functioning under natural farming.*

4. Crop Genotypes and Soil Microbial Biomass: Driving Belowground Biological Activity

Soil microbial biomass represents the living component of soil organic matter, including bacteria, fungi, algae, and other microorganisms. Though it makes up only a small portion of the soil, it acts as an active nutrient reservoir essential for breaking down organic matter and cycling carbon. Since these microbial communities react quickly to how we manage the land and the carbon plants provide, they serve as a sensitive and reliable indicator of overall soil health (Lehman et al., 2015). Advances in soil biological research further demonstrate that understanding microbial communities and their interactions with plants is fundamental for improving soil health and ecosystem functioning (Todd-Brown et al., 2021; Tarnowski et al., 2023).

Crop genotype strongly influences soil microbial biomass by regulating belowground carbon allocation through root biomass, root exudation, and residue quality. Junaidi et al. (2018) demonstrated that wheat genotypes with greater root-to-shoot ratios promoted higher microbial biomass nitrogen and enhanced nitrogen cycling following compost application, indicating that root phenotypic plasticity improves plant–soil interactions under biologically managed systems. Similarly, Craig et al. (2024) reported that genetically distinct Populus genotypes modified soil chemical properties and belowground environments, highlighting the broader influence of plant genetics on soil biological processes. These findings suggest that integrating suitable crop genotypes with natural farming practices can strengthen microbial biomass, improve nutrient cycling, and enhance long-term soil fertility.

5. Crop Genotypes Regulate Soil Enzyme Activity and Nutrient Cycling

Soil enzymes are biologically active proteins produced primarily by soil microorganisms and plant roots that catalyse the decomposition of organic matter and the transformation of nutrients into plant-available forms. Among them, dehydrogenase reflects overall microbial metabolic activity, phosphatase releases inorganic phosphorus from organic compounds, β-glucosidase participates in carbon cycling, and urease regulates nitrogen transformation. As these enzymes respond rapidly to changes in soil biological activity, they are widely recognized as sensitive indicators of soil biological health and nutrient cycling (Lehman et al., 2015). Plant–soil interactions mediated through root-derived carbon further regulate microbial metabolism and enzyme production, emphasizing the close relationship between plants and soil biological processes (Hongbo et al., 2015).

Crop genotype influences soil enzyme activity by regulating root architecture, belowground carbon allocation, and the quantity of root exudates available to rhizosphere microorganisms. Junaidi et al. (2018) demonstrated that wheat genotypes with greater belowground investment enhanced microbial activity and nutrient transformations under organic management, while natural farming practices further stimulate these biological processes by increasing microbial abundance and organic carbon availability. Consequently, higher activities of enzymes such as dehydrogenase and phosphatase have been associated with biologically managed soils, resulting in improved nutrient mineralization and soil fertility. These findings indicate that integrating suitable crop genotypes with natural farming practices can strengthen enzyme-mediated nutrient cycling and enhance the sustainability of agricultural production.

6. Scientific Evidence Linking Crop Genotypes with Soil Biological Health

Growing scientific evidence demonstrates that crop genotype is an important biological factor regulating rhizosphere processes and overall soil health. Genotypic differences in root architecture, belowground carbon allocation, and root exudation influence microbial colonization, nutrient transformations, and soil biochemical processes. Junaidi et al. (2018) showed that wheat genotypes with greater root investment responded more positively to organic amendments by improving microbial biomass, nitrogen cycling, and nutrient uptake. Likewise, Craig et al. (2024) demonstrated that genetically distinct *Populus* genotypes modified soil chemical properties and belowground environments, confirming that plant genetics can influence soil ecosystem functioning across different crop species.

These findings reinforce the concept that improving soil biological health requires integrating suitable crop genotypes with biologically based management practices rather than relying solely on external nutrient inputs. As emphasized by Lehman et al. (2015), maintaining active microbial communities is fundamental for sustaining nutrient cycling and ecosystem resilience, while recent advances in soil biology and microbiome research further highlight the importance of understanding plant–soil interactions for developing sustainable agricultural systems (Todd-Brown et al., 2021; Tarnowski et al., 2023).

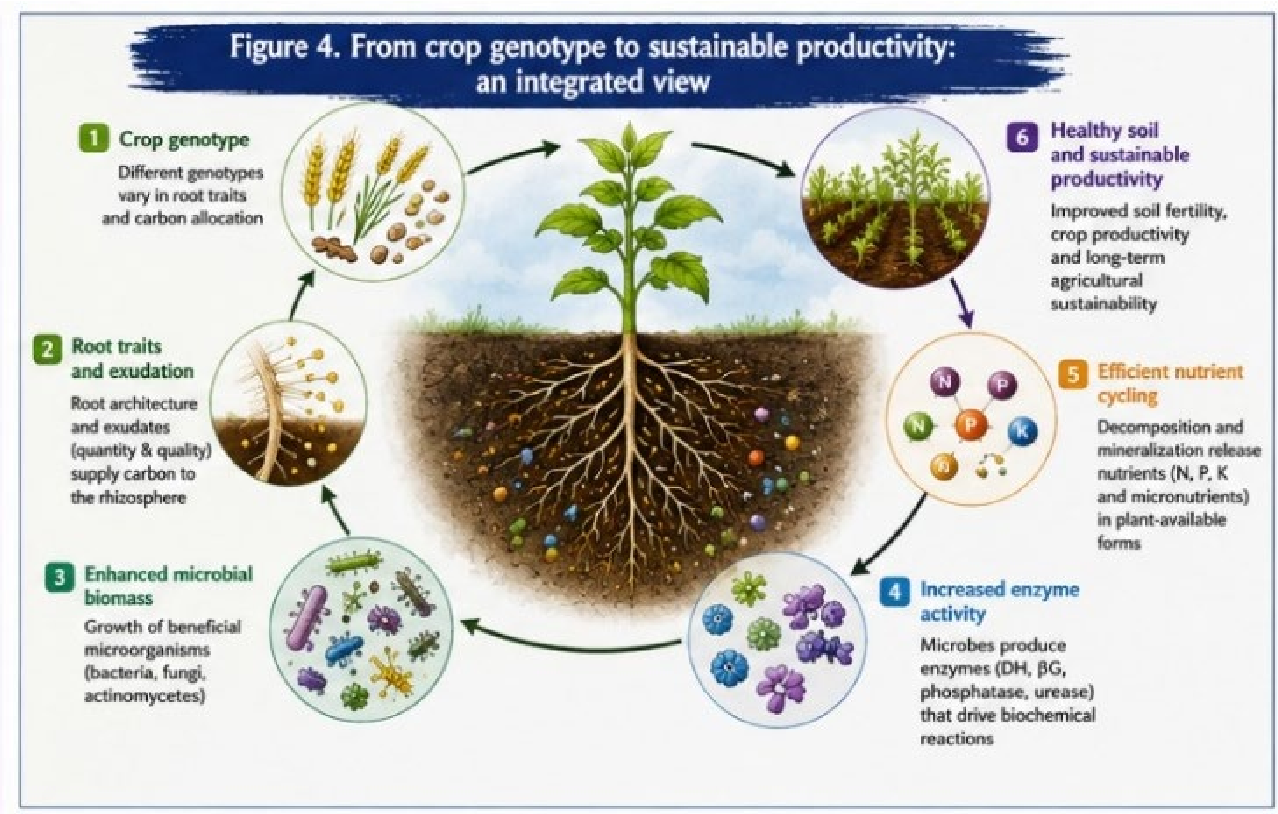


Figure 4. *Schematic representation of the integrated effects of crop genotype and natural farming on rhizosphere processes, showing the regulation of root traits, microbial biomass, extracellular enzyme activity, nutrient cycling, and their collective contribution to soil biological health and sustainable crop production.*

Collectively, these studies indicate that combining genotype selection with natural farming practices offers a promising strategy for enhancing soil microbial biomass, enzyme activity, and long-term agricultural sustainability.

7. Summary

Natural farming relies on healthy soil to keep crops productive and ecosystems functioning. A key factor here is crop genotype, as different plants influence soil life-including microbial biomass and enzyme activity-through their root structures and the carbon they release underground. These interactions help boost soil fertility, resilience, and nutrient cycling. Natural farming practices further support this by providing the organic matter needed for beneficial microbes to thrive. Research shows that pairing the right crop choices with nature-based management improves soil health and long-term sustainability. By combining a crop's genetic potential with thoughtful soil management, we can build more resilient and productive farming systems.

8. Conclusions

Crop genotypes play a pivotal role in shaping soil biological health by regulating rhizosphere interactions, microbial biomass, and enzyme-mediated nutrient cycling. When integrated with natural farming practices, genotypes possessing favourable root traits and greater belowground carbon allocation stimulate beneficial microbial activity, improve nutrient availability, and enhance soil fertility through biologically driven processes. This synergy between crop genetics and ecological soil management strengthens soil resilience, promotes efficient resource utilization, and supports sustainable crop production. Therefore, selecting appropriate crop genotypes alongside biologically based farming practices offers a practical and environmentally sound strategy for improving long-term soil health and agricultural sustainability.

References

Craig, M. E., Harman-Ware, A. E., Cope, K. R., & Kalluri, U. C. (2024). Intraspecific variability in plant and soil chemical properties in a common garden plantation of the energy crop Populus. *Plos one*, *19*(10), e0309321.

Hongbo, S., Sixue, C., & Brestic, M. (2015). Environment-Living Organism's Interactions from Physiology to Genomics. *International Journal of Genomics*, *2015*, 270736.

Junaidi, J., Kallenbach, C. M., Byrne, P. F., & Fonte, S. J. (2018). Root traits and root biomass allocation impact how wheat genotypes respond to organic amendments and earthworms. *PLoS One*, *13*(7), e0200646.

Lehman, R. M., Cambardella, C. A., Stott, D. E., Acosta-Martinez, V., Manter, D. K., Buyer, J. S., ... & Karlen, D. L. (2015). Understanding and enhancing soil biological health: the solution for reversing soil degradation. *Sustainability*, *7*(1), 988-1027.

Tarnowski, M. J., Varliero, G., Scown, J., Phelps, E., & Gorochowski, T. E. (2023). Soil as a transdisciplinary research catalyst: from bioprospecting to biorespecting. *Royal Society Open Science*, *10*(11), 230963.

Todd-Brown, K. E., Abramoff, R. Z., Beem-Miller, J., Blair, H. K., Earl, S., Frederick, K. J., ... & Younger, M. L. (2021). Reviews and syntheses: The promise of big soil data, moving current practices towards future potential. *Biogeosciences Discussions*, *2021*, 1-22.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

ARTICLE ID: 14

Catching the Rain Where It Falls: A Guide to Smart Moisture Conservation in India's Drylands

AUTHORS' DETAILS:

Valluru Naga Venkata Nadh
Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, University of Agricultural Sciences, Raichur, Karnataka

Koppisetti Veera Naga Durga
Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, University of Agricultural Sciences, Raichur, Karnataka

Akasha Deepa P U
Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, University of Agricultural Sciences, Raichur, Karnataka

Sagara R
Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, University of Agricultural Sciences, Raichur, Karnataka

Farming in India's semi-arid tropics and rainfed drylands is a continuous test of resilience. When the monsoon arrives, it rarely brings the gentle, soaking showers that crops need. Instead, rain frequently falls in short, intense cloudbursts. Rather than sinking into the earth to nourish crop roots and recharge the local water table, the water sheets across the field, taking valuable, nutrient-rich topsoil with it. By the time a mid-season dry spell hits, the soil is heavily parched, the crop is severely stressed, and underground borewells remain depleted. For years, the default solution has been drilling deeper wells or simply hoping for the next rain.

But there is a more reliable way to secure water. The most effective, low-cost water storage facility is not a concrete tank or a massive dam it is the field itself. By adopting in-situ moisture conservation (catching the rain exactly where it falls) alongside an understanding of natural soil health and smart technologies, farmers across India can turn their land into a sponge, securing yields even when the weather turns unpredictable.

Here is a comprehensive guide to transforming your farm's relationship with water.

The Biological Foundation – Soil Health and "Whapasa"

Before moving massive amounts of earth to capture water, we must first look at the biological makeup of the soil. Physical structures will not hold water effectively if the soil itself is degraded, compacted, and devoid of life. In natural farming frameworks, there is a critical concept known as Whapasa. This refers not to soaking wet soil, but to the precise microclimate where the soil contains an optimal 50/50 mixture of air and water vapors. This ideal aeration allows roots to thrive, breathe, and absorb moisture efficiently without drowning.

How to build Whapasa in your fields:

- Retain Crop Residue: Do not burn or deeply plow all crop residue. Leaving biological matter on the surface acts as an organic mulch. This shields the soil from the baking sun, drastically reducing the evaporation of whatever moisture you have managed to capture.
- Minimize Deep Tillage: Over-plowing destroys the natural macro-pores created by earthworms and root channels. These pores are the natural pipelines that guide surface rainwater deep underground.
- Foster Soil Microbes: Healthy soils rich in organic carbon act like a natural sponge. Increasing soil organic matter by just 1% allows the soil to hold thousands of extra liters of water per acre.

The Physical Foundation – Shaping Your Land to Hold Water

Once the soil's biological health is addressed, physical land-shaping techniques act as speed bumps for runoff, forcing water to slow down and sink deep into the soil profile.

1. Broad Bed and Furrow (BBF) System

The BBF system is an absolute necessity for managing water in the deep black soils (vertisols) commonly found in the region. These soils are notorious for cracking deeply during droughts, which exposes roots to hot air, and suffocating roots during heavy rains due to waterlogging.

- The Design: The field is shaped into a series of raised flat beds (usually about 150 cm wide) separated by shallow, sunken furrows (about 50 cm wide). Crops like groundnut, chickpea, or sorghum are planted directly on the raised beds.
- During Heavy Rain: The furrows act as safe drainage channels. Instead of water pooling around the stems and drowning the crop, excess water flows safely away at a controlled pace, preventing root rot.
- During Dry Spells: The water stored deep in the furrows slowly seeps sideways into the broad beds. This provides a steady, invisible supply of moisture to the crop roots long after the surface soil looks bone dry.

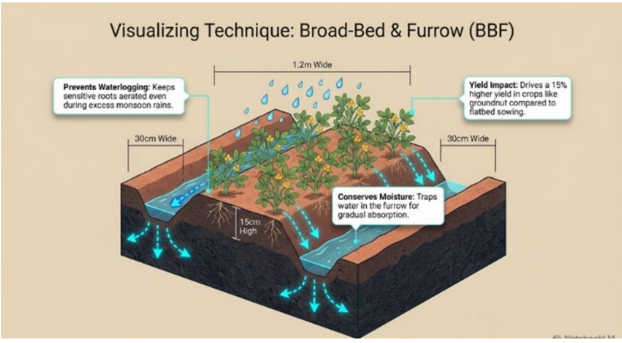


Fig: Broad Bed Furrow(BFF)

2. Contour Bunding

If your land has a noticeable slope, water will naturally accelerate as it moves downhill, taking your most fertile topsoil with it. Contour bunding stops this destructive flow.

- The Design: Small earthen embankments (bunds) are constructed across the slope of the land, carefully following its natural elevation lines.
- The Impact: When rain falls, the runoff flows down the slope but is trapped by the bund. The water ponds quietly behind the embankment, giving it time to percolate deep into the soil. Over time, this raises the local water table and keeps the soil profile moist for weeks longer than flat, unbunded land.
- Stabilization: To make these bunds even stronger, plant deep-rooted grasses or legumes (like vetiver or stylo) on the ridges. This stabilizes the soil, prevents the bund from washing away during extreme storms, and provides extra cattle fodder.

3. Trenching (Staggered and Continuous)

For dryland horticulture, orchards, or degraded lands with steeper slopes, trenching is an aggressive and highly effective approach.

- The Design: Instead of building soil up, you dig down. Trenches are excavated along the contour lines to catch water and soil.
- The Impact: Staggered trenches (short, disconnected pits dug in an overlapping brick-like pattern) are excellent for dryland fruit crops like mango or pomegranate. When a tree is planted just below a trench, its root system has guaranteed access to a concentrated pocket of moisture and captured organic matter that washes into the pit.

The Next Frontier – Smart Farming and Technology

Physical land-shaping does the heavy lifting, but modern technology helps you squeeze the maximum benefit out of every drop.

Precision Laser Land Leveling

Even slight, invisible unevenness in a field causes water to pool in some areas while leaving others completely dry. A laser-guided scraper is towed behind a tractor to grade the field to a mathematically flat surface. When combined with a BBF system, laser leveling ensures absolute uniformity. Every single plant gets the exact same amount of water, cutting irrigation water usage by up to 30%.

IoT Soil Moisture Sensors

Building a contour bund is the first step; knowing exactly how much water is stored underground is the next. Low-cost, battery-powered sensors can be placed in the soil at the root zone level. These sensors measure the exact volumetric moisture content and send the data directly to your mobile phone. Instead of guessing if the crop needs water by looking at the surface, you can see exactly what the roots are experiencing, allowing you to trigger targeted micro-irrigation before the crop begins to wilt.

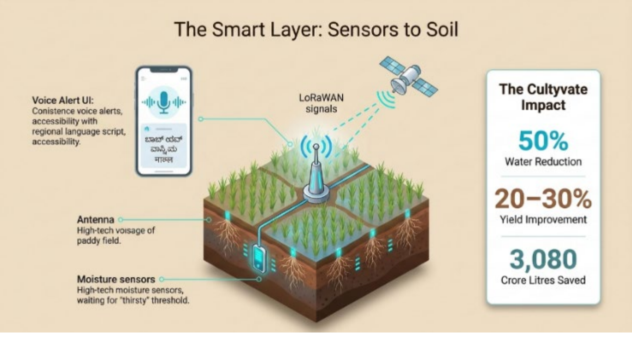


Fig: Utilisation of Sensor technology in Agriculture

Micro-Irrigation

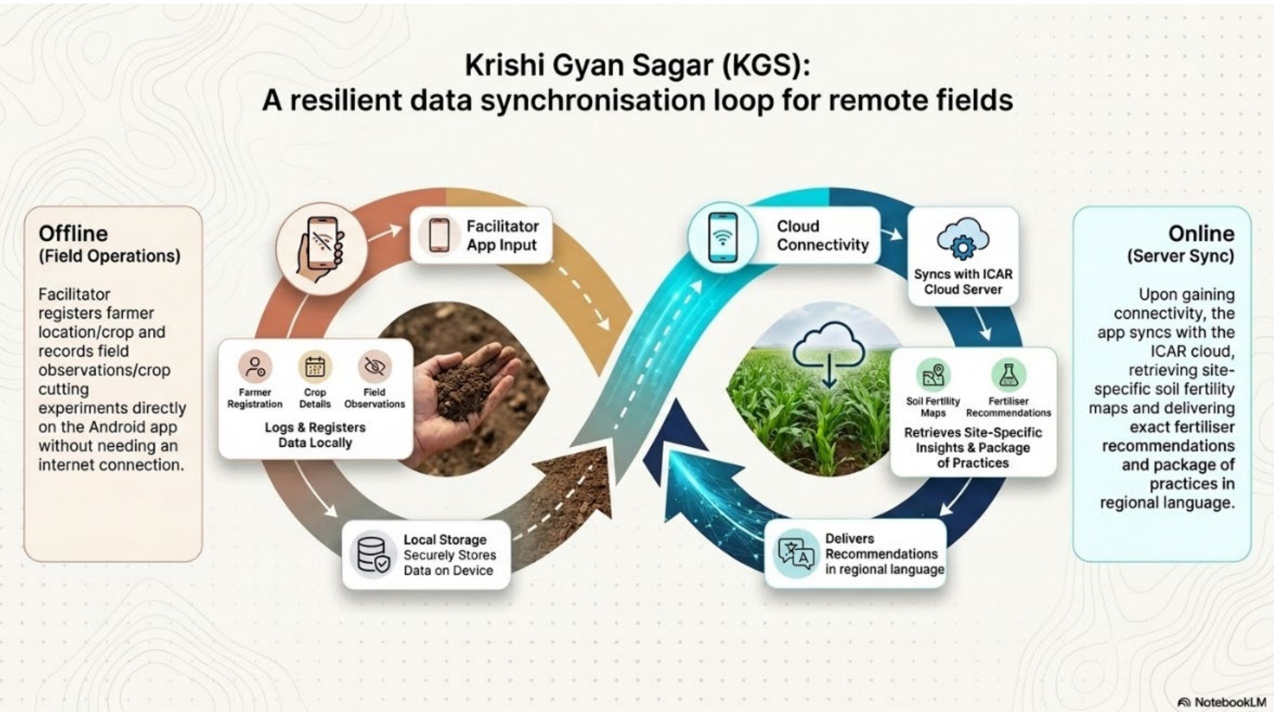
"Per Drop More Crop" When the soil moisture captured by trenches or BBF systems eventually begins to deplete during a severe drought, supplementary irrigation is required. However, flood irrigation wastes massive amounts of water. Transitioning to micro-irrigation (drip and sprinkler systems) ensures that water is delivered directly to the root zone, maintaining the ideal "Whapasa" state without over-saturating the soil.

Predictive Moisture Forecasting & The KGS App

The future of drought-proofing relies on utilizing machine learning to forecast exact field conditions rather than merely reacting to today's weather. By tracking independent variables like local rainfall and soil temperature, predictive models can accurately forecast soil moisture dynamics for the coming week, allowing farmers to perfectly time their drip irrigation and fertilizer applications.

While physical structures physically capture this rainwater, the Krishi Gyan Sagar (KGS) application maximizes its utility by acting as a resilient data synchronization loop that bridges the gap between advanced cloud forecasting and remote agricultural fields. Facilitators can use the app completely offline to securely log farmer registrations, crop details, and vital field observations. Upon gaining network connectivity, KGS automatically synchronizes this localized ground-truth data with the ICAR cloud server to retrieve site-specific soil fertility maps and precise packages of practices. These tailored recommendations are then delivered directly to the user in their regional language, ensuring that the water conserved in the field is paired with data-driven foresight

Fig: Krishi Gyan Sagar Application



Accessing Financial Support for Equipment

Changing how land is prepared and irrigated requires upfront effort and capital. Fortunately, the Government of India has established multiple central schemes specifically targeted at funding moisture conservation and rainfed farming upgrades.

- **Watershed Development Component (WDC-PMKSY):** Designed specifically for rainfed areas, this scheme heavily funds the creation of in-situ moisture conservation structures. Farmers can receive support for ridge area treatment, constructing contour bunds, digging staggered trenches, and building farm ponds to capture runoff.
- **MGNREGA for Land Development:** The Mahatma Gandhi National Rural Employment Guarantee Act is a massive resource for small and marginal dryland farmers. Through the gram panchayat, funds can be utilized to cover the labor costs of digging trenches, constructing field bunds, and land leveling on individual farmholdings, effectively making the physical land-shaping process free for the farmer.
- **Rainfed Area Development (RAD) under NMSA:** The National Mission for Sustainable Agriculture offers financial assistance to farmers adopting integrated farming systems and soil/moisture conservation practices in dryland areas to minimize the risk of crop failure.
- **PMKSY - Per Drop More Crop:** This flagship scheme subsidizes the installation of micro-irrigation systems (drip and sprinklers). Small and marginal farmers can typically avail up to 55% financial assistance on the unit cost, while other farmers receive up to 45%.
- **Sub-Mission on Agricultural Mechanization (SMAM):** This scheme provides 40% to 50% subsidies for purchasing heavy equipment like tractor-drawn BBF makers or laser land levelers. Additionally, if purchasing equipment outright is not viable, the nationwide network of **Custom Hiring Centers (CHCs)** allows farmers to rent advanced machinery by the hour at subsidized, below-market rates.

Conclusion

The days of relying on predictable, perfectly timed monsoons are over. A field managed with in-situ moisture conservation techniques acts as a permanent insurance policy against an unpredictable climate. By combining the natural wisdom of soil health with intelligent land shaping, precision micro-irrigation, robust central government subsidies, and modern predictive technology, farmers across India can take permanent control of their water security and build true drought resilience.

References

- Garg, K. K., Akuraju, V., Anantha, K. H., Singh, R., Whitbread, A. M., & Dixit, S. (2022). Identifying potential zones for rainwater harvesting interventions for sustainable intensification in the semi-arid tropics. *Scientific Reports*, *12*. https://doi.org/10.1038/s41598-022-07847-4
- Prem, M., Ranjan, P., Seth, N., & Patle, G. T. (2020). Mulching Techniques to Conserve the Soil Water and Advance the Crop Production - A Review. *Current World Environment*, *Special Issue*. https://doi.org/10.12944/cwe.15.special-issue1.02
- Tolossa, T. T., Abebe, F. B., & Girma, A. A. (2020). Review: Rainwater harvesting technology practices and implication of climate change characteristics in Eastern Ethiopia. *Cogent Food & Agriculture*, *6*, 1724354. https://doi.org/10.1080/23311932.2020.1724354
- Wani, S. P., Rockstrom, J., & Sahrawat, K. L. (2011). Integrated Watershed Management in Rainfed Agriculture. CRC Press. https://doi.org/10.1201/b11424

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Ritu Mishra
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand

Prathistha Chaudhary
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand

Diksha Joshi
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand

Batta Ganga Bhavani
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand

Priya
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand

ARTICLE ID: 15

Digital Solutions for Modern Farming: The Role of Mobile Applications and Artificial Intelligence

Abstract
The rapid advancement of digital technologies has transformed agriculture by introducing innovative tools that improve productivity, efficiency, and sustainability. Among these technologies, mobile applications and artificial intelligence (AI) have emerged as powerful solutions for addressing the challenges faced by modern farming. Mobile applications provide farmers with easy access to weather forecasts, market prices, crop management practices, pest and disease diagnosis, government schemes, and expert advisory services. AI further enhances decision-making by analyzing large volumes of agricultural data to support precision farming, crop monitoring, irrigation scheduling, pest detection, yield prediction, and resource optimization. Together, these technologies enable timely, data-driven decisions that reduce production risks, improve input-use efficiency, and enhance farm profitability. In countries such as India, where agriculture supports millions of livelihoods, digital solutions are strengthening extension services and narrowing the gap between research and field implementation. As digital infrastructure and smartphone adoption continue to expand, mobile applications and AI are expected to play a central role in building a resilient, productive, and sustainable agricultural sector.
Keywords- Artificial Intelligence, Mobile app, Pest detection, Precision agriculture

Introduction

Agriculture is the foundation of economic development and plays a vital role in ensuring sustainable livelihoods and long-term economic growth. Traditionally focused on food and crop production, the agricultural sector has evolved to encompass processing, value addition, marketing, and distribution of crop and livestock products. Today, it contributes significantly to employment generation, national income, international trade, and the supply of raw materials for various industries, thereby supporting overall economic development (Awokuse & Xie, 2015). However, rapid population growth and increasing pressure on natural resources necessitate the adoption of innovative and sustainable agricultural practices. Artificial intelligence (AI), integrated with emerging technologies such as the Internet of Things (IoT), robotics, drones, sensors, and big data analytics, is transforming modern agriculture into a data-driven and precision-based system. By analyzing real-time and historical information on weather, soil properties, moisture levels, and crop performance, AI enables informed decisions on crop selection, sowing, irrigation, nutrient management, and harvesting. These advancements improve productivity, optimize the use of water, fertilizers, and pesticides, reduce environmental impacts, enhance farm safety, and support sustainable food production to meet the demands of a growing global population.

Mobile applications have become an integral part of modern life, transforming how people access information, communicate, and utilize essential services. Their rapid adoption has also revolutionized agriculture by providing farmers with instant access to scientific knowledge, expert advice, weather updates, and market information. With the increasing availability of smartphones, these digital tools are making agricultural information more accessible, timely, and user-friendly, thereby supporting informed decision-making and improving farm management (Ning et al., 2023). Mobile applications have emerged as effective digital extension tools by providing real-time information on weather forecasts, pest and disease diagnosis, crop management practices, modern agricultural technologies, farm machinery, and market prices. Many applications also connect farmers with agricultural experts, enabling timely technical guidance and practical solutions to field problems.

Sources of Agricultural Information and the Growing Importance of Mobile Applications

Traditionally, farmers relied on extension workers, Krishi Vigyan Kendras (KVKs), universities, and research institutions for agricultural advice. Although internet-based services improved access to information, their adoption in rural areas was limited by poor connectivity and infrastructure. The rapid growth of smartphones has transformed agricultural extension through mobile applications that provide real-time information on crop management, pest and disease diagnosis, weather forecasts, market prices, soil health, irrigation, and government schemes.

To strengthen digital agriculture, the Government of India has launched several mobile applications that deliver reliable, location-specific, and science-based advisories. These applications bridge the gap between research and field practices, enabling farmers to make informed decisions, improve productivity, optimize resource use, and promote sustainable agriculture (Table 1).

Table.1 Smart Agriculture Mobile Applications for Indian Farmers

Mobile App	Developer/Organization	Primary Purpose	Key Features & Applications	Benefits to Farmers
MyIPM	Clemson University, USA	Integrated Pest Management (IPM)	Identifies insect pests, diseases, and weeds; provides management options, pesticide information, and IPM recommendations.	Supports accurate pest diagnosis and encourages responsible pesticide use.
Plantix	PEAT GmbH, Germany	AI-based crop diagnosis	Detects pests, diseases, and nutrient deficiencies from crop images; offers management advice, weather alerts, and expert support.	Enables rapid diagnosis and timely crop protection decisions.
Ag PhD Field Pest Identification	Ag PhD, USA	Pest scouting and identification	Provides pest images, field scouting records, nutrient deficiency guides, and crop loss calculators.	Improves field monitoring and supports informed pest management.
AGRIVI	AGRIVI, Croatia	Digital farm manag	Offers field mapping,	Enhances farm

Mobile App	**Developer/Organization**	**Primary Purpose**	**Key Features & Applications**	**Benefits to Farmers**
		ement	weather-based advisories, pest alerts, crop planning, and farm record management.	planning and promotes efficient use of agricultural inputs.
RiceXpert	International Rice Research Institute (IRRI)	Rice crop advisory	Provides diagnosis of rice pests, diseases, weeds, nutrient disorders, fertilizer calculator, and e-advisory services.	Assists rice growers in making timely crop management decisions.
Mango Cultivation App	ICAR–IIHR, Bengaluru	Mango production management	Offers complete cultivation practices, pest and disease identification, and control recommendations for mango orchards.	Improves orchard productivity through crop-specific guidance.
Krishi Jagran App	Krishi Jagran	Agricultural information portal	Delivers agricultural news, government schemes, market updates, pest advisories, and modern farming	Keeps farmers informed about the latest developments in agriculture.

Mobile App	**Developer/Organization**	**Primary Purpose**	**Key Features & Applications**	**Benefits to Farmers**
			technologies.	
Papaya Cultivation App	ICAR–IIHR, Bengaluru	Papaya crop management	Provides recommendations on cultivation practices, pest and disease management, irrigation, nutrition, and improved varieties.	Helps reduce crop losses and improve papaya production.
Crop Doctor	IGKV–NIC, Raipur	Crop problem diagnosis	Diagnoses crop problems using images and recommends suitable management practices in Hindi and English.	Offers quick solutions and improves access to expert advice for farmers.
Kisan Suvidha	Government of India	Farm advisory services	Provides weather forecasts, market prices, pest and disease management, expert consultation, and government information.	Supports better farm planning and informed day-to-day decision-making.
Farm-O-	C-DAC, Mumbai	Location-	Recommends	Promotes

Mobile App	Developer/Organization	Primary Purpose	Key Features & Applications	Benefits to Farmers
Pedia		specific crop advisory	suitable crops, fertilizer schedules, safe pesticide use, and soil-based management practices.	sustainable farming and efficient resource utilization.
IFFCO Kisan	Indian Farmers Fertiliser Cooperative Ltd. (IFFCO)	Agricultural advisory	Crop advisories, weather updates, market prices, pest management, and expert consultation.	Supports timely farm decisions and improves crop management.
Crop Insurance	Ministry of Agriculture & Farmers Welfare	Crop insurance services	Premium calculation, scheme details, and claim information.	Promotes financial security and informed insurance planning.
Meghdoot	IMD, ICAR & Ministry of Earth Sciences	Weather advisory	Location-specific weather forecasts and agrometeorological advisories.	Helps farmers plan field operations and reduce weather-related losses.
e-NAM	Ministry of Agriculture & Farmers Welfare	Digital agricultural market	Real-time market prices, commodit	Improves market access

Mobile App	Developer/Organization	Primary Purpose	Key Features & Applications	Benefits to Farmers
		ing	y arrivals, and online trading.	and enhances price realization.
Pashu Poshan	National Dairy Development Board (NDDB)	Livestock nutrition	Balanced ration formulation based on animal type and production.	Improves animal health, milk yield, and feed efficiency.

Artificial Intelligence in Agriculture

Agriculture involves continuous decision-making under changing and often unpredictable conditions. Farmers must deal with challenges such as variable weather, fluctuating input costs, declining soil health, weed infestation, pest outbreaks, crop diseases, and the impacts of climate change, all of which influence crop productivity and profitability. Managing these uncertainties requires timely and informed decisions supported by reliable technologies. Among the various factors affecting agricultural production, soil health, crop management, pest and disease control, and weed management play particularly important roles (Eli-Chukwu,2019). Consequently, the application of artificial intelligence (AI) in these areas has gained significant attention for its potential to improve decision-making, optimize resource use, and enhance sustainable agricultural production (Table.2).

Table.2 Major Applications of Artificial Intelligence in Agriculture

Agricultural Domain	AI Technique/Technology	Application	Major Contribution
Soil Management	Management-Oriented Modelling (MOM)	Optimizes nitrogen fertilizer management	Reduces nitrate losses while maintaining crop productivity

Agricultural Domain	AI Technique/Technology	Application	Major Contribution
			through intelligent nutrient management.
	Fuzzy Logic-based Soil Risk Characterization Decision Support System (SRC-DSS)	Soil quality and risk assessment	Assists in classifying soils according to their environmental risks, supporting sustainable land management.
	Artificial Neural Networks (ANN)	Soil texture prediction	Estimates soil texture to support suitable crop selection. Predicts soil moisture for efficient irrigation management. Assesses soil health to improve fertility and productivity. Estimates nutrient availability for precision nutrient management.
Crop Management	CALEX Expert System	Crop operation scheduling	Assists farmers in planning sowing, irrigation, fertilization, and other field operations at appropriate times.
	PROLOG-based Decision Support System	Farm management planning	Integrates weather, machinery, labour availability, and crop information to improve operational and economic efficiency.
	Artificial Neural Networks (ANN)	Crop yield prediction	Forecasts crop yield using climatic and soil parameters, enabling informed management decisions.
	Demeter Autonomous Robot	Automated harvesting	Performs autonomous harvesting with GPS-guided navigation, reducing labour requirements.
	Computer Vision-based Robotic System	Fruit harvesting	Detects fruits and guides robotic harvesting with minimal human intervention.
	Artificial Neural Networks (ANN)	Crop nutrient diagnosis	Identifies nutrient deficiencies at an early stage, allowing timely corrective measures.
	Fuzzy Cognitive Maps	Yield prediction and decision support	Simulates crop growth scenarios to improve farm planning

Agricultural Domain	AI Technique/Technology	Application	Major Contribution
			and productivity.
	Artificial Neural Networks (ANN)	Crop response modelling	Predicts crop performance under varying soil moisture and salinity conditions to optimize irrigation management.
	ANN integrated with Fuzzy Logic	Precision herbicide application	Supports precise herbicide application, reducing unnecessary chemical use and improving crop protection.
Disease and Pest Management	Computer Vision, Genetic Algorithms and ANN	Plant disease identification	Detects diseases rapidly through image analysis, improving diagnostic accuracy and reducing crop losses.
	Rule-based Expert Systems	Pest and disease diagnosis	Provides recommendations for disease identification and appropriate management practices.
	Fuzzy Logic with Geographic Information Systems (GIS)	Pest monitoring	Combines spatial information with intelligent reasoning for location-specific pest surveillance.
	Web-based Intelligent Disease Diagnosis Systems	Disease diagnosis	Delivers real-time disease diagnosis and advisory services through online platforms.
	Fuzzy Logic with Text-to-Speech Interface	Interactive advisory system	Enables user-friendly disease diagnosis through voice-assisted expert recommendations.
	Artificial Neural Networks with GIS	Fruit tree disease diagnosis	Improves disease detection accuracy by integrating spatial information with AI-based prediction models.
	Fuzzy Expert Systems	Pest forecasting	Predicts pest outbreaks and supports timely implementation of integrated pest management practices.
	Artificial Neural Networks (ANN)	Disease prediction	Identifies early disease symptoms using spectral and environmental data, enabling preventive

Agricultural Domain	AI Technique/Technology	Application	Major Contribution
			management.
Weed Management	Artificial Neural Networks and Genetic Algorithms	Weed recognition	Differentiates weeds from crops, supporting targeted weed management strategies.
	Artificial Neural Networks with Invasive Weed Optimization	Weed image segmentation	Enhances the identification of weeds in field images for precision agriculture.
	Robotics with Machine Learning	Mechanical weed removal	Automates weed control, reducing dependence on herbicides and manual labour.
	Unmanned Aerial Vehicles (UAVs) with Machine Learning	Weed mapping	Uses aerial imagery to detect weed infestations and generate field-specific management maps.
	Expert Systems	Weed management planning	Supports farmers in selecting suitable weed management strategies based on field conditions.
	Support Vector Machine (SVM) with ANN	Crop stress and weed detection	Detects nutrient stress and weed presence simultaneously for site-specific interventions.
	Digital Image Analysis integrated with GPS	Precision weed control	Enables accurate identification and GPS-guided herbicide application, minimizing chemical usage.
	UAV-based AI Systems	Field weed surveillance	Rapidly monitors weed populations over large agricultural fields, facilitating timely control measures.
	Learning Vector Quantization (LVQ) with ANN	Weed classification	Classifies weed species efficiently using image recognition techniques, improving precision farming practices.

Conclusion

Mobile applications and artificial intelligence are reshaping modern agriculture by making farming more efficient, precise, and knowledge-driven. These technologies provide farmers with timely access to critical information, support accurate decision-making, and facilitate the adoption of improved agricultural practices. From crop planning and pest management to weather forecasting, market intelligence, and precision resource management, digital tools help increase productivity while reducing costs and environmental impacts. Their integration into agricultural extension systems has also improved the accessibility of scientific knowledge, particularly for small and marginal farmers. Despite challenges such as digital literacy, internet connectivity, and technology adoption, continued investments in digital infrastructure, capacity building, and user-friendly innovations will accelerate their widespread use. The future of agriculture lies in combining technological innovation with sustainable farming practices. By empowering farmers with real-time information and intelligent decision-support systems, mobile applications and AI can contribute significantly to food security, climate resilience, and sustainable agricultural development.

References

Awokuse, T. O., & Xie, R. (2015). Does agriculture really matter for economic growth in developing countries?. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *63*(1), 77-99.

Eli-Chukwu, N. C. (2019). Applications of artificial intelligence in agriculture: A review. *Engineering, Technology & Applied Science Research*, *9*(4).

Ning, B., Zhang, X., Gao, S., & Li, G. (2023). Dp-agm: a differential privacy preserving method for binary relationship in mobile networks. *Mobile Networks and Applications*, *28*(5), 1597-1616.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Rathinaguru E

Agronomist, EID Parry (I) Ltd, Nellikuppam, Cuddalore district, Tamil Nadu

ARTICLE ID: 16

El Niño's impact on Tamil Nadu's sugarcane production: Obstacles, scientific viewpoints and climate-smart adaptation

Abstract

One of India's top sugarcane producers, Tamil Nadu cultivates about 2.4–2.8 lakh hectares annually, with an average production of 95–105 t ha^{-1}, among the highest in the nation. However, the state's sugarcane crop is growing more susceptible to climatic fluctuations. The El Niño–Southern Oscillation (ENSO) is one of the major climatic drivers that significantly affect temperature and rainfall distribution. Even though the Northeast Monsoon (October–December) provides about 48% of Tamil Nadu's yearly rainfall, El Niño can change the behaviour of both the Northeast and Southwest monsoons, leading to higher temperatures, longer dry spells, and unpredictable rainfall. Sugarcane growth, irrigation demand, fertilizer use efficiency, and sugar recovery are all directly impacted by these changes. According to recent simulation studies, a temperature increase of 2–4°C might result in a 3–9% decrease in sugarcane yields and a 4–13% increase in crop water requirements in Tamil Nadu.

Tamil Nadu's climate and sugarcane

Tamil Nadu differs from many sugarcane-growing states because it depends heavily on the monsoon systems.

Important facts include:

Parameter	Tamil Nadu
Annual rainfall	~945 mm
Contribution from Northeast Monsoon (Oct - Dec)	~48%
Contribution from Southwest Monsoon (Jun - Sep)	~30%

Tamil Nadu's reliance on the Northeast monsoon sets it apart. In contrast to northern India, the availability of water for plant-ratoon cane and irrigation reservoir replenishment is closely correlated with rainfall from October to December. **(Gowtham *et al.*, 2019)**

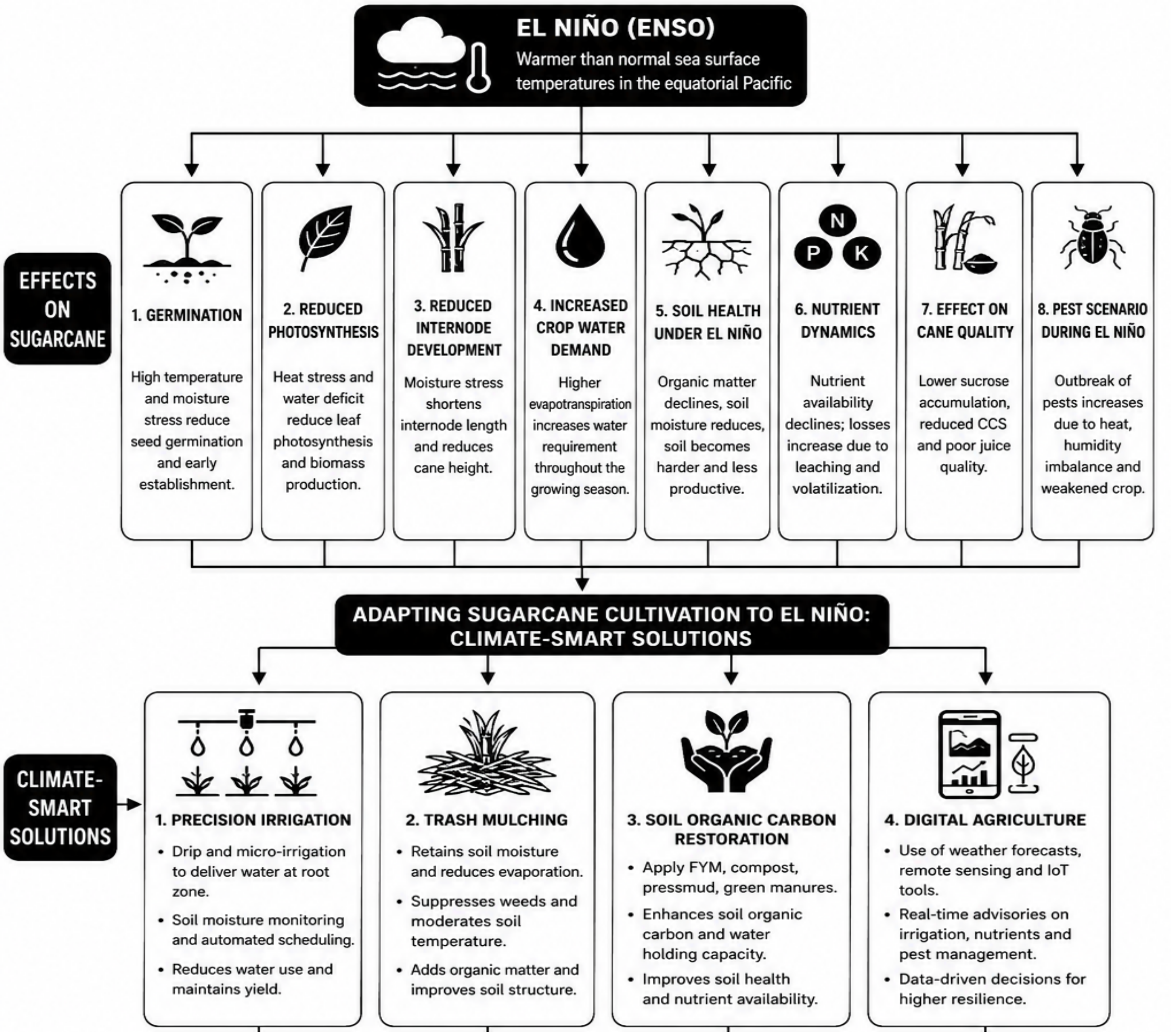
Understanding El Niño

El Niño refers to the abnormal warming of sea surface temperatures in the equatorial Pacific Ocean, altering global atmospheric circulation. In India, El Niño is generally associated with:

- Delayed Southwest Monsoon
- Higher summer temperatures
- Longer dry spells
- Increased evapotranspiration
- Reduced reservoir inflow

However, the relationship with Tamil Nadu is more complex. Research shows that ENSO can also influence the Northeast Monsoon, which supplies nearly half of the state's annual rainfall, making seasonal rainfall prediction particularly important. **(Lakshmi *et al.*, 2025)**

Physiological effects of El Niño on sugarcane:



Why is sugarcane highly vulnerable???

Sugarcane is a long-duration crop (10–14 months in Tamil Nadu) requiring approximately 1,500–1,700 mm of water depending on the agro-climatic zone.

A recent modelling study using the DSSAT-CANEGRO model across Tamil Nadu reported:

- Water requirement ranged from 1540 mm (Southern Zone) to 1700 mm (North-eastern Zone).
- A 2°C temperature increase reduced yield by about 3%.
- A 3°C increase reduced yield by 5%.
- A 4°C increase reduced yield by nearly 9%.
- Water requirement increased by 13% under a 4°C warming scenario. **(Guhan *et al.*, 2024)**

These projections highlight the increasing irrigation burden under warmer climates.

Germination

Moisture stress during planting causes:

- Poor bud sprouting
- Delayed emergence
- Reduced plant population

Every 10% reduction in germination eventually reduces the number of millable canes, directly affecting yield.

Reduced photosynthesis

Higher temperatures cause stomatal closure.
Consequently,

- CO_2 diffusion decreases.
- Photosynthesis declines.
- Dry matter production reduces.

Respiration simultaneously increases, reducing net biomass accumulation.

Reduced internode development

During the grand growth phase,
Water stress reduces:

- Cell elongation
- Cane height
- Internode length
- Single cane weight

Since nearly 60–70% of total biomass accumulates during this stage, drought can significantly reduce final yield.

Increased crop water demand

Higher temperatures increase:

- Reference evapotranspiration (ET_0)
- Crop evapotranspiration (ETc)

This results in:

- More frequent irrigation
- Increased pumping costs
- Greater groundwater extraction

Soil health under El Niño

One of the overlooked impacts of El Niño is its effect on soil biology.
Dry soils reduce:

- Microbial respiration
- Organic matter decomposition
- Nitrogen mineralization
- Phosphorus solubilization

Consequently,

- Nutrient availability decreases.
- Fertilizer use efficiency declines.
- Soil biological activity weakens.

Low soil organic carbon further reduces water-holding capacity, creating a cycle of increasing drought vulnerability.

Nutrient dynamics

During drought,

Nitrogen

- Lower mineralization
- Reduced uptake
- Pale leaves
- Lower chlorophyll content

Potassium

Potassium becomes particularly important because it regulates:

- Stomatal opening
- Osmotic balance
- Water-use efficiency

Adequate potassium nutrition helps sugarcane tolerate drought stress more effectively.

Effect on Cane Quality

Water stress influences juice characteristics differently depending on crop stage.
Possible effects include:

- Lower cane weight
- Reduced juice volume
- Lower recoverable sugar per hectare
- Reduction in Commercial Cane Sugar (CCS) yield due to reduced biomass

Thus, mills may receive cane with acceptable sucrose concentration but lower total sugar output per hectare.

Pest scenario during El Niño

Hot and dry weather generally favours:

- Early Shoot Borer
- Internode borer
- White grubs
- Termites
- Scale insects

Water-stressed crops are physiologically weaker and become more susceptible to insect damage.

Adapting sugarcane cultivation to El Niño: Climate-smart solutions

Precision irrigation

Drip irrigation combined with fertigation can:

- Save 30–50% irrigation water
- Improve nutrient-use efficiency
- Increase water productivity

This is particularly relevant for Tamil Nadu, where groundwater resources are under increasing pressure.

Trash mulching

Maintaining sugarcane trash on the soil surface:

- Reduces evaporation
- Moderates soil temperature
- Improves infiltration
- Conserves moisture

- Enhances soil organic carbon

Soil organic carbon restoration

Application of:

- Pressmud
- Farmyard manure
- Compost
- Green manure
- Biochar

improves:

- Soil aggregation
- Water retention
- Microbial activity
- Nutrient buffering

Increasing soil organic carbon is one of the most sustainable strategies for improving drought resilience.

Digital agriculture

Climate adaptation increasingly depends on:

- Automatic Weather Stations (AWS)
- Soil moisture sensors
- Satellite-based crop monitoring
- AI-assisted irrigation scheduling
- Mobile advisory services

These tools enable farmers to make timely irrigation and nutrient management decisions.

Future perspective

Climate models suggest that temperature and rainfall variability will continue to increase in southern India (IPCC, 2023). Building resilient sugarcane systems in Tamil Nadu will require:

- Climate-resilient varieties
- Precision irrigation
- Regenerative agriculture
- Improved soil organic carbon
- Integrated nutrient management
- Weather-based advisory services

Agronomists, researchers, sugar mills, and farmers must work together to improve adaptation and sustain productivity under future climate scenarios.

Conclusion

El Niño is no longer an occasional climatic anomaly but a recurring challenge for sugarcane cultivation in Tamil Nadu. Rising temperatures, erratic rainfall, and prolonged dry spells increase crop water demand, reduce nutrient-use efficiency, and threaten cane productivity. Scientific evidence from Tamil Nadu indicates that even moderate warming can increase irrigation requirements while reducing yields. Integrating precision irrigation, soil health improvement, balanced nutrition, and digital decision-support systems will be essential for sustaining sugarcane production in a changing climate. Climate-smart agronomy should therefore become a central component of future sugarcane management strategies.

References

- Guhan, V., Annadurai, K., Easwaran, S., Marimuthu, M., Balu, D., Vigneswaran, S., & Navinkumar, C. (2024). *Assessing the impact of climate change on water requirement and yield of sugarcane over different agro-climatic zones of Tamil Nadu. Scientific Reports,* *14*, 8239. https://doi.org/10.1038/s41598-024-58771-8
- Lakshmi, S., Nivethaa, E. A. K., Palanivelu, K., & Ramachandran, A. (2025). *Influence of sunspot activity and El Niño–Southern Oscillation on northeast monsoon rainfall in the coastal districts of Tamil Nadu*. **Mausam**, 76, 577-590. https://doi.org/10.54302/mausam.v76i3.7569
- Gowtham, R., Geethalakshmi, V., Pannerselvam, S., Bhuvaneswwari, K., & Divya, K. (2019). Influence of El Nino and the southern oscillation (ENSO) on climate of Tamil Nadu. **Journal of Pharmacognosy and Phytochemistry.**
- Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Rashid Pervez
Division of Nematology
ICAR – Indian Agricultural Research Institute (IARI)
New Delhi – 110012, India

Chandramani D. Waghmare
Division of Nematology
ICAR – Indian Agricultural Research Institute (IARI)
New Delhi – 110012, India

Pankaj
Division of Nematology
ICAR – Indian Agricultural Research Institute (IARI)
New Delhi – 110012, India

ARTICLE ID: 17

Plant-Parasitic Nematode *Pratylenchus*: An Emerging Serious Threat to Indian Agriculture

Abstract

Pratylenchus is a highly significant plant-parasitic nematode that infects the roots of numerous agricultural crops worldwide, causing severe economic losses. In India, wheat, rice, maize, sugarcane, potato, cotton, soybean, pulses, and vegetable crops constitute the primary sectors affected by this pest. Species such as *Pratylenchus coffeae, Pratylenchus thornei*, and *Pratylenchus zeae* are considered particularly destructive. This nematode penetrates plant roots and destroys the tissues, leading to root lesions, decay, stunted plant growth, reduced uptake of nutrients and water, and a drastic decline in yield. Furthermore, it facilitates the entry of other pathogens such as fungi and bacteria thereby giving rise to complex disease syndromes. This article provides a detailed account of the major species of *Pratylenchus*, their pathogenicity, associated symptoms, and their impact on both the agricultural and national economies. According to various studies, this nematode can cause yield losses ranging from 10 to 60% in crops. Additionally, increased production costs, compromised export quality, and adverse effects on food security are among its major negative consequences. The article places special emphasis on Integrated Nematode Management (INM) strategies for its effective control; these include crop rotation, organic management practices, the use of biocontrol agents, neem cake application, soil solarization, the cultivation of resistant crop varieties, and judicious chemical control measures. In conclusion, *Pratylenchus* represents an emerging and serious threat to Indian agriculture, necessitating the collaborative efforts of farmers, scientists, and policymakers to ensure its sustainable and eco-friendly management.

Introduction

Pratylenchus, commonly known as the root lesion nematode, is a highly significant plant-parasitic nematode (PPN). It causes serious economic damage by infecting the roots of numerous agricultural crops worldwide, including India. Major crops affected in India include wheat, rice, maize, sugarcane, potato, soybean, cotton, pulses, and vegetables. Several species, including *P. coffeae, P. zeae*, and *P. thornei*, are considered economically important due to the severe losses they cause. In coffee-producing regions, *P. coffeae* is responsible for root rot disease, reducing plant longevity, quality, and yield. In commercial crops such as banana, potato, and maize, nematode infestations increase production costs because farmers must invest in pesticides, biological control agents, and soil treatments. The problem is particularly severe in developing countries, where access to advanced management technologies and resistant crop varieties is often limited.

In an agriculture-dependent country like India, *Pratylenchus* significantly affects farmers' incomes. Small and marginal farmers are especially vulnerable because their livelihoods depend heavily on crop production.

The symptoms are often mistaken for nutrient deficiencies or water stress, resulting in delayed diagnosis and ineffective control measures. Consequently, crop losses continue to increase, leading to uneven plant growth and substantially reduced yields at harvest.

The impact of *Pratylenchus* extends beyond individual farms to national agricultural productivity and food security. Widespread infestations can significantly reduce regional crop productivity. Furthermore, infestations adversely affect the quality of export crops, leading to economic losses in international markets. Many countries impose restrictions on nematode-infested agricultural products, further affecting trade. Agricultural research institutions estimate that plant-parasitic nematodes cause crop losses worth thousands of crores of rupees annually in India, with *Pratylenchus* contributing substantially to these losses.

Major species of *Pratylenchus* in India

The following species have been reported from different states of India, including Uttar Pradesh, Haryana, Rajasthan, Andhra Pradesh, Delhi, and others:

- *Pratylenchus coffeae* (Zimmermann, 1898) Goodey, 1951
- *Pratylenchus zeae* (Graham, 1951)
- *Pratylenchus thornei* (Sher and Allen, 1953)
- *Pratylenchus brachyurus* (Godfrey, 1929) Filipjev and Schuurmans Stekhoven, 1941
- *Pratylenchus penetrans* (Cobb, 1917) Filipjev and Schuurmans Stekhoven, 1941
- *Pratylenchus neglectus* (Rensch, 1924) Filipjev and Schuurmans Stekhoven, 1941
- *Pratylenchus indicus* (Das, 1960)
- *Pratylenchus mulchandi* (Nandkumar and Khera, 1970)
- *Pratylenchus microstylus* (Bajaj and Bhatti, 1984)
- *Pratylenchus cruciferus* (Bajaj and Bhatti, 1984)
- *Pratylenchus akrami* (Bajaj and Bhatti, 1984)
- *Pratylenchus hippeastri* (Inserra, Troccoli, Gozel, Bernard, Dunn and Duncan, 2007)
- *Pratylenchus daci* (Fortuner, 1985)
- *Pratylenchus ranjanii* (Mizukubo, 1992)
- *Pratylenchus neocapitatus* (Khan and Singh, 1975)

Pathogenicity and Symptoms

Pratylenchus invades crop roots and destroys root tissues, causing brown to black lesions on roots. Over time, roots begin to rot, resulting in stunted plant growth. Crops affected include wheat, rice, maize, potato, sugarcane, pulses, vegetables, and fruit crops. The infestation reduces the plant's ability to absorb nutrients and water, leading to yellowing, poor growth, and significant yield reduction. Proper management is therefore essential.

The nematode creates wounds in roots that facilitate the entry of other pathogens, including fungi, bacteria, and viruses. Consequently, complex disease syndromes develop that are difficult and expensive to manage. For example, *Pratylenchus* infestations can increase the severity of Fusarium wilt, root rot, and other soil-borne diseases.

As a result, farmers often need to apply higher quantities of chemicals, pesticides, and fertilizers, increasing production costs. Long-term infestations also affect soil fertility and biological balance, reducing the productive capacity of agricultural land.

Economic losses caused by *Pratylenchus*

Globally, plant-parasitic nematodes cause agricultural losses worth billions of dollars each year. Scientific studies estimate annual losses of approximately US$100–125 billion, with *Pratylenchus* species accounting for a significant portion. In wheat-producing countries such as Australia, the United States, Canada, and China, *P. thornei* has been reported to reduce wheat yields by 30–50%.

In India, nematode-induced diseases are estimated to cause losses worth thousands of crores of rupees annually. Economic losses are not limited to yield reduction. Infested fields require additional fertilizer, irrigation, and pesticide inputs. Crop quality also declines, reducing market prices. In export-oriented crops, nematode infestations can significantly reduce international marketability and foreign exchange earnings. In potato and vegetable crops, this pest impairs the quality of roots and tubers, resulting in reduced market value. In sugarcane, infected plants exhibit stunted growth and a decline in sugar content. Similarly, in maize and pulse crops, plants become weakened and display symptoms resembling drought stress, causing financial losses for farmers. Its presence has been notably recorded in states such as Uttar Pradesh, Punjab, Haryana, Rajasthan, Karnataka, Tamil Nadu, and Kerala. In wheat and barley, a 20- 40 % reduction in yield has been observed due to the presence of *P. thornei* and *P. neglectus*. In South India, a severe infestation of *P. coffeae* is frequently observed in coffee and banana crops. In cash crops like sugarcane and maize, it weakens the root system and arrests plant growth, thereby adversely affecting farmers' income.

Management of *Pratylenchus*

For the management of *Pratylenchus* nematodes, the primary steps involve maintaining field sanitation and utilizing healthy seeds or seedlings. Planting material obtained from infested fields should be avoided, as this facilitates the rapid spread of nematodes from one field to another. Ensuring proper drainage systems within the field is also crucial, as nematode infestations are observed to be more severe in areas with excessive moisture. Following the harvest, any infected roots and crop residues remaining in the field should be destroyed to help reduce the nematode population.

Crop Rotation

Crop rotation is an effective strategy for controlling Pratylenchus nematodes. Continuously growing the same type of crop leads to an increase in nematode populations; therefore, non-host crops should be incorporated into the rotation in such fields. For instance, rotating crops such as wheat or vegetables with marigold, mustard, or certain pulses can help reduce nematode numbers. The chemical compounds released from the roots of marigolds (*Tagetes* spp.) are instrumental in controlling nematodes. Similarly, green manure crops such as Dhaincha (Sesbania) and Sanai (Crotalaria) not only improve soil quality but also assist in reducing nematode populations.

Biological Control

Biological control also plays a significant role in controlling *Pratylenchus* nematodes. Incorporating neem cake, Karanja cake, and various organic manures into the soil helps suppress nematode proliferation. The application of neem cake at a rate of 1-2 tons/ha has proven effective in nematode management. Additionally, the use of biocontrol agents such as *Paecilomyces lilacinus, Pochonia chlamydosporia*, and *Trichoderma harzianum* is an effective strategy. These beneficial microorganisms regulate nematode populations by destroying their eggs and bodies. Biological control measures are environmentally safe and also help maintain soil fertility.

Chemical control

Chemical control measures should be employed only when the nematode infestation is severe. Nematicides such as Carbofuran and others may be used in a limited manner and strictly in accordance with scientific recommendations. However, the excessive use of chemical pesticides can be detrimental to both the environment and human health; therefore, they should be used with caution. Seed treatment also plays a supportive role in nematode control. Treating seeds with appropriate chemicals or bio-agents provides protection to the plants during their early stages of growth.

Solarization

Soil solarization is another effective technique for the management of *Pratylenchus* nematodes. During the summer months, the field is thoroughly tilled and then covered with a transparent polyethylene sheet for a period of 4 - 6 weeks. This process raises the soil temperature, leading to a significant reduction in the nematode population. This method is particularly beneficial for vegetable and nursery crops.

Resistant or Tolerant Varieties

The selection of resistant or tolerant crop varieties is also a crucial and effective measure for nematode management. In areas where the infestation of *Pratylenchus* is severe, it is advisable to cultivate crop varieties that possess tolerance to nematodes. This minimizes crop damage and helps maintain stable production levels. Additionally, adopting a balanced fertilizer management strategy is essential. The application of organic manure, compost, and balanced doses of nitrogen, phosphorus, and potash keeps plants healthy and enhances their resilience against nematode attacks.

Integrated Management

Integrated Nematode Management (INM) is considered the most effective strategy for controlling plant nematodes. This approach involves the combined application of various measures including biological, cultural, mechanical, and chemical methods. Rather than relying on a single measure, a combination of different techniques yields more successful and sustainable results. For instance, the effective control of *Pratylenchus* can be achieved by simultaneously employing practices such as crop rotation, the use of neem cake, the application of biocontrol agents, and when necessary limited chemical treatments.

Conclusion

Pratylenchus nematodes are among the most destructive root-infecting plant parasites, significantly affecting both crop yield and quality. Timely diagnosis, the use of healthy planting material, crop rotation, organic amendments, soil solarization, and balanced chemical control can substantially reduce their impact. Farmers should adopt integrated management practices to achieve sustainable agriculture while maintaining soil fertility and improving crop productivity.

Pratylenchus represents an emerging and serious threat to Indian agriculture. Its broad host range, high reproductive potential, and ability to survive within root tissues make it particularly dangerous. Unless timely and sustainable management strategies are implemented, it could become a major challenge to agricultural production and food security. Therefore, farmers, scientists, and policymakers must work together to develop environmentally friendly and scientifically sound solutions for its effective management.

Acknowledgement

Authors are thankful to Director, and Joint Director (Research), ICAR-Indian Agricultural Research Institute, New Delhi, India.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

ARTICLE ID: 18

Role of Nitrate in Seed Germination: Beyond a Nutrient to a Powerful Signalling Molecule

AUTHORS' DETAILS:

Shreya Patil
PhD Scholar, Division of Seed Science and Technology, ICAR-Indian Agricultural Research Institute, New Delhi-110012

Yallavva Madar
PhD Scholar, Division of Seed Science and Technology, ICAR-Indian Agricultural Research Institute, New Delhi-110012

Sharankumar Kesaratagi
PhD Scholar, Division of Seed Science and Technology, ICAR-Indian Agricultural Research Institute, New Delhi-110012

Sunil Biradar
PhD Scholar, Division of Seed Science and Technology, ICAR-Indian Agricultural Research Institute, New Delhi-110012

Abstract
Seed germination is a crucial developmental stage that determines crop establishment, plant growth and final productivity. Successful germination depends on both internal physiological processes and external environmental cues such as water, temperature, light and nutrient availability. Among mineral nutrients, nitrate (NO_3^-) plays a unique dual role by functioning as both an essential nitrogen source and an important signalling molecule. Besides supporting plant nutrition, nitrate regulates seed dormancy, hormone metabolism and the expression of genes involved in germination. Studies have demonstrated that nitrate promotes germination by activating nitrate-responsive signalling pathways, particularly through the transcription factor NIN-like Protein 8 (NLP8), which induces the expression of the ABA catabolic gene *CYP707A2*. This process lowers abscisic acid (ABA) levels, thereby releasing seed dormancy and facilitating radicle emergence. Nitrate also improves seed germination under adverse environmental conditions such as salinity and high glucose concentrations, making it an effective component of seed priming technologies. Understanding the physiological and molecular mechanisms of nitrate signalling provides new opportunities for improving seed quality, stress tolerance and crop establishment. This article discusses the role of nitrate in seed germination, its molecular mechanisms, interaction with plant hormones and its practical significance in modern agriculture.

Keywords: Nitrate, Seed germination, NLP8, CYP707A2, Abscisic acid, Seed priming, Nitrate signaling

Introduction

Seed germination is the first and most critical stage in a plant's life cycle, determining successful crop establishment and productivity. Germination is influenced by several environmental factors, including moisture, temperature, light, oxygen and the availability of nutrients. Among these, nitrate plays a unique role. Beyond serving as an essential nitrogen source, nitrate also functions as a signalling molecule regulating seed germination and several developmental processes. It helps seeds sense favourable environmental conditions and enhances germination by breaking dormancy. In addition, nitrate is widely used in seed priming and has been shown to enhance germination even under adverse conditions such as salinity and high glucose stress. Understanding the role of nitrate can help improve seed germination and ensure better crop establishment.

Nitrate content and sensitivity

Nitrate content and nitrate sensitivity play an important role in regulating seed dormancy and germination. Both externally applied nitrate (exogenous nitrate) and nitrate accumulated during seed development (endogenous nitrate) can promote germination by reducing seed dormancy.

Studies have shown that seeds produced from mother plants supplied with higher nitrate levels contain more endogenous nitrate and exhibit higher germination with reduced dormancy (Alboresi *et al.,* 2005). This response is associated with lower abscisic acid (ABA) levels, a hormone that maintains seed dormancy (Matakiadis *et al.,* 2009). The promotive effect of exogenous nitrate is mainly attributed to its signalling function (Alboresi *et al.,* 2005). However, it varies among species and genotypes and is influenced by environmental factors such as light and after-ripening. Therefore, both nitrate content and nitrate sensitivity determine how effectively seeds respond to nitrate and initiate germination.

Nitrate assimilation and signalling in imbibed seeds

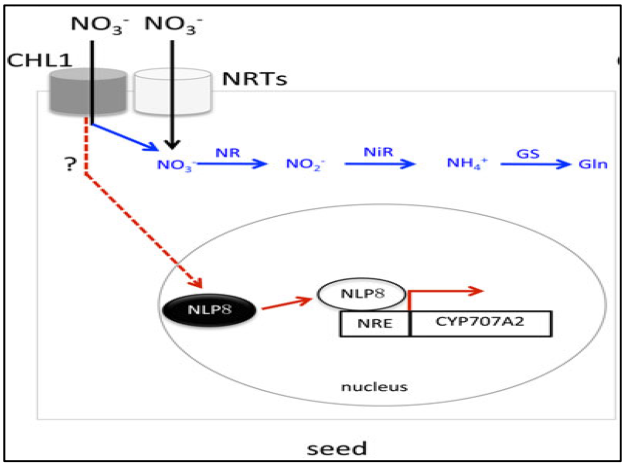


Fig. 1. Schematic representation of nitrate assimilation and signalling in an imbibed seed. NRTs: Nitrate transporters, CHL1: It is a nitrate transceptor, NLP8: transcription factor NR: Nitrate reductase, NiR: Nitrite reductase and GS: Glutamine synthetase

Nitrate uptake from the soil and transport within the plant are mediated by active transport systems involving high- and low-affinity nitrate transporters. Among these, NRT1.1/CHL1 functions as a dual-affinity nitrate transporter whose affinity is regulated by phosphorylation of the T101 residue by CBL-interacting protein kinase 23 (CIPK23). In addition to nitrate transport, CHL1 also acts as a nitrate sensor (transceptor), enabling the perception of external nitrate signals independently of its transport activity (Fig. 1).

Following uptake, nitrate is assimilated into organic nitrogen through sequential reduction by nitrate reductase (NR), which converts nitrate to nitrite, and nitrite reductase (NiR), which further reduces nitrite to ammonium (Fig. 1). The resulting ammonium is incorporated into amino acids and other nitrogen-containing compounds required for plant growth and development.

Apart from its nutritional role, nitrate acts as a signalling molecule that triggers the Primary Nitrate Response (PNR), a rapid transcriptional response that occurs independently of nitrate assimilation. In seeds, the transcription factor NIN-Like Protein 8 (NLP8) serves as the master regulator of the PNR. NLP8 is constitutively localized in the nucleus and is post-translationally activated by nitrate through a mechanism that remains unclear. Activated NLP8 induces the expression of several nitrate-responsive genes, including *CYP707A2*, thereby linking nitrate perception to the regulation of seed germination.

Role of nitrate in seed germination

Nitrate promotes seed germination not only by serving as a source of nitrogen but also by acting as a signalling molecule that regulates seed dormancy and germination. Several studies have demonstrated that the promotive effect of nitrate on germination is independent of its assimilation into nitrogen metabolites. Hendricks and Taylorson (1972) reported that nitrate stimulated the germination of *Amaranthus albus* seeds even in the presence of tungstate, an inhibitor of nitrate reductase (NR), indicating that nitrate itself acts as a signal rather than through its metabolic products. Similarly, Hilhorst and Karssen (1989) demonstrated that nitrate-mediated promotion of *Sisymbrium officinale* seed germination occurs independently of nitrate assimilation. Further evidence was provided by Alboresi *et al.* (2005), who showed that nitrate promoted germination in the *Arabidopsis* nitrate reductase-deficient nia1 nia2 mutant, confirming that nitrate signalling, rather than nitrate reduction, is responsible for stimulating germination. Besides promoting germination under favourable conditions, nitrate also helps seeds overcome the inhibitory effects of salinity and high glucose, making it a promising tool for improving crop establishment under stress (Ikeya *et al.,* 2020). The practical significance of nitrate is evident in the ISTA Rules (2025), which recommend the use of up to 0.2% potassium nitrate (KNO_3) solution (2 g L^{-1}) for breaking physiological dormancy and improving germination in specific crop species.

Nitrate action during seed germination

Nitrate promotes seed germination by modulating hormonal signalling pathways that regulate seed dormancy. Following its perception by the NRT1.1/CHL1 transceptor, the nitrate signalling cascade activates NLP8, which binds to the promoter region of the nitrate-inducible gene *CYP707A2* (Fig.2). This gene encodes abscisic acid (ABA) 8′-hydroxylase, a key enzyme involved in ABA catabolism (Duermeyer *et al.,* 2018).

The increased expression of *CYP707A2* accelerates ABA degradation, thereby reducing endogenous ABA levels in imbibed seeds. Since ABA is the principal hormone responsible for maintaining seed dormancy, its catabolism relieves dormancy and facilitates radicle protrusion and seed germination. Thus, nitrate acts as an environmental signal that links external nitrogen availability with hormonal regulation through the NRT1.1/CHL1–NLP8–CYP707A2 signalling pathway, ensuring successful seed germination under favourable conditions (Duermeyer *et al.,* 2018).

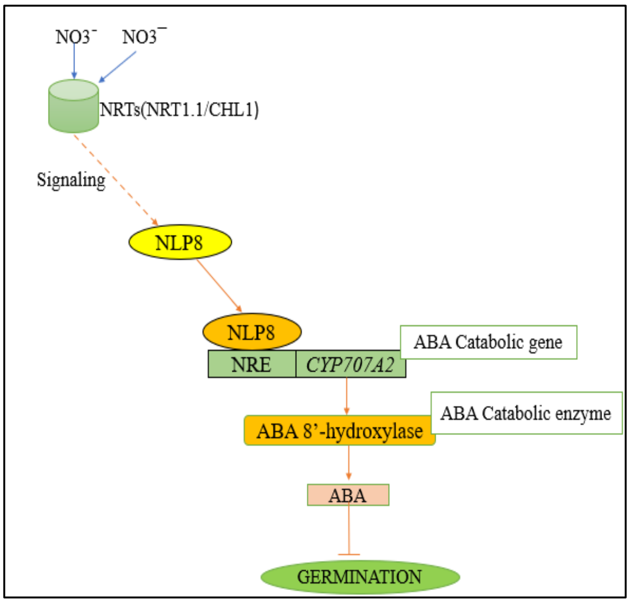


Fig. 2. Mechanism of Nitrate Action during seed germination in *Arabidopsis thaliana*

Conclusion

Nitrate is no longer regarded only as a plant nutrient but also as a powerful signalling molecule that regulates seed germination. By regulating seed dormancy, hormone balance and nitrate-responsive genes, it promotes rapid and uniform germination under both favourable and stress conditions. Its practical applications in seed priming and its recommendation in the ISTA Rules (2025) for breaking physiological dormancy further highlight its importance in seed science and technology. A better understanding of nitrate signalling will support the development of improved seed enhancement strategies, leading to better crop establishment, higher productivity and more sustainable agricultural systems.

References

- Alboresi, A., Gestin, C., Leydecker, M.-T., Bedu, M., Meyer, C., & Truong, H.-N. (2005). Nitrate, a signal relieving seed dormancy in Arabidopsis. Plant, Cell and Environment. 28,500-512.
- Duermeyer, L., Khodapanahi, E., Yan, D., Krapp, A., Rothstein, S. J., & Nambara, E. (2018). Regulation of seed dormancy and germination by nitrate. Seed Science Research, 28(3), 150–157.
- Hendricks SB and Taylorson RB. (1972). Promotion of seed germination by nitrates and cyanides. Nature.237, 169–170.
- Ikeya, S., Aoyanagi, T., Ishizuka, I., Takeuchi, A., & Kozaki, A. (2020). Nitrate promotes germination under inhibition by NaCl or high concentration of glucose. Plants, 9(6), 1–14.
- ISTA Rules for Seed Testing.2025.
- Hilhorst HWM and Karssen CM. (1989). Nitrate reductase independent stimulation of seed germination in Sisymbrium officinale L. (hedge mustard) by light and nitrate. Annals of Botany (Lond) 63, 131–137.
- Matakiadis, T., Alboresi, A., Jikumaru, Y., Tatematsu, K., Pichon, O., Renou, J. P., Kamiya, Y., Nambara, E., & Truong, H. N. (2009). The Arabidopsis abscisic acid catabolic gene CYP707A2 plays a key role in nitrate control of seed dormancy. Plant Physiology, 149(2), 949-960.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Gagan Kumar M

Ph.D. Scholar, Department of Entomology, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India.

Pundalik D Pammar

Ph.D. Scholar, Department of Entomology, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India.

Santosh Halagatti

MSc Scholar, Department of Entomology, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India.

ARTICLE ID: 19

Fall Armyworm Management in Maize: Integrated Solutions for Better Yield

Abstract

Maize (Zea mays L.) is one of India's most important cereal crops, serving as food, feed, and industrial raw material. However, the invasion of the fall armyworm (Spodoptera frugiperda) has become a serious threat to maize production due to its high reproductive capacity, rapid spread, and voracious feeding habit. Yield losses ranging from 20 to 70% have been reported when timely management is not adopted. Effective management of fall armyworm requires an Integrated Pest Management (IPM) approach that combines regular field scouting, cultural practices, biological control, pheromone traps, need-based insecticide application, and modern technologies such as drone-based pesticide spraying. Adoption of these integrated strategies helps minimize crop losses, reduce pesticide misuse, and promote sustainable maize production.

Keywords: Fall armyworm, Maize, Integrated Pest Management, Biological control, Drone spraying, Pheromone trap

Introduction

Maize is popularly known as the "Queen of Cereals" because of its high yield potential and wide adaptability. It is cultivated across diverse agro-climatic regions for food, fodder, poultry feed, starch, ethanol, and industrial products. In recent years, maize cultivation has faced a major challenge due to the invasion of the fall armyworm (FAW), Spodoptera frugiperda, an invasive insect pest native to the Americas (Sharanabasappa et al., 2018; Prasanna et al., 2021).

Since its first report in India during 2018, the pest has spread rapidly across almost all maize-growing states. The caterpillar feeds aggressively on maize leaves, whorls, tassels, and cobs, causing severe damage that ultimately reduces grain yield and quality. Because of its high reproductive capacity, ability to migrate long distances, and resistance to several insecticides, FAW has become one of the most difficult pests to manage (FAO, 2021; ICAR-IIMR, 2023).

Fortunately, timely monitoring and adoption of Integrated Pest Management (IPM) practices can effectively suppress pest populations while protecting beneficial insects and the environment (Prasanna et al., 2021).

Identification of Fall Armyworm

Correct identification is the first step towards successful management.

Egg stage

- Eggs are laid in clusters containing 100–200 eggs.
- Egg masses are covered with greyish scales from the female moth.
- Eggs hatch within 2–4 days.

Larval stage

- Caterpillars pass through six larval instars.
- Young larvae scrape leaf surfaces, producing transparent window-like patches.
- Older larvae are greenish-brown to dark brown.
- Mature larvae possess a characteristic inverted white "Y" mark on the head capsule.
- Four black spots arranged in a square on the eighth abdominal segment are diagnostic features (Sharanabasappa et al., 2018).

Pupal stage

- Pupation occurs in the soil at 2–8 cm depth.
- Pupal duration ranges from 8–12 days.

Adult moth

- Adult moths are nocturnal and capable of flying hundreds of kilometres.
- Females lay nearly 1,000–1,500 eggs during their lifetime.

Symptoms of Damage

The pest can attack maize from seedling to grain formation stage.

Typical symptoms include:

- Window-pane feeding on young leaves
- Irregular holes on unfolded leaves
- Shot-hole appearance
- Feeding within leaf whorls
- Large quantities of fresh frass inside the whorl
- Ragged leaves
- Damage to tassels and developing cobs
- Severe infestation may destroy the growing point.

Life Cycle

Under favourable weather conditions, the complete life cycle is completed within 30–45 days.

Stage	Duration
Egg	2–4 days
Larva	14–22 days
Pupa	8–12 days
Adult	10–21 days

Warm temperatures and humid weather favour rapid multiplication of the pest (Prasanna et al., 2021).

Monitoring and Surveillance

Regular monitoring helps detect infestations before economic damage occurs.

Recommended practices include:

- Weekly field scouting beginning 10 days after sowing.
- Inspect at least 20–25 plants from different locations.
- Observe whorls for larvae and fresh frass.
- Install pheromone traps (5 traps/ha) for monitoring adult moth activity.
- Replace pheromone lures every 3–4 weeks.
- Record infestation levels to decide timely management (FAO, 2021; ICAR-IIMR, 2023).

Cultural Management

Good crop management practices help reduce pest incidence.

Important cultural practices include:

- Timely sowing.
- Deep summer ploughing to expose pupae.
- Crop rotation with non-host crops.
- Removal of heavily infested plants.
- Destruction of crop residues after harvest.
- Balanced fertilizer application.
- Avoid excessive nitrogen application.
- Intercropping maize with legumes where feasible.

Maintaining a healthy crop helps plants tolerate moderate pest damage (FAO, 2021).

Biological Control

Natural enemies play an important role in suppressing fall armyworm populations.

Important parasitoids

- Telenomus remus
- Trichogramma pretiosum
- Chelonus formosanus

Predators

- Ladybird beetles
- Green lacewings
- Earwigs
- Spiders
- Predatory bugs

Microbial biopesticides

Farmers can also use:

- Bacillus thuringiensis (Bt)
- Metarhizium anisopliae
- Beauveria bassiana

- Nuclear Polyhedrosis Virus (NPV)

Conservation of natural enemies reduces dependence on chemical insecticides (Prasanna et al., 2021).

Chemical Management

Chemical insecticides should be applied only after crossing the Economic Threshold Level (ETL) (ICAR-IIMR, 2023).

Recommended insecticides include:

Insecticide	Dose
Chlorantraniliprole 18.5 SC	150–200 ml/ha
Emamectin benzoate 5 SG	220 g/ha
Spinetoram 11.7 SC	250 ml/ha

For better control:

- Spray during early larval stages.
- Ensure spray reaches the leaf whorl.
- Rotate insecticides with different modes of action to delay resistance.

Drone-Based Spraying: A Modern Solution

Agricultural drones are transforming pest management by improving precision and reducing labour requirements.

Advantages of drone spraying

- Uniform spray coverage.
- Better penetration into maize whorls.
- Reduced pesticide exposure to operators.
- Lower water requirement.
- Faster spraying over large areas.
- Timely application during favourable weather.
- Reduced soil compaction.

Integrated Pest Management (IPM): The Best Strategy

No single method can provide complete control of fall armyworm. Therefore, integrating different management practices is the most effective and sustainable approach (FAO, 2021; Prasanna et al., 2021).

Recommended IPM package

- ➢ Timely sowing
- ➢ Weekly crop monitoring
- ➢ Install pheromone traps
- ➢ Encourage natural enemies
- ➢ Use biological control agents
- ➢ Apply insecticides only when required
- ➢ Rotate insecticides
- ➢ Adopt drone-based precision spraying
- ➢ Destroy crop residues after harvest

Benefits of Integrated Management

Farmers adopting integrated pest management can achieve:

- Higher grain yield
- Lower production cost
- Reduced pesticide consumption
- Better protection of beneficial insects
- Reduced environmental pollution
- Improved pesticide efficiency
- Sustainable maize production
- Increased farm profitability (ICAR-IIMR, 2023)

Conclusion: The fall armyworm has emerged as one of the most destructive insect pests affecting maize cultivation worldwide. However, timely monitoring, adoption of Integrated Pest Management practices, conservation of natural enemies, and need-based application of recommended insecticides can effectively minimize crop losses. Modern technologies such as agricultural drones are further enhancing the efficiency of pesticide application by ensuring precise and uniform spray coverage. By combining traditional crop management practices with innovative technologies, farmers can successfully manage fall armyworm, improve maize productivity, and move towards more sustainable and profitable agriculture (ICAR-IIMR, 2023).

References

1. FAO. (2021). Integrated management of Fall Armyworm on maize: A guide for Farmer Field Schools in Africa.
2. Prasanna, B. M., Huesing, J. E., Eddy, R., & Peschke, V. M. (Eds.). (2021). Fall Armyworm in Africa: A Guide for Integrated Pest Management. CIMMYT.
3. Sharanabasappa, Kalleshwaraswamy, C. M., Maruthi, M. S., & Pavithra, H. B. (2018). First report of the fall armyworm, Spodoptera frugiperda, an invasive pest on maize in India. Pest Management in Horticultural Ecosystems, 24(1): 23–29.
4. ICAR–Indian Institute of Maize Research (IIMR). (2023). Integrated Pest Management for Fall Armyworm in Maize.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Yallavva Madar
Ph.D. Scholar, Division of Seed Science and Technology, Indian Agricultural Research Institute New Delhi – 110012

Shreya Patil
Ph.D. Scholar, Division of Seed Science and Technology, Indian Agricultural Research Institute New Delhi – 110012

Sandeep
Ph.D. Scholar, Division of Seed Science and Technology, Indian Agricultural Research Institute New Delhi – 110012

Prakash Sonnad
Ph.D. Scholar, Division of Seed Science and Technology, Indian Agricultural Research Institute New Delhi – 110012

ARTICLE ID: 20

Evolution of Plant Survival: The Science behind Desiccation Tolerance

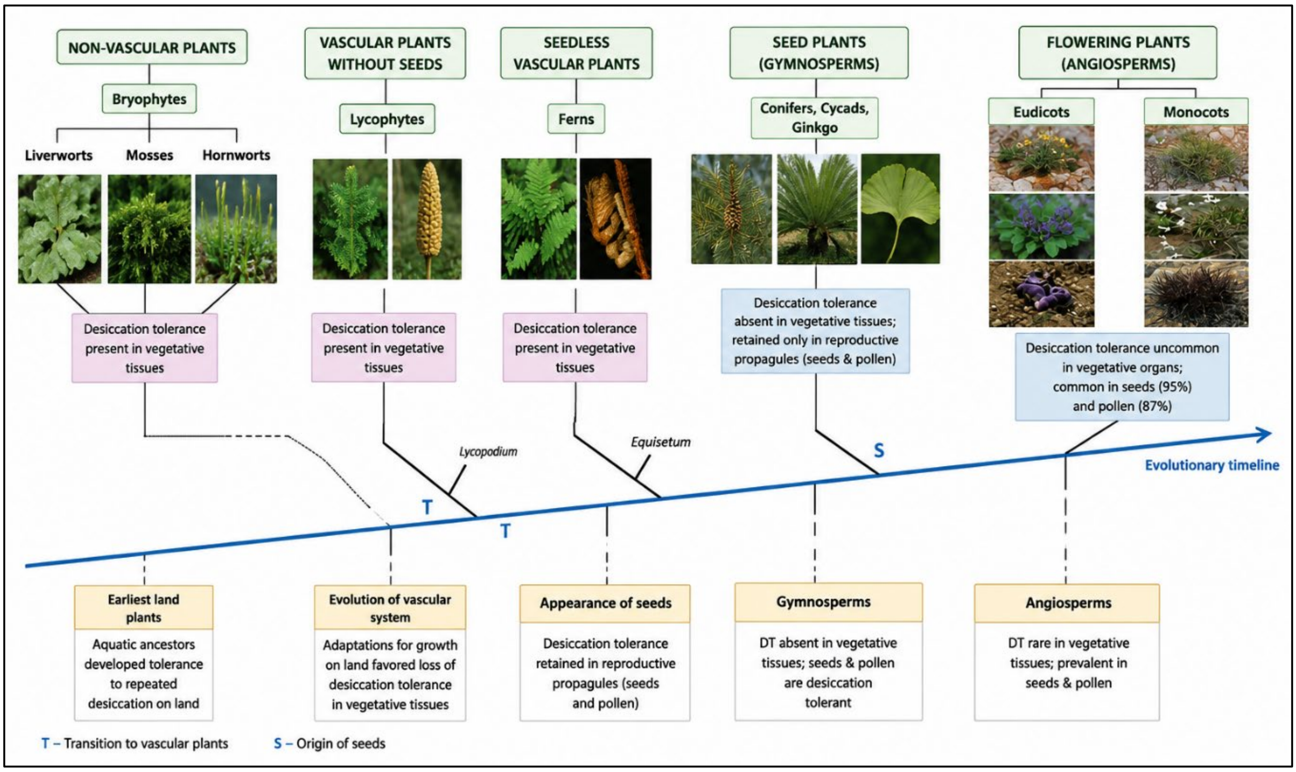
Abstract: Desiccation tolerance (DT) is the remarkable ability of plants and seeds to survive extreme dehydration and resume normal metabolic activity upon rehydration. It is a vital adaptive trait that enables plant survival under drought and other environmental stresses while also ensuring long-term seed viability and successful germination. This article discusses the evolutionary origin of desiccation tolerance, its occurrence in bryophytes, resurrection plants, seeds, and pollen, and its significance in plant adaptation to terrestrial environments. Furthermore, it explains the damaging effects of water loss on cellular structures and describes the physiological, biochemical, and molecular mechanisms that protect seeds during dehydration, including the roles of protective sugars, LEA proteins, glassy state formation, antioxidant systems, and metabolic quiescence. Understanding these mechanisms provides valuable insights for improving seed storage, conservation of plant genetic resources, and developing crops with enhanced tolerance to drought and climate change.

Keywords: Desiccation tolerance, seed viability, Protective sugars, LEA proteins

Introduction:

The scarcest resource in biological systems is water. Water is elixir of life. It is essential for both human and plant health. If we not drinking water for an extended period of time can have serious consequences for our health. The most immediate consequence of not drinking water is dehydration. Without water, our body cannot function properly, and we may experience symptoms such as thirst, dry mouth, dizziness, headache, fatigue, and finally leads to death. Likewise, in plant kingdom some plants having tolerance to low water content and some plants are susceptible. Seeds can be stored for longer period of time based on storage condition and surrounding environment, by drying seeds to optimum moisture condition. Seeds can be dried to a less moisture condition and seed will be survived even in very low moisture condition; it is all because of seeds having character or property or capacity of "desiccation tolerance".

Desiccation tolerance (DT) is the ability of certain plants to survive severe dehydration and recover normal growth after rehydration. It is a complex trait governed by coordinated physiological, biochemical, and molecular mechanisms that enable plants to withstand extreme water loss. These adaptations allow plants to survive in harsh environments, including deserts, alpine regions, and other water-limited habitats. According to Alpert (2005), Leprince and Buitink (2010), and Oliver *et al.* (2005), desiccation tolerance refers to the capacity of organisms to endure water contents below 0.1 g H_2O g^{-1} dry weight and regain normal function upon rehydration without sustaining irreversible damage. Through these unique protective mechanisms, desiccation-tolerant plants can survive prolonged drought, extreme temperatures, and intense radiation.



DT is uncommon in shoots and roots of plants but frequent in seeds and pollen. Extreme water loss resistance and the biological function of DT, which also depends on its capacity to be stored in a dry state (seed longevity).

Evolutionary aspect of Desiccation tolerance:

Terrestrial organisms are subject to the desiccation stress brought on by air dryness on a regular basis. Hence, during the evolution of plant life on land, modifications that allow for survival and/or avoid desiccation were needed (Oliver *et al.*, 2005). An important evolutionary advance that was crucial to the colonization of dry land was the capacity to withstand almost full desiccation. Most likely, DT was primitively present in chlorophytic algae that were forerunners of the first land plants, or bryophytes, which include hornworts, liverworts, and mosses (Farrant and Moore 2011) (fig1). Moving to land exposed creatures that were predominantly aquatic life-style adapted to frequent desiccations caused by heat, sunlight, and wind. As a result, aquatic plants developed a tolerance for dry conditions to survive and thrive in terrestrial habitat. Apparently, to survive desiccation, the early plants would have acquired the ability to dehydrate slowly and rehydrate quickly.

Fig.1 Evolution of desiccation tolerance in plants

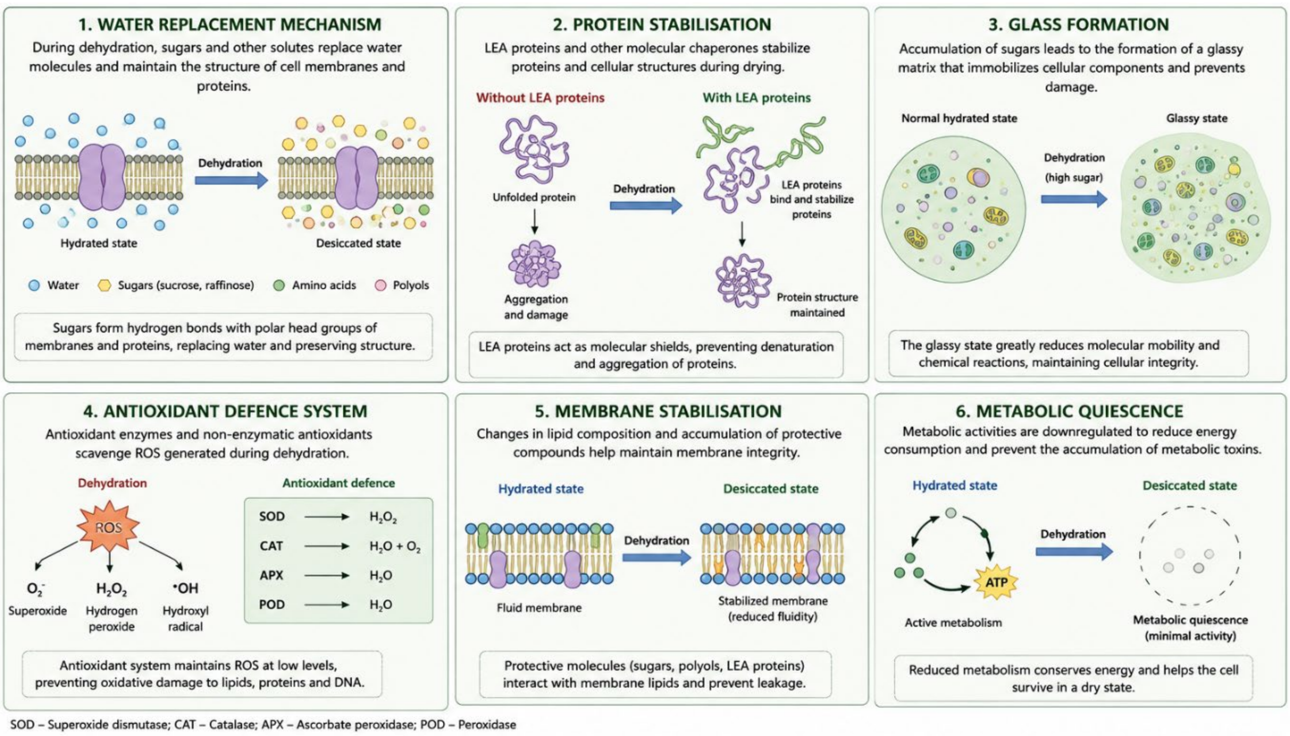
DT is present in bryophytes in vegetative tissue. Higher (vascular) plants rarely have desiccation-tolerant vegetative tissues, in contrast to the bryophytes.

Vascular plants having desiccation tolerance rarely in vegetative tissue those are called “Resurrection plants”. Only 330 species of resurrection plants, or less than 0.15 percent of all vascular plant species, have been documented to be desiccation tolerant in their vegetative portions (Proctor and Pence 2002).

Gymnosperms, such as conifers, do not have any DT in their vegetative tissues, which may be due to an eco-physiological restriction that prevents trees from being desiccation tolerant. when plants evolved on land there was a pressure for faster growth, plant height and dry mass production. there will be formation of water related adaptation such as cuticle stomata, modification of root and vascular system. This favored loss of DT in vegetative tissue and it was retained in reproductive propagules. DT is uncommon in angiosperm vegetative organs; however, it is prevalent in the majority of seeds (95%) and pollen (87%) of the spermatophyte species under investigation (Gaff and

Oliver 2013). Basal lineages of angiosperms do not contain any desiccation tolerant plants (with DT in vegetative tissues), but they are found in later lineages, suggesting that DT in vegetative tissues was lost early during plant evolution and regained later. Not all angiosperm having DT in reproductive propagules. Seeds which tolerate desiccation and long-term dry storage, those are called 'orthodox seed', Which do not tolerate desiccation or desiccant sensitive are called 'recalcitrant'. Orthodox seeds are long lived seeds, which can be dried to low moisture contents 3-5% without any injury and are able to tolerate freezing. Mainly in Rice, Wheat and maize. Recalcitrant seeds are short lived seeds which cannot be dried to moisture content below 20-30% without injury and are unable to tolerate freezing. Intermediate seeds do not confirm fully either to orthodox or recalcitrant category. Some of these seeds may have a limited desiccation tolerance but are sensitive to freezing temperatures. Mainly seen in Neem. This DT is acquired in seeds during early maturation of seed development and accumulate storage compounds like protein, oils and carbohydrate. During late maturation seeds get dried and changes occurs at this stage and there will be change in the level of water potential in plants.

Fig 2: Mechanism of desiccation tolerance



Damaging effect of water loss

As cell lose water, it experiences mechanical and structural stresses. There will be decrease in volume and increase in cytoplasmic compaction and viscosity. As the water content of the plant decreases, the cells lose turgor pressure, which can cause the plant to wilt. Dehydration can cause damage to the membranes that surround plant cells, leading to leakage of cellular contents and disruption of cellular functions. It can also lead to an increase in oxidative stress, which can damage proteins, lipids, and other cellular components.

Mechanism of desiccation tolerance

The mechanism of desiccation tolerance in seeds involves several interconnected physiological and biochemical processes. One of the key mechanisms of desiccation tolerance is the ability of seeds to prevent damage to cellular through the synthesis and accumulation of protective molecules, such as sugars, polyols, and antioxidants. These molecules act as stabilizers of cellular components and help to prevent damage from oxidative stress and free radical formation. desiccation-tolerant seeds have the ability to enter a state of metabolic quiescence during dehydration. This is achieved through the downregulation of metabolic processes and the accumulation of storage compounds, such as lipids and proteins, which can be used to fuel germination once water becomes available again. Overall, the mechanism of desiccation tolerance in seeds is a complex and multifaceted process that involves the coordination of several physiological and biochemical adaptations. These adaptations allow seeds to survive in unpredictable and challenging environments, and are critical for the long-term survival of plant species. Seeds survive extreme drying through several natural protective mechanisms that keep their cells alive until water becomes available again.

- Natural sugars replace water**:** As seeds dry, sugars such as sucrose and raffinose replace water around cell membranes and proteins. This helps maintain their structure and prevents damage.
- Protective proteins (LEA proteins): During seed maturation, special proteins called Late Embryogenesis Abundant (LEA) proteins accumulate. They stabilize proteins and cell structures, protecting them from drying stress.
- Glassy state formation: The cell contents become a glass-like solid with very low molecular movement. This "glassy state" preserves cell components and allows seeds to remain viable for long periods.
- Antioxidant defence: Antioxidants and heat-shock proteins reduce damage caused by harmful reactive oxygen species (ROS) produced during drying, helping seeds recover when they absorb water again.

Conclusion: Desiccation tolerance is a key evolutionary adaptation that allows plants, particularly seeds, to withstand severe water loss while maintaining viability. It plays a crucial role in seed longevity and successful germination after rehydration. The acquisition of desiccation tolerance during seed maturation involves coordinated physiological, biochemical, and molecular changes, including the accumulation of protective sugars, LEA proteins, antioxidants, and the formation of a stable glassy state. These mechanisms protect cellular structures from dehydration-induced damage and oxidative stress. A better understanding of desiccation tolerance will contribute to improved seed storage technologies, conservation of biodiversity, and the development of climate-resilient crop varieties capable of withstanding increasing drought stress under changing environmental conditions.

References:

- Ballesteros, D., Pritchard, H. W., & Walters, C. (2020). Dry architecture: Towards the understanding of the variation of longevity in desiccation-tolerant germplasm. In *Seed Science Research*. Cambridge University Press.
- Hoekstra, F. A., Golovina, E. A., & Buitink, J. (2001). Mechanisms of plant desiccation tolerance. *Trends in plant science*, **6(9)**, 431-438.
- Dekkers, B. J., Costa, M. C. D., Maia, J., Bentsink, L., Ligterink, W., & Hilhorst, H. W. (2015). Acquisition and loss of desiccation tolerance in seeds: from experimental model to biological relevance. *Planta*, **241(3),** 563-577.

Just Agriculture Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Monika L.S
MBA Scholar, Department of Agri-business Management, UAS, GKVK, Bengaluru-560065

Dr. Raju R.
Senior Scientist, ICAR-Indian Institute of Horticultural Research, Bengaluru-560089 (Karnataka)

Charumati M.K
MBA Scholar, Department of Agri-business Management, UAS, GKVK, Bengaluru-560065

ARTICLE ID: 21

BUSINESS POTENTIAL OF FRESH-CUT FRUITS AND VEGETABLES IN INDIA

INTRODUCTION

Fresh-cut fruits and vegetables are among the fastest-growing segments of the food processing industry, driven by increasing demand for convenient, healthy, and ready-to-eat (RTE) or ready-to-cook (RTC) products. These products are washed, peeled, cut, and hygienically packaged, offering freshness and nutritional value while reducing preparation time. Their short shelf life of 3–7 days necessitates efficient cold chain management and appropriate packaging.

The industry contributes to reducing post-harvest losses through value addition, improving farmer incomes, and strengthening agricultural supply chains. Globally, the fresh-cut produce market is projected to grow from USD 36 billion in 2024 to USD 63 billion by 2030 at a CAGR of 6.5%. In India, although the segment accounts for less than 1% of the fruits and vegetables market, it has strong growth potential, supported by urbanisation, organised retail, quick-commerce, and changing consumer preferences. Overall, the industry plays a significant role in promoting convenient, nutritious food and sustainable growth in the food processing sector.

MARKET SIZE, GROWTH TRENDS, AND INDUSTRY EVOLUTION

The fresh-cut fruits and vegetables industry is one of the fastest-growing segments of the food processing sector, driven by rising demand for convenient, healthy, and value-added food products. Although it represents only a small share of the overall fruits and vegetables market, it is growing at a much faster rate.

Table 1. Global and Indian Market Size of Fruits and Vegetables and Fresh-Cut Produce

Market Segment	Geography	Market Size in 2024	Forecast	Growth Rate (%)
Fruits & Vegetables	Global	USD 850–860 billion	USD 1.27 trillion by 2033	4.5–5.0
Fresh-Cut Fruits & Vegetables	Global	USD 8–12 billion	USD 15–25 billion by 2030	6–10
Fruits & Vegetables	India	USD 240–250 billion	Growing steadily with urbanisation	5–6
Fresh-Cut Fruits & Vegetables	India	USD 0.1–0.2 billion (₹800–1,600 crore)	USD 0.3–0.6 billion by 2030	15–25

Globally, the fruits and vegetables market was valued at **USD 850–860 billion** in 2024 and is projected to reach **USD 1.27 trillion** by 2033, growing at **4.5–5.0% CAGR**. In comparison, the fresh-cut produce market is estimated at **USD 8–12 billion** and is expected to reach **USD 15–25 billion** by 2030, with a higher growth rate of **6–10% CAGR**.

In India, the fruits and vegetables market is valued at **USD 240–250 billion**, while the fresh-cut segment remains relatively small at **USD 0.1–0.2 billion (₹800–1,600 crore).** However, it is projected to grow at **15–25% CAGR** by 2030, supported by urbanisation, organised retail, quick-commerce, changing lifestyles, and increasing demand for hygienically processed foods.

The industry has evolved rapidly over the past decade, with accelerated growth after the COVID-19 pandemic due to greater consumer preference for hygienic packaged foods. Advances in cold chain infrastructure, packaging technologies, and digital supply chains have further strengthened the sector. India's horticulture production has also increased from **280.7 million tonnes in 2013–14** to **367.72 million tonnes in 2024–25**, ensuring a strong raw material base for value-added processing.

Table 2. Growth Trends in the Fresh Fruits and Vegetables Market

Segment	Estimated CAGR (2018–2025)	Primary Drivers
Global Overall (Fresh)	4.6%	Population growth, health trends
India Market	5.9%	Urbanisation, retail expansion
Fresh-cut Produce	6.5%	Consumer convenience, snacking
Processed Fruits &Vegetables	6.8%	Value addition, longer shelf life
Organic Fruits & Vegetables	7.7%	Wellness, premiumization

Overall, the fresh-cut fruits and vegetables industry has strong growth potential in India, supported by abundant agricultural production, technological advancements, favourable government initiatives, and rising consumer demand.

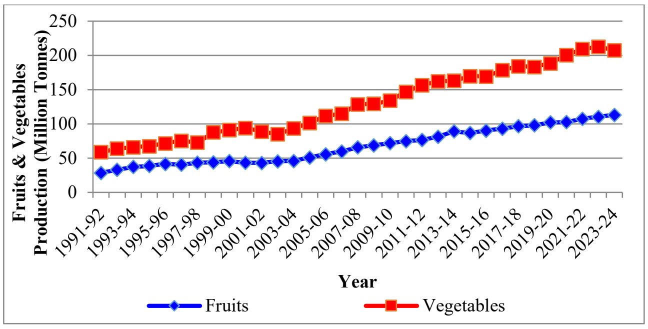


Fig. 1. Growth in Fruits and Vegetables Production in India

DEMAND AND SUPPLY DRIVERS, AND CONSUMER BEHAVIOUR

The growth of the fresh-cut fruits and vegetables industry is driven by increasing consumer demand, improved supply chain infrastructure, and changing lifestyles.

On the demand side, rapid urbanisation, busy lifestyles, dual-income households, and rising health awareness have increased demand for Ready-to-Eat (RTE) and Ready-to-Cook (RTC) products. Consumers prefer fresh-cut produce because it is convenient, hygienic, and saves preparation time. Rising disposable incomes, organised retail, and quick-commerce platforms have further accelerated market growth.

On the supply side, advancements in cold chain infrastructure, packaging technologies, and logistics have improved product quality and distribution. Government initiatives such as PMKSY, Mega Food Parks, and the PLI Scheme have encouraged investment in food processing, while agritech innovations have enhanced supply chain efficiency and farmer-market linkages.

The consumer preferences are primarily influenced by convenience, freshness, hygiene, packaging, and product quality. Demand is increasing among urban households, working professionals, students, hotels, restaurants, cloud kitchens, and health-conscious consumers.

Table 3. Factors Influencing Consumer Preference for Fresh-Cut Fruits and Vegetables

Sl. No.	Factors	Rank
1	Convenience	1
2	Appearance and Freshness	2
3	Time Saving	3
4	Clean and Attractive Packaging	4
5	Availability in Desired Quantity	5
6	Taste	6
7	Price	7

Source: Prasanna et. al., (2022)

A study by **Prasanna et al. (2022)** found that convenience was the most important factor influencing purchase decisions, followed by freshness, time-saving, packaging, availability, taste, and price. The study also reported that **44.2%** of consumers purchased fresh-cut fruits and vegetables once a week, indicating growing acceptance of convenience-based food products.

Table 4. Frequency of Consumption of Fresh-Cut Fruits and Vegetables

Particulars	Category	Percentage of Consumers
Consumption Frequency	Once a week	44.2%
	Other frequencies	55.8%

Overall, rising consumer demand, supportive government policies, improved infrastructure, and changing lifestyles are expected to sustain the growth of India's fresh-cut fruits and vegetables industry.

PESTLE ANALYSIS AND PORTER'S FIVE FORCES

The fresh-cut fruits and vegetables industry operates in a favourable business environment shaped by policy support, technological advancements, and changing consumer preferences.

1. PESTLE Analysis

- **Political:** Government schemes such as PMKSY, PLI, and Mega Food Parks promote food processing and cold chain development.
- **Economic:** Rising incomes, urbanisation, and abundant horticultural production support market growth.
- **Social:** Increasing demand for convenient, hygienic, and healthy RTE and RTC foods drives consumption.
- **Technological:** MAP, IoT, AI, and cold chain technologies improve shelf life and supply chain efficiency.
- **Legal:** Compliance with FSSAI and HACCP standards ensures food safety and quality.
- **Environmental:** Sustainable packaging, efficient cold storage, and waste management reduce environmental impact.

2. Porter's Five Forces

- **Threat of New Entrants:** Moderate
- **Supplier Power:** Low to Moderate
- **Buyer Power:** High
- **Threat of Substitutes:** Moderate
- **Competitive Rivalry:** High

Overall, the industry has strong growth potential, supported by favourable policies, technological innovation, and rising consumer demand, although businesses must effectively manage competition, food safety, and supply chain challenges.

OPERATIONS, PROCESSING, PACKAGING, AND SUPPLY CHAIN

The fresh-cut fruits and vegetables industry depends on efficient processing, appropriate packaging, and a reliable cold chain to maintain product quality, safety, and freshness.

1. Operational Flow

The production process includes harvesting, sorting, washing and sanitisation, cutting, packaging, cold storage, and refrigerated distribution. Maintaining hygiene and temperature throughout the process is essential.

2. Shelf Life and Preservation

Fresh-cut produce has a shelf life of **3–7 days** under refrigeration. Technologies such as **Modified Atmosphere Packaging (MAP),** edible coatings, vacuum cooling, and anti-browning treatments help extend shelf life and preserve quality.

Table 5. Day-wise Quality Index of Freshness

Day	Quality Index (Without MAP)	Quality Index (With MAP)
Day 0	100% (Fresh)	100% (Fresh)
Day 3	45% (Unacceptable)	85% (Very Fresh)
Day 6	5%(Spoiled)	70% (Good)
Day 9	0%	50% (Threshold reached)

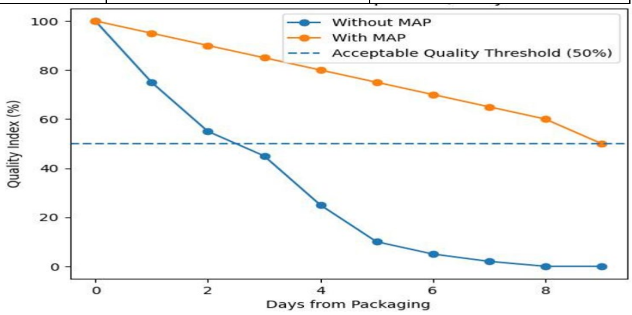


Fig. 2. Shelf-life Extension with Acceptable Quality Threshold

3. Packaging and Supply Chain

Advanced packaging technologies, including MAP, breathable films, vacuum packaging, and smart packaging, improve food safety and shelf life. Efficient cold chain systems, supported by IoT, RFID, ERP, and blockchain, reduce spoilage and enhance traceability.

4. Sustainability and Quality Control

Organic processing waste can be utilised for compost or animal feed. Sustainable packaging, efficient cold storage, and compliance with **FSSAI** and **HACCP** standards ensure food safety, minimise waste, and strengthen consumer confidence.

Overall, efficient operations, modern packaging, and robust cold chain management are essential for the sustainable growth of the fresh-cut fruits and vegetables industry.

BUSINESS MODELS AND COMPETITIVE LANDSCAPE

The fresh-cut fruits and vegetables industry is expanding rapidly due to increasing demand for convenient, high-quality, and ready-to-eat products.

1. Business Models

Major business models include:

- **Direct-to-Consumer (D2C):** Direct sales through websites, apps, or outlets.
- **Subscription Model:** Regular delivery of fresh-cut products with predictable demand.
- **Quick-Commerce (Q-commerce):** Fast delivery through platforms such as Blinkit, Zepto, and Swiggy Instamart.
- **B2B Institutional Model:** Supply to hotels, restaurants, cloud kitchens, and catering services.
- **Retail Private Labels:** Retailers market fresh-cut products under their own brands.

Many businesses now adopt hybrid multi-channel models combining retail, D2C, and quick-commerce to expand market reach.

2. Competitive Landscape

The Indian market includes startups, organised retailers, and global companies competing on freshness, hygiene, packaging, pricing, and delivery. **BigBasket Fresho** demonstrates a successful hybrid model using efficient farm-to-consumer sourcing, FEFO inventory management, and quick-commerce delivery.

Key success factors include efficient supply chains, technology adoption, quality assurance, strong branding, and customer convenience.

Overall, businesses that focus on operational efficiency, innovation, and product quality are well positioned for sustainable growth.

FINANCIAL ANALYSIS AND UNIT ECONOMICS

The profitability of the fresh-cut fruits and vegetables industry depends on effective cost management, efficient operations, pricing strategies, and supply chain control. Although processing and cold-chain requirements increase costs, value addition enables premium pricing and attractive margins.

7.1 Price Comparison of Fresh and Fresh-Cut Fruits

Fresh-cut products are priced higher than whole fruits because of washing, cutting, sanitisation, packaging, and refrigeration. This value addition increases production costs while offering greater convenience and hygiene.

Table 6. Pricing Comparison of Whole Fruits and Fresh-Cut Fruits in India

Fruit	Whole Fruit Price (₹/kg)	Quantity Used (kg)	Raw Material Cost (₹)	Total Fresh-Cut Production Cost (₹)	Value Addition (₹)
Mango	50	1.5	75	97	22
Papaya	20	1.5	30	52.6	22.6
Pineapple	30	2	60	83.76	23.76
Pomegranate	160	2	240	262.66	22.66
Fruit Mix (Average)	—	—	—	124	—

Source: Amith, 2012

7.2 Unit Economics and Profitability

Fresh-cut products generally achieve **gross margins of 50–70%**, depending on product type, production cost, and selling price. Premium products such as salad and fruit bowls offer higher margins than cut vegetables.

Table 7. Unit Economics of Fresh-Cut Products

Scenario	Cost (₹)	Price (₹)	Gross Margin (%)
Best Case	18	65	72.3
Mid-High	22	65	66.2
Mid-Low	18	45	60.0
Worst Case	22	45	51.1

Table 8. Margin Analysis Across Product Categories

Category	Gross Margin (%)	Business Strategy
Salad Bowls	40–55	High value-added, premium segment
Fruit Bowls	35–45	Convenience-driven, urban demand
RTC Kits	30–40	Fast-growing, decision-solving products
Cut Vegetables	20–30	Volume-driven, essential items

Break-even depends on fixed costs and contribution margins, while profitability improves through efficient operations, economies of scale, reduced wastage, and an optimal product mix.

Table 9. Break-Even Scenarios

Scenario	Fixed Cost (₹/month)	Contribution Margin	Sales Needed
Optimistic	₹10 lakh	40%	₹25 lakh
Mid-Range	₹15 lakh	32.5%	₹46 lakh
Conservative	₹20 lakh	25%	₹80 lakh

Major cost components include raw materials (40–50%), labour (15–20%), packaging (10–15%), logistics (10–20%), and marketing/overheads (5–10%). Key financial risks are raw material price fluctuations, perishability, logistics costs, and demand uncertainty.

Cost and Price Analysis of Watermelon

Fresh-cut watermelon demonstrates the value-addition potential of the industry. Although whole watermelon retails at about **₹40/kg**, only **55–60%** is edible, increasing the effective raw material cost to **₹65–70/kg**. After processing, packaging, refrigeration, and logistics, the total production cost reaches **₹115–145/kg**, while the selling price ranges from **₹150–400/kg**, providing estimated margins of **20–50%.**

Table 10. Cost and Price Analysis of Watermelon

	A. Watermelon price levels in India	
Sl. No.	**Market Level**	**Price Range (₹/kg)**
1	Wholesale (mandi)	20-30
2	Retail (average)	30-70
3	Premium urban retail	80-100
4	Selected base price (for analysis)	40
	B. Processing Loss & Effective Cost	
	Parameter	**Value**
1	Raw watermelon price (₹/kg)	40

2	Edible portion (%)	55–60
3	Waste (peel, trimming) (%)	40–45
4	Effective usable quantity (kg)	~0.6
5	Adjusted cost per kg (usable fruit) (₹/kg)	65–70
	C. Cost Structure of Fresh-Cut Watermelon	
	Cost Component	**Cost (₹/kg)**
1	Raw material (adjusted)	65
2	Labour (cutting, handling)	20 – 30
3	Packaging	10 – 15
4	Cold storage & logistics	10 – 20
5	Wastage risk	10 – 15
6	Total cost	115 – 145
	D. Price Comparison (Fresh vs Fresh-Cut)	
	Type	**Price Range (₹/kg)**
1	Fresh watermelon	30 – 70
2	Fresh-cut watermelon	150 – 400
3	Price difference	3x – 6x higher
	E. Profitability Estimate of cut and packed watermelon	
	Parameter	**Value**
1	Total cost (₹/kg)	115 – 145
2	Selling price (₹/kg)	150 – 300
3	Estimated margin (%)	20 – 50
4	Risk factor	High (spoilage, unsold inventory)

The fresh-cut watermelon illustrates the strong value-addition potential of fresh-cut produce, but profitability depends on efficient processing, cold chain management, and effective control of spoilage and wastage.

CHALLENGES AND SWOT ANALYSIS

The fresh-cut fruits and vegetables industry offers strong growth potential but faces challenges related to perishability, costs, infrastructure, and consumer acceptance.

1. Key Challenges

- Short shelf life (3–7 days) requiring efficient cold chain management.
- High processing, packaging, and refrigeration costs.
- Limited cold chain infrastructure and supply chain inefficiencies.
- Raw material price fluctuations and consumer concerns about food safety and freshness.

2. SWOT Analysis

Strengths	**Weaknesses**
• Abundant horticultural production. • Growing demand for healthy and convenient foods. • Expansion of organised retail and quick-commerce.	• High perishability and processing costs. • Fragmented supply chains and inadequate cold storage.
Opportunities	**Threats**
• Growth of online grocery, healthy snack markets, and exports. • Technology adoption and government support through schemes such as PMKSY.	• Spoilage risks, price-sensitive consumers, competition from traditional markets, and climate-related supply disruptions.

The industry's future growth depends on improving cold chain infrastructure, reducing costs and wastage, adopting technology, and strengthening consumer confidence.

STRATEGIES AND FUTURE OUTLOOK

The fresh-cut fruits and vegetables industry has strong growth potential, supported by rising consumer demand, technological advancements, and favourable government policies.

Key Strategies

- Strengthen farm-to-consumer supply chains and cold chain infrastructure.

- Adopt technologies such as AI, IoT, blockchain, and digital supply chain systems to improve efficiency and traceability.
- Use advanced packaging technologies, including Modified Atmosphere Packaging (MAP), to extend shelf life.
- Expand through multi-channel distribution (D2C, quick-commerce, retail, and B2B).
- Focus on food safety, sustainable packaging, and brand building to enhance consumer trust.

Future Outlook

The industry is expected to grow steadily due to increasing urbanisation, health awareness, organised retail, and quick-commerce. Advances in technology, greater investment, product innovation, and export opportunities will further support growth.

Long-term success will depend on efficient supply chains, innovation, quality assurance, and sustainable business practices.

CONCLUSION

The fresh-cut fruits and vegetables industry is a growing segment of food processing, driven by demand for convenient and healthy foods. Despite challenges such as short shelf life and high operational costs, technology, innovation, and improved infrastructure offer strong growth opportunities. Efficient supply chains, quality control, and value addition can reduce post-harvest losses, generate employment, and support India's food processing sector.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Dr. Shubhangi Nigam
M.V.Sc. (GBPUAT, Pantnagar), NET (Veterinary Microbiology and Immunology)

Dr. Sourabh Swami
Ph.D Enrolled (GBPUAT, Pantnagar), NET (Veterinary Public Health & Epidemiology)

ARTICLE ID: 22

Climate-Smart and Welfare-Centred Livestock Systems: Pathways for Sustainable Development

Livestock systems are increasingly recognized not merely as production enterprises, but as integrated socio-ecological systems critical for food security, nutrition, livelihoods, ecosystem services and climate resilience. Globally, livestock support over one billion people and contribute significantly to agricultural economies, while in India they remain central to smallholder farming and rural development. Yet the sector faces a "triple challenge": meeting growing demand for animal-source foods, reducing environmental footprints, and ensuring animal welfare under accelerating climate change (Billoto F et al., 2024)

Sustainable livestock development now requires a shift from productivity-driven models toward climate-smart, welfare-centred and One Health-oriented systems. Traditional mixed crop–livestock systems already embody many sustainability principles through nutrient recycling, manure use, crop residue feeding and livelihood diversification. Strengthening such circular systems, rather than replacing them with purely industrial models, is vital for resilience (Kebreab E et al., 2026)

Animal welfare has emerged as a cornerstone of sustainability rather than a separate ethical concern. Guided by standards of the World Organisation for Animal Health (WOAH), welfare encompasses nutrition, health, behaviour, housing and mental well-being. Good welfare improves productivity through better fertility, disease resistance and stress tolerance. This becomes especially important under climate stress, where heat waves impair milk yield, reproduction and immunity. Thus welfare and adaptation are increasingly inseparable.

Climate change poses profound threats to livestock through heat stress, feed and water scarcity, altered vector ecology and emerging disease risks, including zoonoses. At the same time, livestock contribute to greenhouse gas emissions, particularly methane and nitrous oxide. The response, however, is not to view livestock simply as a problem, but to transform systems through climate-smart livestock approaches that integrate adaptation, mitigation and productivity (Hristov, A. N., et al. 2025)

Key adaptation strategies include heat-resilient housing, shade and cooling systems, drought-tolerant fodder, resilient indigenous breeds and early warning systems. Mitigation measures include precision feeding, improved digestibility, methane-reducing feed additives, better manure management and biogas systems. Many of these interventions simultaneously enhance welfare, efficiency and environmental performance (Hossein-Zadeh, N. G., et al. 2026)

A major opportunity lies in adopting circular bioeconomy models, where livestock waste becomes a resource rather than a liability. Manure-to-biogas systems, integrated crop–livestock farming and nutrient recycling reduce emissions while improving soil fertility and rural energy security. Such models are particularly relevant for India's smallholder systems (Swastika, D. K. S., et al., 2024)

Digital technologies are accelerating this transformation. Precision livestock farming using sensors, AI, wearable devices and computer vision enables real-time monitoring of animal health, welfare and productivity. These tools can detect heat stress, lameness, disease and behavioural changes early, improving both management and resilience. Combined with climate forecasting and disease surveillance, digital livestock systems strengthen preparedness under One Health framework (Jiang, B., et al. 2023)

The One Health perspective is fundamental to sustainable livestock development. Better welfare and husbandry reduce disease risks, antimicrobial dependence and zoonotic spillover potential. Sustainable livestock systems thus contribute not only to productivity but also to public health, ecosystem health and antimicrobial resistance containment.

These transformations align strongly with the United Nations Sustainable Development Goals, contributing to poverty reduction, food security, climate action, biodiversity conservation and responsible production. For India, policy pathways include climate-smart livestock missions, indigenous breed conservation, digital livestock initiatives, methane-smart strategies and welfare-sensitive governance reforms (Zhang, T., et al. 2024).

The future of livestock lies not in maximizing output at ecological cost, but in optimizing productivity, welfare and resilience together. This requires moving from livestock production to livestock stewardship. Sustainable livestock systems must be viewed as part of the solution to climate change, not merely contributors to it (FAO and WHO).

As emphasized by the Food and Agriculture Organization, sustainable livestock transformation is central to resilient food systems. The challenge before policymakers is therefore not whether livestock systems should change, but how rapidly they can be redesigned to support a humane, climate-resilient and sustainable future.

References

- Bilotto, F., Harrison, M. T., Vibart, R., Mackay, A., Christie-Whitehead, K. M., Ferreira, C. S., ... & Chang, J. (2024). Towards resilient, inclusive, sustainable livestock farming systems. *Trends in Food Science & Technology*, *152*, 104668.
- Petrini, A., & Wilson, D. (2005). Philosophy, policy and procedures of the World Organisation for Animal Health for the development of standards in animal welfare. *Revue Scientifique Et Technique-Office International Des Epizooties*, *24*(2), 665.
- Kebreab, E., Pressman, E. M., Meo-Filho, P., & Lucas, K. R. G. (2026). Sustainable Ruminant Production: Circular Systems, Nutrition, and Methane Mitigation. *animal*, 101772.
- Hristov, A. N., & Solomon, S. (2025). Perspective: enteric methane mitigation and its impact on livestock hydrogen emissions. *Journal of dairy science*, *108*(1), 1-5.
- Hossein-Zadeh, N. G. (2026). Advancing climate-resilient livestock systems: Next-generation emission mitigation strategies and integrated technological innovations. *Veterinary and Animal Science*, 100588.
- Swastika, D. K. S., Priyanti, A., Hasibuan, A. M., Sahara, D., Arya, N. N., Malik, A., ... & Atman, A. (2024). Pursuing circular economics through the integrated crop-livestock systems: An integrative review on practices, strategies and challenges post Green Revolution in Indonesia. *Journal of Agriculture and Food Research*, *18*, 101269..
- Jiang, B., Tang, W., Cui, L., & Deng, X. (2023). Precision livestock farming research: A global scientometric review. *Animals*, *13*(13), 2096.
- Zhang, T., Nickerson, R., Zhang, W., Peng, X., Shang, Y., Zhou, Y., ... & Cheng, Z. (2024). The impacts of animal agriculture on One Health—Bacterial zoonosis, antimicrobial resistance, and beyond. *One Health*, *18*, 100748.
- Food and Agriculture Organization, World Health Organization, World Organisation for Animal Health, & United Nations Environment Programme. (2022). *One Health Joint Plan of Action (2022–2026).* Rome/Geneva/Paris/Nairobi.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Dr. Shubhangi Nigam
M.V.Sc. (GBPUAT, Pantnagar), NET (Veterinary Microbiology and Immunology)

Dr. Sourabh Swami
Ph.D Enrolled (GBPUAT, Pantnagar), NET (Veterinary Public Health & Epidemiology)

ARTICLE ID: 23

Smart Poultry Farming: Integrating Avian Health, Precision Technologies and Sustainable Production

Abstract
Poultry farming has become a major source of affordable animal protein and rural livelihood. However, infectious diseases, heat stress, antimicrobial resistance, welfare concerns and rising production costs threaten productivity. Precision poultry farming integrates sensors, automation, artificial intelligence, data analytics and smart health monitoring to improve disease prevention, feed efficiency, welfare and sustainability.
Keywords: Poultry farming, precision farming, avian health, AI, biosecurity, climate-smart poultry.

Introduction

Poultry farming has progressed from traditional backyard rearing to scientifically managed commercial production. Poultry meat and eggs contribute significantly to food security because they provide affordable, high-quality protein, vitamins and minerals (Churchil, 2022). Modern poultry production depends on improved genetics, balanced nutrition, biosecurity, vaccination, environmental control and efficient management. Yet, the sector faces increasing pressure from avian influenza, Newcastle disease, infectious bronchitis, coccidiosis, bacterial infections, heat stress and antimicrobial resistance.

Precision poultry farming offers a shift from reactive to preventive management. Its basic principle is to "measure continuously and manage intelligently." Sensors, cameras, automated feeders, smart drinkers, acoustic devices and artificial intelligence are used to monitor the flock and farm environment in real time. These technologies help detect early changes in feed intake, water consumption, bird movement, temperature, humidity, ammonia and disease risk (Berckmans, 2017).

Poultry production includes backyard, semi-intensive and commercial systems. Backyard poultry supports rural nutrition and income, especially among smallholders, but often suffers from poor housing, weak disease control and low productivity. Commercial broiler and layer systems use improved breeds, scientific feeding, controlled housing, lighting programmes, vaccination and biosecurity to achieve rapid meat production and high egg output. Integrated poultry farming, where manure is used for composting, biogas, crop fertilization or fish farming, also supports circular and climate-smart agriculture.

Avian health remains the foundation of profitable production. Viral diseases such as avian influenza, Newcastle disease and infectious bursal disease cause major economic losses. Highly pathogenic avian influenza requires strict surveillance, biosecurity and control measures because of its high mortality and trade impact (WOAH, 2023). Bacterial diseases such as salmonellosis, colibacillosis and mycoplasmosis reduce growth and egg production, while coccidiosis and ectoparasites further compromise performance. Disease prevention should rely on vaccination, clean water, hatchery sanitation, litter management, pest control, proper stocking density and veterinary supervision.

Biosecurity is the most economical disease-control tool. External biosecurity prevents disease entry through controlled farm access, visitor restriction, quarantine and vehicle disinfection. Internal biosecurity prevents disease spread by sanitation, all-in all-out management, segregation of age groups, equipment disinfection and safe carcass disposal. Strong biosecurity also reduces unnecessary antimicrobial use.

Precision technologies improve both health and production. Environmental sensors measure temperature, humidity, ammonia, carbon dioxide and ventilation efficiency. Smart feeding and watering systems identify abnormal consumption patterns, which may indicate disease, heat stress or equipment failure. Acoustic monitoring detects abnormal flock sounds such as coughing or distress calls, helping identify respiratory problems earlier (Mahdavian et al., 2021). Computer vision systems assess bird distribution, gait, activity, feather cover, crowding and mortality.

Artificial intelligence combines production, behavioural and environmental data to generate alerts and decision support. It may help predict disease risk, heat stress, poor growth or reduced egg production. Precision nutrition further improves profitability by matching nutrients with bird age, genetic potential and production stage. Phase feeding, amino acid balancing and enzyme supplementation reduce feed wastage and improve efficiency (Moss et al, 2021).

Gut health is increasingly important in antibiotic-reduced poultry farming. Probiotics, prebiotics, synbiotics, organic acids and phytogenic additives support digestion, immunity and performance (Kogut & Arsenault, 2016). This approach also helps reduce antimicrobial dependence, supporting One Health goals.

Welfare and climate resilience are now central to sustainable poultry production. Welfare indicators include behaviour, mobility, feather condition, injury, mortality, stocking density and thermal comfort. Heat stress reduces feed intake, growth, egg production, shell quality and immunity. Climate-smart poultry farming uses insulated housing, ventilation, evaporative cooling, cool drinking water, heat-tolerant breeds and early heat-warning systems.

Big data and genomics are shaping the future of poultry farming. Farm records, sensor data, hatchery performance and health information can support productivity benchmarking, disease forecasting and traceability (Wolfert et al., 2017). Genomic selection can help develop birds with improved feed efficiency, disease resistance and heat tolerance.

For India, smart poultry farming must be affordable and scalable. Low-cost sensors, mobile advisory services, solar brooders, digital disease alerts and veterinary extension can help both commercial farms and smallholders. The future of poultry lies in combining health, nutrition, welfare, climate adaptation and digital technologies into one integrated system.

Conclusion

Smart poultry farming can make poultry production more productive, sustainable and resilient. By integrating biosecurity, vaccination, precision nutrition, AI-based monitoring, welfare assessment and climate-smart practices, poultry farms can detect problems early, reduce losses and improve profitability. Healthy birds, smart technology and sustainable management form the foundation of future poultry production.

References

Berckmans, D. (2017). General introduction to precision livestock farming. *Animal Frontiers*, *7*(1), 6-11.

Mahdavian, A., Minaei, S., Marchetto, P. M., Almasganj, F., Rahimi, S., & Yang, C. (2021). Acoustic features of vocalization signal in poultry health monitoring. *Applied Acoustics*, *175*, 107756.

Churchil, R. R. (2022). Growth, structure and strength of Indian poultry industry: A review. *Indian Journal of Poultry Science*, *57*(1), 1-10.

Kogut, M. H., & Arsenault, R. J. (2016). Gut health: The new paradigm in food animal production. *Frontiers in veterinary science*, *3*, 71.

WOAH. (2023). *Terrestrial animal health code: Avian influenza*. World Organisation for Animal Health.

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming–a review. *Agricultural systems*, *153*, 69-80.

Moss, A. F., Chrystal, P. V., Cadogan, D. J., Wilkinson, S. J., Crowley, T. M., & Choct, M. (2021). Precision feeding and precision nutrition: a paradigm shift in broiler feed formulation?. *Animal Bioscience*, *34*(3), 354.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 6
Issue – 12
August, 2026

www.justagriculture.in

AUTHORS' DETAILS:

Sarvan Kumar

Genetics & Plant Breeding Laboratory, Department of Agriculture,
Sri Guru Teg Bahadur Khalsa College, Sri Anandpur Sahib
(Affiliated to Punjabi University, Patiala)

ARTICLE ID: 24

Innovative Approaches in Hybrid Seed Production of Oilseed Mustard (*Brassicas sp.*)

Abstract

Hybrid seed production in oilseed Brassicas has emerged as an effective approach to improve seed yield, oil quality, and adaptableness by exploiting heterosis. Among the cultivated Brassica species, *Brassica juncea* (Indian mustard), *B. napus*, *B. rapa*, *B. carinata*, and *B. nigra* are economically important for edible oil, vegetables, condiments, and industrial applications. Although conventional open-pollinated varieties have contributed significantly to mustard production, their yield potential has reached a plateau, necessitating the adoption of hybrid breeding technologies. Cytoplasmic Male Sterility (CMS) has become the most reliable and commercially successful system for hybrid seed production in mustard, utilizing the three-line breeding system comprising the CMS (A-line), maintainer (B-line), and restorer (R-line). Other approaches, including self-incompatibility (SI), genetic male sterility (GMS), chemical hybridizing agents (CHA), and modern biotechnological techniques such as the Barnase–Barstar system, marker-assisted selection (MAS), and genome editing, have further strengthened hybrid breeding programs. Successful hybrid seed production depends on proper maintenance of parental lines, synchronization of flowering, optimum planting ratio, effective pollination by honeybees, strict rouging, adequate isolation distance, and adherence to seed certification standards to ensure genetic purity. Agronomic practices such as appropriate sowing time, balanced nutrient management, irrigation scheduling, and supplementary pollination also play a vital role in maximizing hybrid seed yield and quality. Hybrid mustard varieties generally exhibit 15–30% higher productivity than conventional varieties along with improved oil content, disease resistance, stress tolerance, and wider adaptability. This review highlights the botanical characteristics, evolutionary relationships, breeding principles, innovative hybrid seed production approaches, maintenance of parental lines, field management practices, and seed quality standards in oilseed Brassicas. The integration of conventional breeding with advanced molecular and biotechnological tools offers significant opportunities for developing high-yielding, climate-resilient, and genetically pure hybrid cultivars, thereby contributing to sustainable oilseed production and strengthening edible oil security.

Key words: Hybrid, Mustard, seed production, CMS, CHA, seed standard

Introduction

The mustard plant is a plant species belongs to family Brassicaceae/ cruciferae and the genera Brassica and Sinapis. It is the largest important group, which includes number of economic plants, grown for oilseeds, edible roots, stems, leaves, buds, or seeds etc. The family Brassiceae is important as many of its wild relative have a prospective value as source of oil, condiments and other products.

They also known by the trade name of rapeseed, mustard, Hindi Rai –Sarso . Species are *Brassica napus, B. juncea, B. carinata*. It had arisen more than once with diverse progenitors and in different localities i.e. China, Eastern India and the Caucasus the present day two centers of diversity. The seed of mustard is used as spice. Seeds are grinded and mixed with vinegar, water and other liquids makes a yellowish colored condiment which is known as prepared mustard. The green leaves of mustard are used as vegetable and by pressing its seeds we obtain mustard oil.

Hybrid seed production in Brassica is the process of producing genetically pure **F_1 hybrid seed** by crossing two selected parental lines under controlled pollination, usually through **cytoplasmic male sterility (CMS)** or **self-incompatibility**, to exploit heterosis for higher productivity, better oil quality, and improved adaptability.

Hybrids have been commercialized in Indian mustard in India. In Indian mustard many cytopasmic male sterility system have been developed but most off the hybrids developed so far are based upon either moricandia or ogura cms fertility restorer system. The 1sthybrid NRCHB 506 was developed by Directorate of Rapeseed and Mustard Research, Bharatpur and released for commercial cultivation in 2009.The potential of the conventionally bred open pollinated varieties has been exploited to its maximum level resulting in a platue in the productivity level, which breeder often calls as yielding depressed. Here we need exploit heterosis i.e. hybrid vigour to break the yield platue.

Development of a successful hybrid seed production technology in a crop is essential for the extension of hybrid technology to farmers. Standardization of sowing time and planting ratio is an important for economic hybrid seed production and it is more valid for a species, which is predominantly self-pollinated. A higher frequency of male rows in a planting ratio sown at optimum time gives higher hybrid seed set in Indian mustard.

Importance of Brassicas

- Oil is used for cooking, frying and making pickles
- Green tender plant is used as vegetable
- Whole seed is used for preparing pickles and flavoring vegetables and curries
- Oil is also used for making vegetable ghee, hair oil, soap, lubricating oil, and in tanning industries

Evolution of Brassica species:

- B. napus = B. compestris x B. oleracia
- B. carinata = B. nigra x B. oleracia
- B. juncea = B. nigra x B. compestris

Botanical Description

Mustard belongs to Cruciferae and genus Brassica. Brassica includes the following important oilseed species:

Inflorescence: Raceme

Flower type: Perfect, bisexual, cross-pollinated tendency

Floral structure

- 4 sepals
- 4 petals (cross-shaped)
- 6 stamens (4 long + 2 short = tetradynamous)
- 1 pistil with superior ovary

Pollination behavior

- Mostly self-pollinated but shows **20–30% natural cross-pollination**
- Pollinating agents: bees, insects, wind

Anthesis & stigma receptivity

- Flower opens early morning (6–9 AM)
- Stigma receptive 1 day before anthesis to 3 days after

Rapeseed (Brassica rapa var. sarson and toria): It is a herbaceous annual plant. The plant is shorter than mustard (rai). Plant height ranges between 45 and 150 cm. The roots are more or less surface feeder and the root system has limited depth with an extensive lateral spread. The stems are usually covered with a waxy deposit. In rape, leaves are borne sessile and are glabrous and hairy. Fruits are thicker than those of mustard (rai) and are laterally compressed, with a beak, one-third to half their length. Seeds are either yellow or brown with a smooth seed coat. Rape is self-pollinated but cross pollination also takes place to some extent

Mustard (Brassica juncea): It is known as rai, raya or laha. The plants are tall (90-200 cm), erect and much branched. The plant bears normally long and tapering roots. The leaves are not dilated at the base and clasping as in the case of rape but are stalked, broad and pinnatified. The fruits (pods) are slender and only 2.0-6.5 cm long strongly ascending or erect with short and stout beaks. The colour of seed is brown or dark brown. Seed coat is rough, mustard is self-pollinated but cross-pollination also takes place to some extent.

Mustard (Brassica nigra): This species was cultivated as a spice as early as 3000 BC. Although it may originate in Asia Minor-Iran, it is now widespread through out Europe, Africa, Asia, India and the Far East

B. juncea.: Central Asia-Himalayas are a primary center of diversity for this species, with migration to China, India and the Caucasus .Perhaps it is the oldest of the cultivated amphidiploids, it is mentioned since ancient times. B. juncea is grown for oil-seed usage in India and presently gaining importance in Canada and USA as an alternative to rapeseed i.e.B.napus

Innovative hybrid seed production in oilseed *Brassicas* relies on advanced crossing mechanisms, particularly the **barnase/barstar system, Cytoplasmic Male Sterility (CMS),** and **Molecular Marker-Assisted Selection (MAS).** These technologies overcome self-incompatibility and labor-intensive manual emasculation, significantly enhancing yield, oil quality, and disease resistance. Some important point on breeding prospective as

- ❖ Hybrid breeding in Brassica is based on the exploitation of heterosis.
- ❖ Cytoplasmic Male Sterility (CMS) is the most widely used system for commercial hybrid seed production.
- ❖ Three parental lines are generally involved: A-line (CMS line), B-line (Maintainer line), and R-line (Restorer line).
- ❖ Selection of parents is based on general and specific combining ability, genetic diversity, and desirable agronomic traits.
- ❖ Controlled pollination ensures genetic purity and high-quality F_1 hybrid seed.
- ❖ Hybrid Brassica varieties provide 15–30% higher yield than conventional open-pollinated varieties under suitable conditions.

Some Important Species

Indian group	International name	species	Common name	Local name	Chromosome number(2n=)
Sarson	Indian colza	1. Brassica rapa var. yellow sarson	Turnip rape	Yellow sarson	20
		2. B. rapa var. brown sarson		Brown sarson	20
Toria	Indian rape	1. B.rapa var. yellow toria.	Indian rape	Yellow toria	20
		2. B.rapa var. black toria		Black toria	20
Rai	Mustard	1.B.juncea	Indian mustard	Rai ,Raya, Laha	36
		2.B.juncea var. rugosa	rugosa	Pahari rai	36
		3.B.nigra	Black mustard	Banarasi rai	16

❖ F_1 hybrids are more uniform and possess improved oil content, disease resistance, stress tolerance, and wider adaptability.

Major Innovative Approaches use for Hybrid Seed Production:

Approach	Method	Principle	Examples/ Remarks
Cytoplasmic Male Sterility (CMS)	Three-line breeding system (A-, B-, and R-lines)	Male sterility controlled by cytoplasm and restored by nuclear restorer genes	Most widely used commercial approach in Brassica
Self-Incompatibility (SI)	Sporophytic Self-Incompatibility (SSI)	Self-pollen is rejected, allowing only cross-pollination	Common in *Brassica rapa* and *B. oleracea*; limited commercial use
Genetic Male Sterility (GMS)	Nuclear male sterility	Male sterility controlled by recessive nuclear genes	Mainly used in breeding and experimental hybrid development
Chemical Hybridizing Agents (CHA)	Chemical induction of male sterility	Temporary suppression of pollen production	Useful where CMS is unavailable; less common commercially
Biotechnological Approaches	Barnase–Barstar system, gene editing	Genetic engineering or genome editing to create male sterility	Mainly research and advanced breeding programs

1. Cytoplasmic Male Sterility (CMS) – Three-Line System Method

This is the **most successful and commercially adopted method** for hybrid seed production in mustard.

It involves three parental lines:

- **A-line (CMS line):** Male sterile and used as the female parent.
- **B-line (Maintainer line):** Maintains the A-line because it has the same nuclear genome but fertile cytoplasm.
- **R-line (Restorer line):** Carries fertility restorer (Rf) genes that restore fertility in the F_1 hybrid.

Steps

1. Maintain the A-line by crossing A × B.
2. Produce hybrid seed by crossing A × R.
3. Harvest seed only from the A-line rows.
4. The harvested seed is the F_1 hybrid seed.

Advantages

- High genetic purity.
- No manual emasculation.
- Economical for large-scale seed production.
- High yield due to heterosis.

2. Self-Incompatibility (SI) System Method

Mustard exhibits sporophytic self-incompatibility (SSI) in several Brassica species.

Principle

- Self-pollen fails to fertilize the stigma.
- Only pollen from genetically different plants is accepted.
- Cross-pollination occurs naturally through insects, mainly honeybees.

Steps

1. Grow two compatible parental lines together.
2. Ensure adequate bee activity for pollination.
3. Harvest hybrid seed from the designated female parent.

Advantages

- Natural crossing mechanism.
- No emasculation required.

Limitations

- Strongly influenced by environmental conditions.
- Less reliable than CMS for commercial seed production.

3. Genetic Male Sterility (GMS) Method

Male sterility is governed by recessive nuclear genes (msms).

Steps

1. Maintain sterile plants through heterozygous fertile plants.
2. Identify male-sterile plants before flowering.
3. Allow pollination from fertile male parents.
4. Harvest hybrid seed from sterile plants.

Advantages

- Simple genetic control.
- Useful in breeding programs.

Limitations

- Identification and maintenance of sterile plants are labor-intensive.
- Less suitable for commercial hybrid seed production.

4. Chemical Hybridizing Agents (CHA) Method

Chemical gametocides are sprayed to induce temporary male sterility.

Steps

1. Spray the female parent at the appropriate growth stage.
2. Pollen production is suppressed.
3. Cross-pollination occurs from the male parent.
4. Harvest hybrid seed from treated female plants.

Advantages

- No need for CMS or GMS lines.
- Can be applied to diverse genotypes.

Limitations

- Sterility may be incomplete.
- Chemical dosage and timing are critical.
- Environmental factors influence effectiveness.

5. Biotechnological Approaches Methods

- Barnase–Barstar system
- Transgenic male sterility
- CRISPR/Cas-based genome editing

Principle

Genes controlling pollen development or fertility restoration are manipulated to produce stable hybrid seed production systems.

Advantages

- High precision.
- Stable male sterility.
- Potential for improved hybrid breeding.

Limitations

- Regulatory restrictions.
- High development cost.
- Limited commercial use in mustard.

Hybrid seed production requires multiplication of three parental lines; A (CMS), B (Maintainer) and R (Restorer) lines, separately in addition to hybrid (F1) seed production. Hybrid seed production program requires four isolated plots, simultaneously, one each for three (A, B, & R) lines and forth one hybrid seed production. Methods of maintainer and restorer lines multiplication are similar to that of a pureline method; hence, planting methods for CMS (A) line multiplication and hybrid seed production are being presented here. Hybrid seed production requires panting CMS (A) and R (restorer) lines in such a manner so that "A" line pants obtain abundant pollen for fertilizer from R lines, however increasing number of R line shall increase the cost off seed production.12:2 planting ratio of A and R lines for hybrid seed production as well as for multiplication of A lines were found appropriate, on the bases of prescribed 45 cm row to row distance. Parental lines are multiplied / maintained separately in isolated plots by plants to progeny row methods. Nucleus seed of CMS line (A) is maintained by raising 2 rows of maintainer (B) lines adjacent to 12 rows of A (CMS) line. The off type progenies of A and B lines are removed. Similarly the parent stocks off R line are maintained in isolation. Breeder involved in nucleus / breeder seed multiplication should know breeding behavior and the impact of environmental conditions on the crop particularly, the diagnostic characteristics of the variety parental lines. At the harvest the maintainer rows (B) lines are harvest first. Later on the remaining rows off seed (A line) parent are harvested and bulked. Strict rogueing is advised during flowering to rogue out the fertile plants from seed parent. The commercial F1 hybrid seed is produced by growing seed parent (A line) and restorer (R line) in 12:2 row ratios as followed in case of maintenance of seed parent. The row of restorer parent (R line) are harvested first and bulked followed by harvesting of seed parent. The seed from the parent is processed and packed as hybrid seed.

Maintenance of nucleus seed

CMS is sown in seed multiplication plot with its maintainer line (B line) in 4:2 ratios for hybrid seed production. In order to have high pollen pressure, planting may be 3:2 or 1:1 if pollen parent is poor pollen production. The B line is male fertile line and it is isogenic line of A line except its cytoplasm is fertile. The seed harvested separate of both line and threshed also separately A and B line. Harvested A line seed used as hybrid seed production as female parent line. Proper isolation distance is 200 meter. Off type plant should be remove before flowering for insure genetic purity. Restorer line (R-line) is male fertile. It is maintained just like by open pollination in isolation of 200 meter.

Breeder and foundation seed production of mustard:

Breeder seed is the progeny of nucleus seed. In breeder seed production three different lines, CMS line (A Line), Maintainer Line (B line) and restorer line (R line) should have to multiply in different isolated fields (200 m). CMS line: The seed parent (A line) is grown with its maintainer line in 4:2 ratios. For high pollen pressure two-four rows of B-line around the field may be grown. B line: B and R line self fertile and may be multiply by open pollination in an isolation field with 200 m. in production of breeder seed 3 linegap should be kept after 5-6 line to facilitate inspection of the field by breeder and monitoring team. Rouging should be carefully and perfect stages. Off-type plants distinguish on the basis of morphological characters should be removed before flowering.

Synchronized flowering of male and female parents in Mustard

Oilseed Brassicas have indeterminate flowering habit. Early onset of flowering in the female parent as compared to the pollen parents invariably results in female plants getting taller. This reduces the hybrid seed set as the access of the pollen to the stigma is reduced. Detopping of alternate plant of male parent (in 2M : 4F/2M : 6F) ratio coupled with additional application of N (@ 25 kg/ ha) between pollinator rows after flowering was found effective to ensure pollen supply for longer duration

Brief Cultural Practices

Land requirement:

At least previous 3 years mustard not to grown in same field. Land should be free from volunteer plants. It should be deep, fertile well drained.

Isolation distance: 200 meter from other field of same crop.

Seed treatment: Thiram 3g/kg seed or Bavistin 2g/kg seed.

Seed rate: Seed parent: 1875 g/ha and R line 875 g/ha

Planting ratio: 4:2 or 8:2 Female: Male

Spacing: row to row 45 cm and plant to plant 15-20 cm

Irrigation: Two irrigations required at one pre boom flowering stage another is pod filling stage.

Critical stages for irrigation:

Rosette stage
Flowering
Pod formation
Avoid irrigation during maturity (causes shattering & disease).

Manure & fertilizer: FYM: 20-25 tonnes/ha, N: P: K 100: 60: 40 (N apply in split dose).

Rouging:

- Off-type plants
- Diseased plants
- Early or late flowering types
- Plants with different leaf or flower colour
- Tall or dwarf variants

Stages of rouging

- Vegetative
- Flowering (most important)
- Maturity

Keep honey bee hives: 5-10 beehives per hectare.

Supplementary pollination: Rope pulling is more effective

Harvesting: Male lines are harvested first followed by female line when siliqua are mature.

Seed yield: 2.5 -2.5 t/ha

General requirement and Specific requirement

Factor	Maximum permitted (%)*	
	Foundation	Certified
Off types	0.10	0.50
Objectionable weed plants	0.050	0.10

Field standard for hybrid seed production: Indian minimum seed certification standards (IMSCS) prescribed standard for seed quality control, certain field and seed standard are essential, which should be followed during seed production and subsequent seed processing.

Seed standards

Factors	Maximum permitted (%)*	
	Foundation	Certified
Pure seed (minimum)	97.0%	97.0%
Inert matter (minimum)	3.0%	3.0%
Other crop seed (maximum)	10/kg	20/kg
Other distinguishable variety (maximum)	0.10%	0.50%
Total weed seed (maximum)	10/kg	20/kg
Objectionable weed seed (maximum)	5/kg	10/kg
Germination (minimum)	85%	85%
Moisture (minimum)	8.0%	8.0%
For vapour proof containers (maximum) Mustard	5%	5%
Rapeseed	7%	7%

Isolation distance

Contaminants	Minimum distance (meters)			
	Foundation		Certified	
	Self Compatible type	Self Incompatible type	Self compatible type	Self Incompatible type
Field of the other varieties of the same spp.	200	100	50	50
Field of the same variety not confirming to varietal purity requirement for certification	200	100	50	50
Field of rocket salad and any of the other species of the genus Brassica	50	100	25	50

Seed storage:

Mustard having good storability in seed under ambient condition of mind climate maintaining germination (85%) for at least two planting season recommended in IMSCS. However, hybrid seed being high value commodity, germination and vigour of the seed need to be maintained as high as possible. For this reason hybrid mustard seeds are dried below 6-8 % moisture and storage in sufficiently cool, dry, and hygienic ambience.

Conclusion

Hybrid seed production in oilseed Brassicas, particularly *Brassica juncea*, is a key strategy for improving yield, oil quality, and stress tolerance through the exploitation of heterosis. CMS-based hybrid breeding is the most successful commercial approach, while self-incompatibility, genetic male sterility, and modern biotechnological tools further enhance breeding efficiency. Successful hybrid seed production requires proper maintenance of parental lines, synchronized flowering, effective pollination, strict rouging, and adherence to seed certification standards. The integration of conventional and molecular breeding technologies will support the development of high-yielding, climate-resilient Brassica hybrids, contributing to sustainable oilseed production and national edible oil security.

References:

1) Diksha* and Aastha Khatri (2024) Agronomic management of Indian mustard (Brassica juncea (L.) Czern & Cosson) Just agriculture Vol. 5 Issue- 2, October 2024 (e-ISSN: 2582-8223)7-14 ***www.justagriculture.in***
2) Guman Singh (2023) Hybrid seed Production Technology in Indian Mustard (Brassica juncea)*Curr.Agri.Tren.:e-Newsletter,2*(8),20-23 **http://currentagriculturetrends.vitalbiotech.org/**
3) Neha Yadav (2022) Hybrid Seed Production in Mustard (Brassica Spp.) e-Magazine for Agricultural Articles Vol: 02, Issue: 06 ISSN: 2582-9882 http://www.agriarticles.com
4) Syed Abu Bakr Haider Bukhari (2021) Mustard as Medicinal Plant: Sources, Botanical Features, Genetics and Application. Scholars Bulletin Abbreviated Key Title: Sch Bull ISSN 2412-9771 (Print) ISSN 2412-897X (Online) Scholars Middle East Publishers, Dubai, United Arab Emirates 123-129. DOI: 10.36348/sb.2021.v07i05.001