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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 01

Strengthening Environmental Sustainability of Punjab's Rice–Wheat System through a roadmap of Soil Health Management

Abstract

The rice–wheat system remains central to Punjab's food-grain economy, but its long-term performance now depends on how efficiently the system uses soil, water, nutrients, residues and energy. The earlier version of this article identified nutrient imbalance, declining soil organic matter, groundwater depletion, residue burning and intensive tillage as interconnected sustainability concerns. This revised article retains that core concept but converts it into a field-oriented soil-health roadmap. The need is particularly urgent because the Central Ground Water Board's 2024 assessment estimated Punjab's overall stage of groundwater extraction at 156.87%, with 115 of 153 assessment units classified as over-exploited. At the same time, there is evidence that practical interventions are already changing farm practice: the Commission for Air Quality Management recorded 5,114 paddy fire counts in Punjab during the 2025 harvesting season, 53% below 2024 and 93% below 2021. Punjab Agricultural University also reported expansion of direct-seeded rice from 2.53 lakh acres in 2023–24 to 2.93 lakh acres in 2024–25, while short- and medium-duration rice varieties covered about 74% of the rice area during kharif 2024. The article proposes an integrated approach built around five field decisions: test the soil, plan nutrient inputs, retain/recycle residues, save irrigation water and review the results after every season. Practical options include soil-test-based fertilization, judicious nitrogen and phosphorus use, short-duration rice varieties, suitable DSR methods, residue-retaining wheat establishment through Happy Seeder/Super Seeder/Smart Seeder or other locally suitable implements, organic matter recycling, and record-based monitoring. The emphasis is not on adopting every technology on every farm, but on selecting a locally suitable combination according to soil type, irrigation source, residue load, machinery access, crop sequence and farm economics. Such an approach can connect soil health with resource-use efficiency, climate resilience and environmental sustainability without compromising the practical realities of Punjab farming.

Keywords: soil health; rice–wheat system; Punjab; groundwater; crop residue management; direct-seeded rice; conservation agriculture; nutrient-use efficiency; climate resilience; sustainable intensification

1. Why soil health has become a farm-management issue

The Punjab rice–wheat system is not simply a two-crop sequence; it is a tightly coupled production system in which water, soil structure, crop residue, nutrient management, machinery and sowing time influence one another. The original article correctly framed soil health as the link between productivity and environmental sustainability. The practical implication is that soil health should not be treated as an isolated laboratory score. A farmer experiences soil health through infiltration, ease of tillage, rooting, nutrient response, irrigation requirement, residue decomposition, lodging, weed pressure and yield stability.

Punjab's current resource indicators show why this integrated perspective is necessary. The CGWB Ground Water Resources of Punjab – 2024 report estimated the state's overall stage of groundwater extraction at 156.87%; 115 of 153 assessment units were classified as over-exploited, four as critical, 12 as semi-critical and 22 as safe. This does not mean that every farm has the same groundwater problem, but it does demonstrate that the state-level water balance is under severe pressure.

At the same time, the residue-burning problem is showing measurable improvement. CAQM reported 5,114 farm-fire counts in Punjab in the 2025 paddy harvesting season, compared with 10,909 in 2024 and 71,304 in 2021. The decline should not be interpreted as a reason to relax efforts; rather, it demonstrates that machinery, extension, enforcement, community action and alternative residue-management practices can collectively change field behaviour.

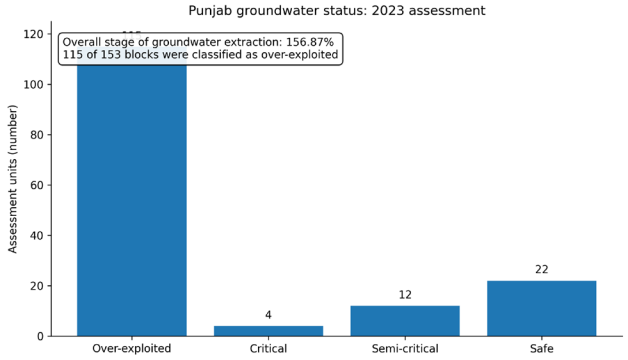


Figure 1. Groundwater assessment status of Punjab (2023 assessment year).

Source: Central Ground Water Board, Ground Water Resources of Punjab – 2024. The report uses GEC-2015 methodology and data for the 2014–2023 period.

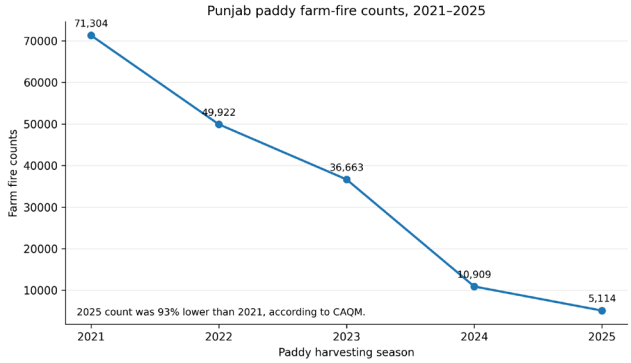


Figure 2. Punjab paddy farm-fire counts during the 2021–2025 harvesting seasons.

Source: Commission for Air Quality Management (CAQM), 1 December 2025. Counts refer to the official monitoring period of 15 September–30 November.

2. The soil-health problem is interconnected, not individual

Pressure in the system	What it can do to the field	Management response
Repeated puddling and intensive tillage	Weak aggregation, compaction/hard layers, slower infiltration and greater dependence on timely field operations.	Use minimum/zero tillage where recommended; avoid unnecessary passes; maintain residue cover.
Imbalanced fertilizer use	Unnecessary input cost, nutrient imbalance and lower nutrient-use efficiency.	Use current soil-test and PAU recommendations; apply nutrients at the right rate, time and method.
Low organic matter return	Lower biological activity, weaker aggregation and reduced water-holding capacity.	Recycle suitable residues; use FYM/compost/green manure where locally available and agronomically appropriate.
Paddy water demand	High irrigation requirement and pressure on groundwater in vulnerable blocks.	Use suitable short-duration varieties, DSR where appropriate, and scientific irrigation scheduling.
Open-field residue burning	Loss of nutrients/organic material and smoke pollution; loss of residue as a resource.	Use in-situ or ex-situ residue management through available machinery and local custom hiring services.
Delayed wheat establishment	Yield risk from late sowing and greater pressure to remove/burn residue quickly.	Plan harvesting, residue management and wheat sowing as one operation rather than separate decisions.

The key message is therefore simple: soil-health management should be designed around the entire

rice–wheat calendar. A decision that saves water but creates a residue-management bottleneck, or a nutrient practice that increases yield but wastes fertilizer, is not an integrated solution.

3. Soil testing: the first practical step

A soil test should be the starting point for fertilizer decisions rather than a formality after fertilizer has already been purchased. The Soil Health Card framework assesses 12 parameters: N, P, K, S, Zn, Fe, Cu, Mn, B, pH, electrical conductivity and organic carbon. Official guidance recommends sampling from 15–20 cm depth using a V-shaped cut, taking soil from several points of a representative field, mixing the subsamples and sending a representative sample to an approved laboratory.

For a farmer managing a rice–wheat rotation, the practical rule is to sample after harvest when there is no standing crop and to keep separate samples for clearly different soil or management zones. Do not mix saline patches, manure heaps, bunds, waterlogged spots or visibly unusual areas with the main field sample. The objective is not to obtain an impressive report; it is to obtain a representative report that can actually guide the next nutrient decision.

- Keep the latest soil-test report with the farm record and compare it with previous reports rather than treating each test as an isolated result.
- Follow crop-specific recommendations from the current PAU Package of Practices and the soil-test interpretation.
- Avoid applying phosphorus automatically to rice when the preceding wheat crop has already received the recommended phosphatic fertilizer, unless the current recommendation specifically indicates otherwise.
- For nitrogen, avoid the habit of applying multiple bags at once; use the recommended rate, timing and crop-specific indicators/advisories.
- Where micronutrient deficiency is suspected, confirm it through soil/plant diagnosis rather than using a blanket micronutrient mixture.

4. Nutrient management: from 'more fertilizer' to 'right fertilizer'

The practical objective is not maximum fertilizer use but maximum nutrient-use efficiency. Recent PAU farmer-extension activities in 2026 have repeatedly emphasized soil-test-based fertilization, judicious urea and phosphorus use, and the use of biofertilizer approaches where recommended. The current PAU Kharif Package of Practices also advises applying fertilizers according to soil test, omitting phosphorus in rice following a wheat crop that received the recommended phosphatic dose, and using nitrogen judiciously.

An integrated nutrient-management plan can combine mineral fertilizers, crop residues, farmyard manure or compost, green manuring and suitable microbial inputs. Organic materials should not be viewed as a direct one-for-one replacement for mineral fertilizer; their value also lies in improving soil biological processes, aggregation and nutrient cycling. Equally, biofertilizers should be used as recommended products and methods rather than as a substitute for all nutrient inputs.

5. Residue is a resource: make the wheat-sowing decision before rice harvest

One of the most practical improvements in the rice–wheat system is to treat paddy residue management and wheat establishment as a single operation. The objective is to harvest rice, distribute residue uniformly and establish wheat without burning. PAU's current Rabi 2025–26 recommendations include Happy Seeder, Super Seeder and PAU Smart Seeder options for sowing wheat in combine-harvested paddy fields without residue burning or removal. PAU also documents zero-till drilling and other residue-management options.

The choice of machine should be based on residue condition, field size, tractor power, soil moisture, availability through a custom hiring centre and the operator's ability to calibrate the machine. A technically appropriate machine used poorly can produce poor establishment; therefore, calibration and field demonstration matter as much as access to the machine.

- Before rice harvest: confirm access to a suitable combine with residue-spreading/SMS capability and book the wheat-sowing machine.

- At rice harvest: aim for uniform residue distribution rather than concentrated straw heaps.
- At wheat sowing: check seed placement, depth, residue flow and field moisture; follow the current PAU machine-specific guidance.
- If machinery is not owned, use a Custom Hiring Centre, cooperative or KVK-linked service rather than purchasing equipment solely for a small acreage.
- Never burn simply because residue management was not planned in advance.

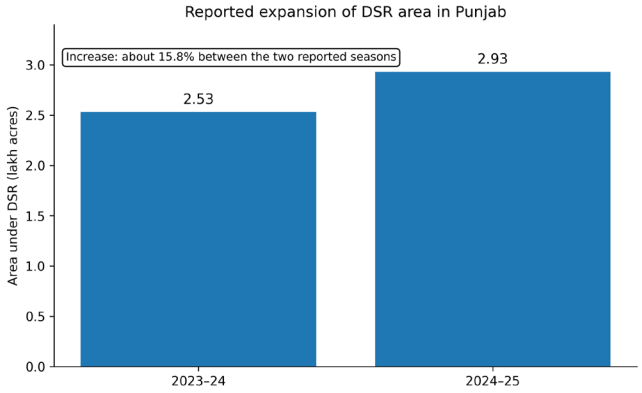


Figure 3. Reported expansion of direct-seeded rice (DSR) area in Punjab.

Source: Punjab Agricultural University, August 2025. Reported DSR area increased from 2.53 lakh acres in 2023–24 to 2.93 lakh acres in 2024–25.

6. Water management: choose the system, not just the irrigation

Groundwater conservation in Punjab cannot be achieved through a single irrigation rule. It requires alignment of rice duration, establishment method, irrigation scheduling, soil condition and the succeeding wheat sowing date. PAU reported in April 2025 that short- and medium-duration rice varieties covered about 74% of the state's rice area during kharif 2024, with PR 126 and PR 131 accounting for about 43% and 19%, respectively.

DSR is another option, but it should not be presented as a universal replacement for transplanted rice. Weed management, soil condition, irrigation control and farmer skill strongly influence outcomes. PAU's 'Tar-wattar DSR' approach delays the first irrigation and is intended to save water while supporting crop establishment; its performance depends on following the recommended establishment and weed-management package.

- Select rice duration according to the local recommendation and the wheat-sowing target.
- Use DSR only where the field, irrigation management and weed-control capacity are suitable.
- Do not equate frequent ponding with better crop growth; follow the crop- and method-specific irrigation schedule.
- Stop irrigation before maturity according to the current PAU recommendation to avoid unnecessary pumping.
- Measure or at least record irrigation events. A farmer cannot improve water productivity without knowing how much and how often water is applied.

7. Organic matter and biological soil health

Soil organic carbon is a useful indicator because it is connected with aggregation, nutrient cycling, microbial activity and water retention. However, increasing organic carbon is a gradual process. Farmers should therefore avoid expecting a large change from a single manure or residue application.

A realistic strategy is to return a greater proportion of crop biomass to the soil, use farmyard manure or compost when available and suitable, introduce green manuring where the cropping calendar permits, and reduce unnecessary soil disturbance. Long-term continuity matters more than one-time applications. The objective is to maintain a regular carbon input while avoiding practices that create waterlogging, nutrient immobilisation or operational problems.

8. Conservation agriculture: select the combination that fits the farm

Conservation agriculture is often discussed as if it means one machine or one tillage method. In practice, it is a management package built around reduced soil disturbance, soil cover and crop diversification. In Punjab's rice–wheat system, zero-till wheat, residue-retaining seeders, short-duration rice, DSR in suitable fields, and crop diversification can be combined in different ways.

Period	Priority decision	What to do	Record
After wheat harvest / pre-rice	Soil diagnosis	Take representative soil samples; review previous soil-test trend; plan nutrients and residue use.	Soil-test values, last fertilizer dose, field problems
Rice establishment	Water + nutrient efficiency	Choose locally recommended duration and establishment method; use soil-test-based nutrients; plan irrigation.	Variety, DSR/transplanting, irrigation dates
Rice crop	Avoid unnecessary inputs	Monitor crop, weeds and nutrients; follow PAU schedule; avoid blanket urea/phosphorus use.	Fertilizer quantity and dates; irrigation events
Rice harvest	Residue plan	Ensure uniform residue spread; arrange CRM machine before harvest; avoid burning.	Machine/service used, residue condition
Wheat establishment	Timeliness + soil cover	Use suitable zero-till/Happy Seeder/Super Seeder/Smart Seeder/surface seeder according to field conditions.	Sowing date, machine, seed rate, field moisture
Wheat crop	Efficient nutrient + water use	Apply fertilizer and irrigation according to current PAU recommendations; monitor weeds and crop condition.	Irrigation, fertilizer, weed-control operations
After wheat harvest	Review	Compare yield and input records; repeat soil testing at the recommended interval; modify next-season plan.	Yield, irrigation, fertilizer, fuel and soil-test trend

9. A practical season-wise soil-health calendar

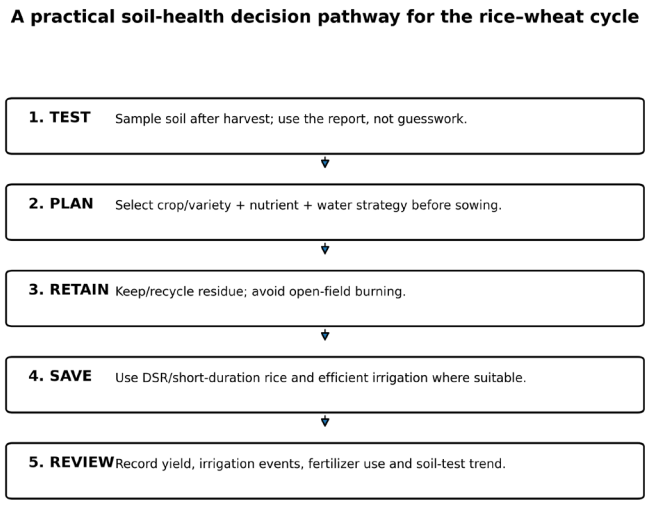


Figure 4. A practical decision pathway for integrating soil, nutrient, residue and water management.

Prepared from the principles and recommendations of the Soil Health Card framework, Punjab Agricultural University Packages of Practices and current PAU/ICAR extension guidance.

10. What should a farmer actually measure?

Practical sustainability improves when it becomes measurable. A farmer does not need a sophisticated laboratory on the farm; a simple annual record can reveal whether the management system is improving.

Indicator	Simple farm record	Why it matters
Soil test	pH, EC, organic carbon and nutrients at the recommended interval	Shows whether fertility and salinity trends are stable or changing.
Water	Number/date of irrigations; hours of pumping where feasible	Creates a baseline for water-saving decisions.
Fertilizer	kg/acre of urea, DAP/MOP or other products	Shows whether input use is rising without corresponding

		yield benefit.
Residue	Burned/not burned; machine used; residue condition	Links residue management with soil cover and operational cost.
Yield	kg/acre for rice and wheat	Allows input-use efficiency and profitability to be compared.
Cost	Fuel, labour and machinery-service cost per acre	Prevents adoption decisions based only on agronomic claims.
Timeliness	Rice harvest and wheat sowing dates	Captures the operational benefit of short-duration rice and timely residue management.

11. Extension support: the missing link between recommendation and adoption

The earlier article correctly identified extension services as a key mechanism for adoption. Current field activities in Punjab show that this remains highly relevant. PAU-KVKs have continued to conduct village-level demonstrations on soil sampling, balanced fertilization, residue management and Happy Seeder-based wheat establishment during 2025–2026. These activities are important because many soil-health practices are knowledge-intensive: correct sampling, machine calibration, variety selection, irrigation timing and nutrient scheduling cannot be communicated effectively through a single printed recommendation.

A stronger extension model would combine four elements: (i) one-season field demonstrations, (ii) farmer records of costs and resource use, (iii) follow-up after harvest, and (iv) access to machinery and advisory services through KVKs, Farm Advisory Service Centres, cooperatives and Custom Hiring Centres. Digital advisories can complement, but not replace, local field support.

12. What farmers should avoid

- Applying fertilizer because a neighbour applied it, without considering the field's soil-test status and crop requirement.
- Adding phosphorus routinely to rice when the preceding wheat crop already received the recommended phosphatic fertilizer, unless a current recommendation indicates a need.
- Purchasing a residue-management machine without considering annual acreage, tractor power, machine capacity, operator skill and local service alternatives.
- Choosing a long-duration rice variety only because it has been used traditionally, when a suitable shorter-duration PAU recommendation can meet the production objective.
- Using DSR without a plan for weed management, irrigation and field suitability.
- Burning residues because machinery was arranged too late; residue management should be planned before rice harvest.
- Assuming that one year of improved yield proves that soil health has improved. Soil-health change should be assessed through repeated indicators and field performance over time.

13. A realistic five-rule soil-health strategy for Punjab

Rule 1 — Test before you treat. Use a representative soil sample and current crop-specific recommendations.

Rule 2 — Plan rice and wheat together. Variety duration, harvest date, residue management and wheat sowing are one operational chain.

Rule 3 — Keep residue in the system. Use the most suitable in-situ or ex-situ option available locally; avoid open-field burning.

Rule 4 — Save water through system design. Use suitable rice duration, DSR where appropriate and scientific irrigation scheduling.

Rule 5 — Measure what you change. Record fertilizer, irrigation, machinery, sowing date, yield and cost so that the next decision is evidence-based.

Conclusion

Punjab does not need a choice between food security and environmental sustainability; it needs a more efficient rice–wheat production system in which soil, water, residue and nutrient decisions are made together. The evidence now available shows both the scale of the challenge and the feasibility of change. Groundwater extraction remains a serious structural concern, while residue-burning counts have fallen substantially and DSR and resource-efficient rice varieties are expanding. The practical lesson is that sustainability should be built into routine farm operations rather than treated as a separate environmental programme.

A workable soil-health strategy begins with a soil test, continues with balanced and crop-specific nutrient management, returns more organic material to the soil, protects residues from burning, selects water- and time-efficient rice options where suitable, and establishes wheat without unnecessary soil disturbance. Extension institutions, Custom Hiring Centres, KVKs, Farm Advisory Service Centres and farmer groups can make these practices easier to implement by combining demonstrations with machinery access and follow-up advisory support. Ultimately, the most useful indicator of soil-health management is not whether a farmer has adopted a fashionable technology, but whether the farm can maintain productivity with lower avoidable input losses, better resource efficiency and greater resilience over successive seasons.

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Just Agriculture Multidisciplinary *e- newsletter*

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 02

Solving the Banana Propagation Bottleneck: Role of Micropropagation, Market and Future

Introduction

Banana (*Musa* spp.) stands as one of the world's most important food crops, ranking fourth in gross value of production globally and serving as a staple for millions across tropical and subtropical regions. Despite its agricultural significance, conventional propagation methods have long constrained the industry's capacity to meet growing demand for quality planting material. The sterile, triploid nature of most cultivated banana varieties renders traditional breeding and seed-based propagation impractical, making vegetative propagation through suckers the primary conventional method. This approach, however, suffers from severe limitations: low multiplication rates, disease transmission, and slow propagation cycles.

Micropropagation—the *in vitro* propagation of plants under aseptic conditions—has emerged as a transformative solution to these challenges. Over the past five decades, tissue culture technologies for banana have evolved from experimental protocols to sophisticated commercial systems capable of producing millions of disease-free plantlets annually.

The Rationale Behind Micropropagation in Banana

1. Addressing the Propagation Bottleneck

The fundamental constraint of conventional banana propagation lies in its biological nature. Edible bananas are seedless and triploid, propagating exclusively through vegetative means. Each mother plant typically produces only 5 to 10 suckers depending on the variety, and these suckers require extended periods to develop sufficiently for transplantation. This low multiplication rate creates a critical bottleneck in the supply chain for quality planting material. Micropropagation directly addresses this limitation. Through shoot tip culture, a single explant can yield multiple shoots within weeks, with multiplication rates far exceeding any conventional method. The technique enables the rapid multiplication of selected elite genotypes, allowing new cultivars to reach commercial scale in a fraction of the time required through sucker-based propagation.

2. Disease-Free Planting Material

Perhaps the most compelling rationale for micropropagation in banana is its capacity to produce pathogen-free planting material. Conventional propagation through suckers facilitates the transmission of devastating diseases, including Banana Bunchy Top Virus (BBTV), *Fusarium oxysporum* f. sp. *cubense* (causing Fusarium wilt), and various nematode and weevil infestations. Once introduced into a field, these pathogens can devastate entire plantations. The scientific basis for pathogen elimination through micropropagation lies in the meristematic tissue's natural barrier properties. The apical meristem, a tiny dome of rapidly dividing cells measuring approximately 0.1 mm in diameter, is rarely penetrated by internal pathogens. By excising and culturing these meristematic regions under sterile conditions, micropropagation produces plants free from viruses, fungi, and bacteria that would otherwise propagate with the parent material.

1. Genetic Uniformity and Quality Control

Micropropagation through shoot tip culture ensures the production of genetically uniform, true-to-type planting material. Because the technique relies on existing meristems rather than callus intermediary stages, the regenerated plants retain the genetic fidelity of the donor mother plant. This uniformity is commercially valuable, as it ensures consistent agronomic performance, synchronized harvesting, and uniform fruit quality—advantages that are challenging to achieve with sucker-derived planting material.

Stages of Banana Micropropagation:

1. Selection of mother plant: sword suckers, disease free
2. Selection of explant: apical meristem, healthy shoot tips
3. Surface sterilization: tween-20, mercuric chloride, sodium hypochlorite, double distilled water
4. Culture initiation: Murashige and skoog media, Banana multiplication media
5. Shoot multiplication: PGRs like BAP, Kinetin used
6. Rooting: PGRs like IAA, NAA, IBA used
7. Hardening of plantlets: plantlets gradually exposed to external environment conditions
8. Acclimatization and field transfer: field establishment, disease free, good quality, true-to-type plantlets produced for mass multiplication and commericialization.

Commercialization of Banana Micropropagation

From Laboratory to Industry

The commercialization of banana micropropagation has grown substantially since the first reports of in vitro culture in the 1960s and 1970s . Today, tissue culture laboratories—sometimes referred to as "biofactories"—operate globally, producing millions of banana plantlets annually for both domestic and export markets. The technology has been scaled up to commercial laboratories for production of planting materials, with field evaluation demonstrating genetic stability and high yields.

Temporary Immersion Bioreactor Systems

A significant advancement in commercial micropropagation has been the development of temporary immersion systems (TIS) and bioreactors. These systems represent a departure from conventional semi-solid media culture, offering several advantages for large-scale production. Temporary immersion bioreactors periodically immerse plant material in liquid culture medium, facilitating improved nutrient uptake and gas exchange. Research comparing TIS with conventional methods has demonstrated superior outcomes. Studies on banana cv. 'Dwarf Cavendish' found highest shoot multiplication in TIS compared to liquid or solid medium systems. Temporary immersion bioreactors have been shown to reduce hyperhydricity, lower ethylene and CO_2 levels in culture vessels, and improve shoot proliferation and plant growth due to enhanced explant surface exposure to liquid media. Furthermore, physiological evaluations indicate that TIB systems improve rooting, produce longer shoots with higher dry mass, and enhance photosynthetic rates compared to gelled medium cultures.

Available Commercial Technologies

Research institutions have developed numerous technologies available for commercialization. The ICAR-National Research Centre for Banana in India, for instance, offers a portfolio of tissue culture technologies including low-cost protocols for mass propagation of varieties like Grand Naine and Rasthali, temporary immersion bioreactor systems for large-scale micropropagation, and embryogenic cell suspension technology for Hill banana. These technologies target both efficiency improvements and cost reduction, addressing critical barriers to widespread adoption.

Recent Novel Achievements

Somatic Embryogenesis and Embryogenic Cell Suspensions

While shoot tip culture remains the predominant commercial method, somatic embryogenesis represents a more advanced approach with significant potential. Somatic embryogenesis involves the differentiation of somatic cells into embryos capable of regenerating complete plants, and in banana, this process has been achieved using shoot apexes of axillary buds to induce embryogenic cell suspensions (ECS). This technology has been scaled to commercial laboratories for production of genetically identical,

disease-free plantlets. The significance of somatic embryogenesis extends beyond propagation efficiency. It serves as a prerequisite for genetic modification and genome editing technologies, enabling the development of improved banana varieties with traits such as disease resistance and stress tolerance. Recent reviews have highlighted progress in understanding the molecular mechanisms underlying somatic embryogenesis, factors influencing the process, and strategies for improving regeneration in recalcitrant cultivars.

- **Double-Decker Temporary Immersion Bioreactor (DDTIB)**

A recent innovation addresses limitations of existing bioreactor designs. The Double-Decker Temporary Immersion Bioreactor (DDTIB) was developed to overcome problems such as media contamination risk, inadequate nutrient exchange, and space inefficiency in previous systems. This self-illuminated system incorporates a separate media tank for refilling, allowing contaminated media to be removed without disturbing plantlets. Research on bio-immunized Grand Naine banana demonstrated that DDTIB regeneration produced significantly higher biomass compared to conventional systems, with optimized parameters of 6-hour immersion frequency and 3-minute immersion time yielding superior shoot regeneration.

- **Bio-Immunization Integration**

The integration of micropropagation with bio-immunization represents a novel approach to enhancing plantlet quality. Bio-immunization involves the application of compounds that stimulate the plant's innate immune system, inducing production of protective enzymes and pathogenesis-related proteins.When combined with micropropagation in DDTIB systems, bio-immunized banana plantlets demonstrated enhanced resistance against destructive pathogens like *Fusarium oxysporum* f. sp. *cubense* TR4. This integration of propagation technology with plant defense priming represents a significant advance in producing not just disease-free, but disease-resistant planting material.

Conclusion

Micropropagation has become indispensable to the modern banana industry, addressing fundamental biological constraints that limit conventional propagation. The rationale is compelling: rapid multiplication of elite genotypes, elimination of devastating pathogens, and production of uniform, high-quality planting material. Commercial adoption has accelerated through technological refinements, particularly temporary immersion bioreactor systems that improve efficiency and reduce costs. Recent achievements in somatic embryogenesis, bioreactor design, and bio-immunization integration continue to expand the capabilities and value proposition of banana micropropagation. As the industry faces mounting pressures from climate change, emerging diseases, and increasing demand for food security, these technologies will play an increasingly critical role in sustaining global banana production.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 03

Lead Farmers Leading the Leap: How to Choose, Train and Support Them

Summary

Farmers trust what they see on a neighbour's field more than what they hear in a meeting. Lead farmer programmes in India, such as Farmer Friends, Frontline Demonstration hosts and Krishi Sakhis, rest on this idea, yet adoption often stops at the demonstration plot. Drawing on studies from India and other countries and on field experience in Telangana, this article explains how to choose, train and support lead farmers and gives a ten-point selection checklist.

Introduction

In India, one extension officer often serves many villages and thousands of farmers. To widen reach, several programmes work through lead farmers. The Agricultural Technology Management Agency (ATMA) guidelines provide one Farmer Friend for every two villages (DAC, 2010). Krishi Vigyan Kendras (KVKs) hold Frontline Demonstrations (FLDs) on farmers' fields and women Krishi Sakhis now work as para-extension workers in several states (PIB, 2024).

Choosing a farmer and giving free inputs does not by itself lead to wider adoption. The lead farmer has to be the right person, trained to teach, supported for more than one season and linked to other farmers and markets. This article explains each of these steps, using studies from India and abroad and our field experience in Telangana.

Seeing is believing

"Seeing is believing" is one of the oldest principles of extension. Seaman A. Knapp built demonstration work in the United States in the early twentieth century on the idea that farmers accept a practice once they see its results on a farm. Rogers (2003) calls this observability, the easier the results seen, the faster a technology spreads.

Where the demonstration is held matters. A farmer looking at a university plot may say, "That is university land; conditions there are different from mine." The same technology on a neighbour's field, with the same soil, water and management, is much harder to dismiss. This is what a lead farmer adds to a demonstration.

Evidence from the field

In 12 districts of Uttar Pradesh, a study of 1,496 farmers revealed the adoption of wheat variety HD-2967 promoted by KVKs is about 28 per cent of farmers in demonstration villages had never attended a KVK programme, yet many learnt of the variety from farmers friends. Among these "network" farmers, adoption rose by about 10 per cent (Varshney *et al.*, 2022). In Warangal, Telangana, a farmer grew paddy variety KNM 1638, received for popularisation under the PJTAU Village Adoption Programme. His crop drew neighbor farmers' attention and he went on to promote the variety in the area.

In Karnataka, the Digital Green approach used short videos made by local farmers about their own practices. Across 16 villages and 1,470 households, adoption of some practices was up to seven times higher than under the Training and Visit approach and the method was about ten times more cost-effective (Gandhi *et al.*, 2009). In Quzhou county, China, scientists lived in villages under the Science and Technology Backyard approach and worked with leading farmers on wheat and maize. Yields of these leading farmers rose from 67.9 to 97.0 per cent of the attainable yield and across 93,074 households in the county the figure rose from 62.8 to 79.6 per cent (Zhang *et al.*, 2016).

How well farmer-to-farmer learning works depends on three things: whom we choose, how we train them and how long we support them.

Step 1. Choose the right lead farmer

Similar rather than superior: In 120 villages of Malawi, researchers compared the usual lead farmers, who were richer and better educated, with "peer farmers" who were ordinary farmers like their neighbours. Given a small reward linked to results, peer farmers raised their neighbours' knowledge and adoption sharply; the lead farmers did not respond to the reward in the same way. Similar farm size was the strongest reason neighbours believed the messenger (BenYishay and Mobarak, 2019).

Two or three, not one: In 200 Malawi villages, many farmers tried a new practice only after hearing of it from more than one person they knew (Beaman *et al.*, 2021). Two or three well-connected lead farmers per village work better than one.

Check affordability: In KVK and ATMA programmes in Telangana, lead farmers were mostly the larger and more influential farmers, yet their land, water and crops were often close to their neighbours' and neighbours did copy them. The real test is whether a two-acre neighbour can afford the same practice and expect the same result. If not, the neighbour will only watch.

Credible and quick with information: A farmer who openly credits the university variety or the KVK advice ("This seed came from the university and it worked on my land") makes neighbours positive before they try anything. A farmer who uses a smartphone passes information while practicing for better monitoring and evaluation is preferable.

Include women deliberately. Women were chosen as lead farmers only now and then, mostly in Self Help Group (SHG) linked programmes. Under the Krishi Sakhi programme, women farmers receive 56 days of training as para-extension workers; about 34,000 had been certified against a target of 70,000 (PIB, 2024). Table 1 turns these points into a field checklist. It is a practical guide, not a tested scale.

Table 1. Lead farmer selection checklist (2 = high, 1 = medium, 0 = low; maximum 20)

Quality	How to check in the field	Score 2 / 1 / 0	Basis
1. Similar farm	Compare land size, water source and crops with most village farmers	2 same class; 1 a little bigger; 0 much bigger or irrigated among rainfed	BenYishay and Mobarak (2019)
2. Trusted adviser	Ask 10 farmers: "Whom do you ask when your crop has a problem?"	2 named by 4 or more; 1 by 2–3; 0 by 1 or none	Rogers (2003)
3. Well connected	Membership in FPO, SHG, milk society, water users' group	2 two or more groups; 1 one; 0 none	Beaman *et al.* (2021)
4. Open about money	Ask last season's cost and loss; check for a cost notebook	2 shares all, keeps records; 1 yield only; 0 hides	Field experience

Quality	How to check in the field	Score 2 / 1 / 0	Basis
5. Positive about extension	Listen to how the farmer speaks of past advice and varieties	2 credits openly; 1 neutral; 0 negative	Field experience
6. ICT ready	Check apps, WhatsApp groups and how fast advice is passed on	2 same-day sharing; 1 uses, rarely shares; 0 no use	Field experience
7. Visible plot	Visit the site; count farmers passing daily	2 roadside or village centre; 1 partly seen; 0 remote	Rogers (2003)
8. Willing to share cost	Agree on share of input cost before sowing	2 half or more; 1 some; 0 wants all free	Field experience
9. Time to teach	Ask about family labour and other occupations	2 keen and available; 1 limited; 0 unwilling	Kiptot and Franzel (2014)
10. Tries new things	Ask what was new on the farm in the last three seasons	2 two or more; 1 one; 0 none	Rogers (2003)

Note: FPO = Farmer Producer Organisation; ICT = Information and Communication Technology. A score of 14 or more is suitable. Include at least one woman per village.

Step 2. Train the lead farmer to teach, not only to farm

Teach the full package. When neighbours saw variety, spacing, fertiliser and plant protection working together, they copied the whole package, not only the seed. The lead farmer should be able to explain why each step matters.

Teach openness about money. Lead farmers readily shared yields but seldom costs or mistakes. A cost board at the plot showing input and labour costs, yield, price received and one thing that went wrong answers the first question every visitor asks.

Teach field days and videos. The lead farmer should practise leading a group through the plot in local words. A paddy farmer in Warangal district learnt drum seeder sowing at the Regional Agricultural Research Station (RARS), Warangal and then taught it through his own Telugu YouTube videos to more than 300 farmers. Farmers trusted him because he was one of them, on land like theirs.

Step 3. Support the lead farmer beyond one season

Stay for two or three seasons. Most neighbours did not copy in the same season. They waited for one full harvest and a good price, then tried the practice in the next season or two. A project that leaves after one season stops just when spread begins.

Reward with recognition. In northern Uganda, farmers promised public recognition before their village raised neighbours' knowledge by 0.42 standard deviations, against 0.27 (not statistically significant) for those promised a private gift (Shikuku *et al.*, 2019). The Warangal drum seeder farmer was honoured during kisan melas, which encouraged him to keep teaching. A name board at the plot, a certificate at a Kisan Mela and a place on an exposure visit cost little.

Help the lead farmer earn from the role. Among 99 volunteer dairy trainers in Kenya, most joined to learn or to help others, but after three years income from inputs and services had become a main reason to stay (Kiptot and Franzel, 2014). Indian lead farmers can earn from quality seed production, custom hiring, bio-input sales or grain cleaning and grading.

Avoid the free inputs trap. This was the most common cause of failure in our field work. When seed, fertiliser and sprays are free, neighbours conclude, "It

worked because it was free. I cannot afford it." The lead farmer should pay part of the cost and the real cost should appear on the cost board.

Link the lead farmer to a buyer

Neighbours copy faster when there is an assured buyer. In our experience, a Farmer Producer Organisation (FPO), company or exporter buying the produce did more to speed up copying than training alone. Sahyadri Farmer Producer Company, Nashik, Maharashtra, began in 2011 and grew to about 8,000 farmers and 11 FPOs; in 2017 it was India's leading grape exporter with a 14 per cent share, its growers following GlobalGAP practices with company support (Paty *et al.*, 2018). Neighbours follow the first grower who meets the buyer's standard because they see the method and the export price together. Bhoosiri Millets Farmers Producer Company in Karnataka, with around 1,000 members and a turnover of about ₹3 crore, shows the same pull through processing.

Proven adopters can also be grown into trainers. Under Andhra Pradesh Community Managed Natural Farming (APCNF), champion farmers became internal Community Resource Persons (CRPs) at about one per 100 farmers, reaching about 5,23,000 farmers in 3,015 villages in its first phase, 2015–18 (CEEW, 2024).

Table 2. Lead farmer models and what India can scale up

Programme and place	What made others follow	Use in India
KVK FLDs, Uttar Pradesh	Friends shared what they saw	Choose well-connected FLD farmers
Peer farmers, Malawi	Similar farms, small reward for results	Pick similar farmers; reward results
Social recognition, Uganda	Public praise before the village	Certificates and name boards
Science and Technology Backyard, China	Problems solved on the spot by resident scientists	Fixed monthly scientist visits
Sahyadri Farms, Maharashtra	Export price and GlobalGAP support	FPO crop leads for export crops
Bhoosiri Millets FPC, Karnataka	Processing and an assured buyer	Millet FPOs with small processing
Drum seeder farmer, Warangal	RARS training, Telugu YouTube videos, awards	Train and honour video farmers
APCNF andhra Pradesh	One CRP per 100 farmers, SHG support	Grow trainers from within the village

Note: FPC = Farmer Producer Company. Sources as cited in the text.

Conclusion

A lead farmer is a mentor living in the village, not a receiver of free inputs. Extension agencies should choose farmers whom neighbours see as their own, score candidates rather than pick by convenience and train them to show costs and mistakes as well as yields. They should stay with each lead farmer for at least two or three seasons, reward the work with recognition and an income role and link the farmer to an FPO or buyer. The better measure of a lead farmer's work is not the yield of the demonstration plot but the number of neighbours who adopt the practice within two seasons.

Acknowledgment

The authors thank the farmers and extension functionaries of Telangana whose field experience shaped this article.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 04

Genetic improvement of *Lathyrus sativus* L. Using modern breeding tools

Introduction

Grass pea (*Lathyrus sativus* L.), also known as Indian vetch, chickling vetch, or Khesari, is a resilient grain legume prized for its exceptional ability to thrive under severe environmental stresses, including drought and poor soils. Often dubbed an "insurance crop," it delivers reliable yields in resource-constrained environments, making it a cornerstone of sustainable agriculture and a vital lifeline for smallholder farmers in regions vulnerable to climate change (Vaz Patto and Rubiales, 2014a; Mahapatra *et al*., 2020). Nutritionally, the seeds are an excellent source of dietary fiber, essential minerals, carbohydrates and protein (25–30%) particularly the essential amino acid lysine offering critical food security in underprivileged communities (Campbell, 1997).

Despite its immense agronomic potential, widespread adoption of grass pea is severely limited by β-N-oxalyl-L-α, β-diaminopropionic acid (β-ODAP or BOAA), a naturally occurring neurotoxin. Prolonged reliance on seeds rich in β-ODAP, especially during times of famine, can cause neurolathyrism an irreversible neurological disorder leading to spastic paralysis of the lower limbs. Consequently, breeding cultivars with minimal β-ODAP levels without sacrificing agronomic performance remains the central objective of grass pea research (Spencer *et al*., 1986; Emmrich *et al*., 2019).

While conventional breeding has yielded some progress, efforts have long been hindered by a narrow genetic base, a large genome size and a lack of genomic tools. Fortunately, recent developments in next-generation sequencing, molecular markers and high-throughput phenotyping anchored by the newly available chromosome-scale reference genome have opened new avenues for gene discovery, quantitative trait locus (QTL) mapping and genome-wide association studies (GWAS) (Vigouroux *et al.*, 2024).

Integrating genomics, phenomics and modern molecular breeding strategies provides a transformative framework for grass pea enhancement. Combining precise marker-assisted selection, genomic selection and genome editing with high-throughput phenotypic screening allows breeders to decipher complex agronomic traits efficiently. This integrated paradigm promises to accelerate the delivery of climate-resilient, high-yielding grass pea varieties featuring safe β-ODAP levels and enhanced nutritional profiles (Dixit *et al*., 2016; Vigouroux *et al*., 2024).

Genetic resources for future crop improvement

While the strategy focuses on conserving and promoting the use of *Lathyrus sativus,* two related pulse species (*L. cicera* and *L. ochrus*), that are less widely grown but also liable to induce lathyrism, are also considered.

The genus *Lathyrus* comprises approximately 160 species. They are primarily native to temperate regions of the world, with approx. 52 species originating in Europe, 30 in North America, 78 in Asia, 24 in tropical East Africa, and 24 in temperate South America1. Lathyrus species that are grown as a pulse – *i.e.* that are harvested as a dry seed for human consumption which includes: *L. sativus*, *L. cicera*, *L. ochrus* and to a lesser extent L. *clymenum*. Another species that is occasionally grown for human consumption but for its edible tubers rather than its seed is L. *tuberosus*, known as the tuberous pea or earthnut pea. Other species that are of commercial importance, especially for their ornamental value or for forage or feed, includes *Lathyrus aureus* (Golden Pea), *Lathyrus annuus* (Red Fodder Pea), *Lathyrus japonicus* (Sea Pea), *Lathyrus latifolius* (Everlasting Pea), *Lathyrus linifolius* (Bitter Vetch), *Lathyrus nervosus* (Lord Anson's Blue Pea), *Lathyrus nissolia* (Grass Vetchling), *Lathyrus odoratus* (Sweet Pea), *Lathyrus pratensis* (Meadow Vetchling), *Lathyrus sphaericus* (Spring vetchling), *Lathyrus sylvestris* (Flat Pea-vine) and *Lathyrus tingitanus* (Tangier Pea) (https://genebanks.cgiar.org/resources/crops/grasspea).

Genetic resourses saving for future strategy concentrates on the ex situ conservation of the three main pulse species: *Lathyrus sativus, L. cicera* and *L. ochrus*. Collections of other Lathyrus species, for example of *L. odoratus* (the common sweet pea) for ornamental use and species of actual or potential importance as pasture or forage crops, are largely excluded from this strategy, although it is recognized that many could prove to be useful as a source of genes for the genetic improvement of the three target pulse species.
(https://genebanks.cgiar.org/resources/crops/grasspea).

Molecular breeding in *Lathyrus*

Several approaches have examined phylogenetic relation- ships within lathyrus, including morphological analysis, crossability studies, karyotyping, chromosome banding, in situ hybridization and molecular markers. DNA-based molecular markers, particularly Inter Simple Sequence Repeat (ISSR) markers, play an important role in the characterization and genetic improvement of legume crops. ISSR markers amplify DNA segments located between adjacent microsatellite or simple sequence repeat (SSR) regions. These amplified fragments generally range from less than 100 bp to approximately 300 bp and are generated using primers composed of short tandem repeat (STR) motifs, typically 16–25 bp in length, arranged in opposite orientations (Lalrinmawii *et al.,* 2023).



Figure 1. Morphological variation in crop and seeds

ISSR markers integrate the advantages of microsatellite and amplified fragment length polymorphism (AFLP) techniques while maintaining the simplicity and wide applicability associated with Random Amplified Polymorphic DNA (RAPD) markers. A major advantage of this technique is that it

does not require prior knowledge of DNA sequence information for primer design, making it a rapid, reliable and cost-effective approach. ISSR markers are extensively applied in genetic diversity analysis, phylogenetic investigations, genome mapping, gene tagging and evolutionary studies. They have been successfully employed to identify molecular markers associated with drought tolerance in *Lathyrus sativus* genotypes, supporting the development of stress-resilient cultivars (Younis *et al.,* 2020; Das *et al.,* 2021).

Marker-Assisted Breeding

The success of marker-assisted selection (MAS) largely relies on the availability of molecular markers that are tightly linked to the target trait. Among the available marker systems, expressed sequence tag simple sequence repeat (EST-SSR) markers exhibit a high level of sequence conservation and are often transferable across related species. The genomic resources for *Lathyrus* remain limited, with only 178 ESTs reported for *L. sativus* and 126 for *L. cicera*, in contrast to the much larger collection of 8,702 ESTs available for *L. odoratus* (Lambein *et al.,* 2019). Advances in high-throughput and high-density genotyping technologies have made association mapping a powerful alternative to traditional biparental mapping populations, as it exploits historical recombination events accumulated over many generations, enabling high-resolution analysis within a relatively short timeframe (Morrell *et al.,* 2012; Cobb *et al.,* 2013). Therefore, there is a pressing need to develop a comprehensive genetic linkage map for *Lathyrus*, together with the identification of important genes and quantitative trait loci (QTLs) that can be effectively utilized in MAS and compared with genomic information from related species. Such genomic resources, including linkage maps, gene cloning and MAS strategies, will accelerate the incorporation of desirable alleles for reduced ODAP concentration and enhanced methionine content into locally adapted cultivars, thereby improving their nutritional quality and agronomic value (Cobb *et al.,* 2013).

Omics enabled improvement in grasspea

Molecular breeding of grasspea (*Lathyrus sativus* L.) has advanced at a relatively slow pace, and the crop has received limited attention in terms of biotechnology research and investment. Several constraints have hindered progress in its molecular improvement, including its large genome size (1C = 8.12 Gbp), inadequate characterization of available germplasm and the low level of research funding resulting from its cultivation mainly in resource-limited regions. The relatively small number of researchers engaged in grasspea improvement has further slowed the development and implementation of modern molecular breeding approaches (Sarkar *et al.,* 2019). The availability of genomic resources for grasspea is still insufficient. By May 2020, the National Center for Biotechnology Information (NCBI) database contained only 178 expressed sequence tag (EST) sequences for this species. In addition, the limited number of molecular markers has prevented the construction of high-density genetic linkage maps, thereby reducing the resolution and effectiveness of quantitative trait loci (QTL) detection and mapping (Skiba *et al.,* 2004a,b; Vaz Patto *et al.,* 2006). Another significant limitation is the lack of a complete reference genome sequence for grasspea, which continues to impede genomic research and molecular breeding efforts (Hao *et al.,* 2017). The following sections summarize recent progress in grasspea genomics and molecular breeding, while highlighting the current challenges, future prospects and the potential application of advanced genomic tools for the genetic improvement of this important legume species (Sarkar *et al.,* 2019).

Molecular Marker Development

The availability of molecular markers in grasspea (*Lathyrus sativus* L.) remains limited, creating a major constraint for the effective implementation of molecular breeding programs. Therefore, there is a pressing need to develop a greater number of functionally informative molecular markers to support genetic improvement and marker-assisted breeding strategies (Lioi and Galasso, 2013). To address the shortage of anchor markers, researchers have utilized expressed sequence tag–simple sequence repeat (EST-SSR) markers derived from closely related legume species for genetic diversity analysis,

evolutionary studies and linkage mapping. In addition, the availability of cross-species transferable markers, together with computational mining of expressed sequence tag (EST) data deposited in the NCBI GenBank database, has facilitated the rapid and cost-efficient development of genic SSR (EST-SSR) markers in this (CAPS) and derived CAPS (dCAPS) markers have been developed by sequencing previously monomorphic SSR fragments and validating them using recombinant inbred line (RIL) populations of *Lathyrus cicera* (Almeida *et al.,* 2014a,b; Shiferaw *et al.,* 2017). Although the lack of a reference genome has restricted genomic studies in grass pea, the emergence of next-generation sequencing (NGS) technologies has greatly accelerated the genome-wide discovery of simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs). These advances are expected to improve the efficiency of positional gene cloning and quantitative trait loci (QTL) mapping (Xu *et al.,* 2018). In recent years, several transcriptome-based investigations have significantly expanded the genomic resources available for grass pea (Xu *et al.,* 2018; Rathi *et al.,* 2019). The first transcriptome analysis, performed using the 454 FLX Titanium pyrosequencing platform, resulted in the identification of 651,827 SSR loci. Based on these sequences, 50,144 non-redundant primer pairs were designed, which subsequently produced 74 polymorphic markers, 70 monomorphic markers, while 144 primer pairs failed to generate PCR amplification products (Yang *et al.,* 2014).

Genetic Mapping / Linkage Mapping

The development of molecular breeding strategies in grasspea (*Lathyrus sativus* L.) has been constrained by the limited availability of reliable molecular marker systems. The number of high-density genetic linkage maps developed for this crop remains considerably lower than that of other extensively investigated legume species. Dense genome linkage maps are essential for identifying quantitative trait loci (QTLs) controlling complex traits across the genome. Once detected, these QTLs can be tagged with closely linked molecular markers, facilitating marker-assisted selection (MAS) and map-based cloning of candidate genes, thereby improving the efficiency of grasspea breeding programs. The earliest molecular linkage map for grasspea was developed by (Chattopadhyay 2011). However, a major drawback of this map was that nearly 12% of the molecular markers exhibited segregation distortion, which increased the occurrence of false linkages in the F_2 mapping population and reduced the reliability of estimated genetic distances. To investigate the inheritance of the tendril trait (Hanada and Hirai 2003) applied bulked segregant analysis (BSA) to an F_2 population of sweet pea (*Lathyrus odoratus*), generated from a cross between the tendrilled cultivar 'Grace' and the tendril-less cultivar 'Snoopea Purple'. Their analysis identified the RAPD marker WB32a, which was closely linked to the gene controlling tendril development (Skiba *et al.* 2004a) constructed another genetic linkage map using 92 backcross-derived individuals obtained from a cross between the ascochyta blight-resistant accession 'ATC 80878' and the susceptible accession 'ATC 80407'. This study facilitated the identification of two QTLs associated with stem resistance to ascochyta blight in grass pea (Manly *et al.,* 2001). More recently, RNA sequencing (RNA-Seq)-based molecular markers, including simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs), have been employed to generate a genetic linkage map for *Lathyrus cicera*, demonstrating the usefulness of next-generation sequencing technologies in linkage analysis (Santos *et al.,* 2018). Despite these advances, further efforts are required to identify genomic regions controlling important agronomic traits and adaptation to climate-related stresses. Mapping these traits and developing tightly linked molecular markers will enhance the efficiency of marker-assisted selection, enabling the rapid incorporation of desirable alleles into elite grass pea cultivars and accelerating crop improvement (Manly *et al.,* 2001).

Functional Genomics Appliance for Grasspea Improvement

Most transcriptomic investigations in grasspea (*Lathyrus sativus* L.) have primarily focused on generating large-scale genomic resources, particularly simple sequence repeat (SSR) and single

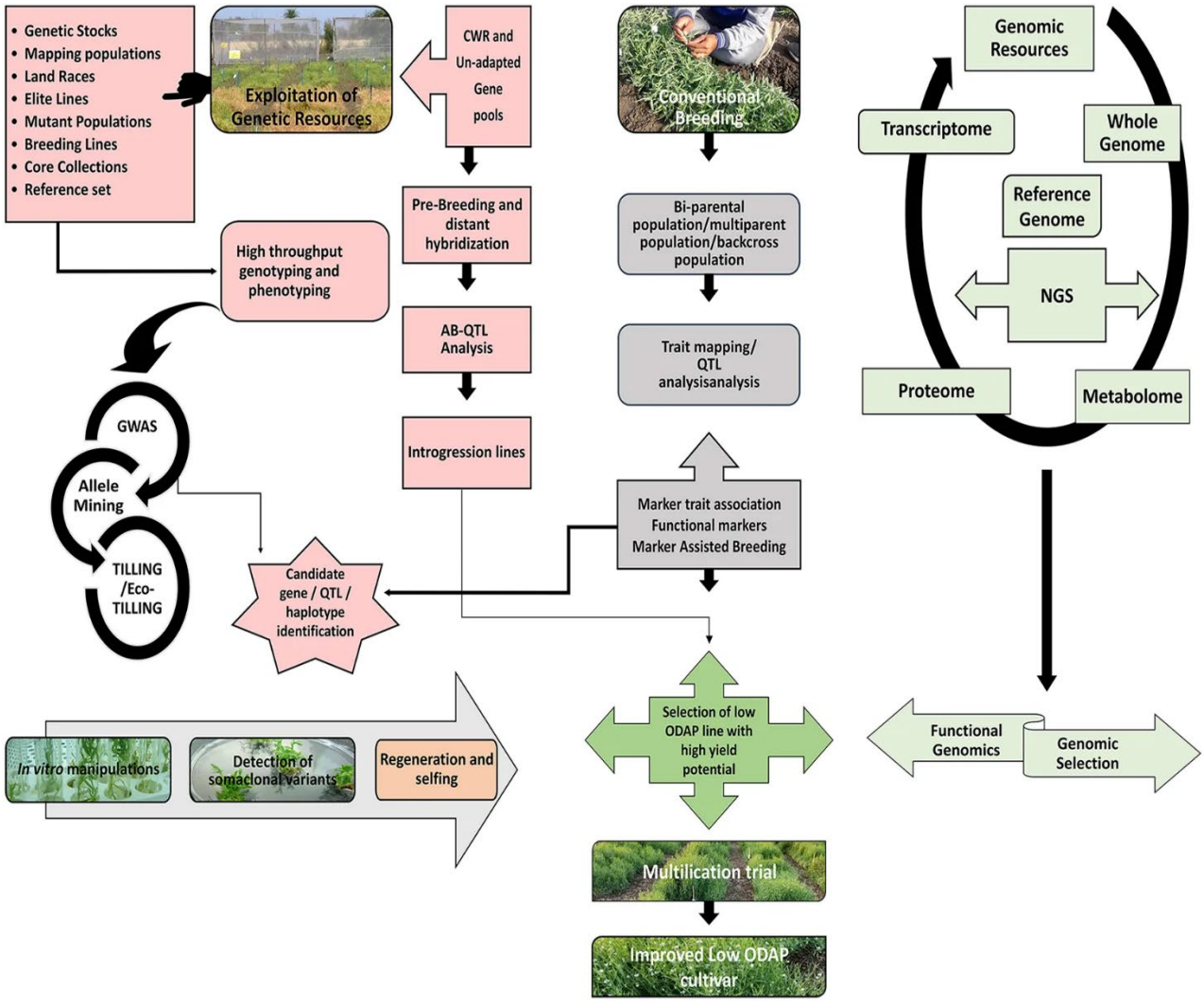
nucleotide polymorphism (SNP) markers, to support molecular linkage mapping and map-based gene cloning (Yang *et al.,* 2014; Hao *et al.,* 2017). Comparatively few studies have explored the genes and molecular mechanisms responsible for resistance to biotic and abiotic stresses or the regulatory pathways involved in the biosynthesis of β-N-oxalyl-L-α,β-diaminopropionic acid (β-ODAP), the principal neurotoxin present in grass pea (Emmrich, 2017; Xu *et al.,* 2018; Rathi *et al.,* 2019). The first comprehensive transcriptome analysis examining gene expression during the interaction between grasspea and the rust pathogen was reported by (Almeida *et al.* 2014b), providing valuable insights into the molecular basis of rust resistance. Global transcriptional responses of grass pea following infection with Ascochyta lathyri, improving the understanding of host defense mechanisms against ascochyta blight (Almeida *et al.* 2015). Transcriptome sequencing has also been employed to identify genes and regulatory networks associated with β-ODAP biosynthesis at different developmental stages of the grasspea cultivar 'LZ', thereby contributing to the understanding of toxin accumulation during plant growth (Xu *et al.,* 2018). Their study identified 137 transcription factors (TFs) involved in dehydration responses, together with genes encoding enzymes associated with abscisic acid (ABA) and cytokinin biosynthesis, highlighting their potential roles in drought adaptation. In addition to transcriptomic analyses, a comparative proteomic study on the grasspea cultivar 'LP-24' was carried out to examine protein expression under salinity and low-temperature stress. This investigation identified 67 differentially expressed proteins, providing insights into common signaling pathways involved in tolerance to these abiotic stresses (Chattopadhyay *et al.,* 2011). Metabolomic approaches have been applied to characterize the metabolic pathways associated with β-ODAP biosynthesis, offering a deeper understanding of toxin production and its regulation in grass pea (Liu *et al.,* 2017).

The European grasspea cultivar 'LS007' has recently been sequenced, resulting in a draft genome assembly of approximately 6.3 Gbp with an N50 value of nearly 59.7 kbp. The estimated genome size of grasspea ranges from 5.456 to 8.471 Gbp (Emmrich *et al.,* 2020). The availability of this draft genome represents a significant milestone for grass pea research, providing an essential resource for whole-genome resequencing, genome annotation and the identification of genes with previously unknown functions. Integrating genomic information with transcriptomic, proteomic and metabolomic datasets can provide a comprehensive understanding of candidate genes and the molecular pathways governing important agronomic traits and stress resistance. Future research should emphasize the development of high-density genome-wide molecular markers to strengthen advanced genomic breeding strategies, including genome-wide association studies (GWAS) and genomic selection (GS). These approaches will facilitate the discovery of rare and favorable alleles and their efficient incorporation into cultivated germplasm. Modern breeding methods, such as the Advanced Backcross Quantitative Trait Loci (AB-QTL) strategy, chromosome segment substitution lines (CSSLs) and exotic introgression libraries, can further enhance the utilization of useful genetic variation while minimizing undesirable background effects. In addition, the implementation of rapid generation turnover (RGT) techniques can shorten breeding cycles and accelerate genetic improvement. Among reverse genetics approaches, Targeting Induced Local Lesions in Genomes (TILLING) and Eco-TILLING have considerable potential for functional gene analysis in crops such as grasspea, where genomic information has historically been limited. Their application in this species remains at a proof-of-concept stage because the currently available mutant populations are relatively small (Gurung and Pang, 2011). To overcome this limitation, researchers at the John Innes Centre have developed ethyl methanesulfonate (EMS)-mutagenized populations in two grasspea varieties to facilitate high-throughput screening for low-β-ODAP mutants (Emmrich, 2017). In addition, the RevGenUK TILLING platform, originally established for model legume species, has been expanded to include grass pea and employs next-generation sequencing (NGS)-

based deep sequencing to identify rare induced mutations efficiently (Robson, 2014). Strengthening international collaboration will be crucial for the future genetic improvement of grasspea. Sharing genotyping information from core germplasm collections and integrating phenotypic data generated under diverse environmental conditions will improve the efficiency of genomic analyses and breeding programs. Such collaborative efforts are expected to accelerate the development of high-yielding, stress-tolerant, nutritionally improved and low-ODAP grass pea cultivars, thereby promoting the advancement of this underutilized but agriculturally important legume (Gurung and Pang, 2011).

Genome editing

Genome editing has emerged as a powerful approach for introducing precise and targeted modifications into plant genomes. This technology relies on engineered nucleases together with the cell's natural DNA repair mechanisms to generate specific alterations in DNA sequences, including nucleotide substitutions, insertions and deletions (Meng *et al.,* 2017; Ji *et al.,* 2019). Over the past decade, genome-editing technologies have been successfully implemented in a wide range of model plants, field crops and horticultural species, demonstrating their potential for accelerating crop improvement (Kim *et al.,* 2017; Lin *et al.,* 2020; Tripathi *et al.,* 2020). Among the available genome-editing platforms, the CRISPR/Cas9 system has become one of the most widely adopted because of its simplicity, efficiency and precision. It enables the creation of desirable genetic variations, expands the available gene pool and facilitates the rapid development of improved cultivars within shorter breeding cycles. In legume crops, CRISPR/Cas9 has been applied successfully to



modify several agronomically important traits, including flowering time (Dai *et al.,* 2020), node number (Bao *et al.,* 2019) and resistance to soybean mosaic virus in soybean (Zhang *et al.,* 2020). The technology has also been utilized to enhance biological nitrogen fixation in cowpea (Ji *et al.,* 2019) and improve drought tolerance in chickpea (Badhan *et al.,* 2021). In addition to improving agronomic performance, CRISPR/Cas9 has been employed to modify seed-quality characteristics by targeting genes associated with nutritional and anti-nutritional components using optimized transformation protocols (Li *et al.,* 2019; Wang *et al.,* 2020). Genome editing has been used to enhance the accumulation of sulfur-containing amino acids, such as methionine (Met) and cysteine, thereby improving seed nutritional quality (Warsame *et al.,* 2018). Since methionine metabolism is closely associated with β-N-oxalyl-L-α,β-diaminopropionic acid (β-ODAP) biosynthesis, increasing methionine levels may contribute to lowering β-ODAP accumulation in grass pea. Despite its considerable potential, the application of CRISPR/Cas9 in grass pea (*Lathyrus sativus* L.) remains challenging. The species exhibits poor susceptibility to foreign DNA uptake and stable integration, together with a low regeneration capacity, making genetic transformation difficult and limiting the practical use of genome-editing technologies. On going research aims to establish efficient CRISPR/Cas9-based protocols for grass pea improvement. Current efforts are focused on modifying genes and regulatory networks involved in β-ODAP biosynthesis, as well as enhancing resistance to biotic and abiotic stresses, with the ultimate objective of developing nutritionally superior and climate-resilient grass pea cultivars (Emmrich, 2017).

Figure 2. Integrative breeding and genomic approaches for development of low-ODAP grass pea cultivars. The figure depicts that exploitation of genetic resources can be achieved either through utilizing members of GP-I as well as CWR or unadapted gene pools through opting pre-breeding and distant hybridization strategy which will further lead to the discovery of candidate genes/ haplotype or QTLs. Simultaneously, conventional breeding strategy can be opted for development of different kinds of mapping populations for establishing marker-trait associations. Genomic resources can be deployed via NGS approach. Functional genomics and Genomic selection can also be utilized for unraveling the genetic mechanism of key biosynthetic pathways as well as estimation of breeding values for selection of superior cultivars. Different *in vitro* strategies can also be successful for detection of low-ODAP somaclonal variants. All these approaches ultimately lead to the development of stable low-ODAP cultivars with good agronomic base. CWR, Crop Wild Relatives; AB-QTL, Advanced Backcross QTL; GWAS, Genome Wide Association Study; TILLING, Targeting Induced Local Lesions in Genomes; QTL, Quantitative Trait Loci; NGS, Next Generation Sequencing.

Source: Cai *et al.,* 2020.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 05

The Humble Egg: A Small Food with a Big Story

Abstract

Eggs are a nutrient-dense and affordable source of high-quality animal protein. Egg provides 70-75 Kcal energy, 6-6.5 g protein, 4.57 g fat and 24.72 mg Calcium. The power of eggs lies in muscle building, tissue repairing, boosting immunity, improving brain and heart health. Value added products such as egg powder, egg pickle, egg sausage and liquid egg products, improve nutritional benefits, increase shelf life and diversify the utilization of eggs in food industry. Indigenous poultry birds under backyard poultry production promote income opportunities, nutritional security and sustainable production. They are more resistant to diseases, extreme climatic conditions like summer heat and cold winter stress and can thrive well under low input management system. Therefore, improved and high yielding chicken and duck germplasms need to be provided to the farmers for livelihood security and achieving nutritional security in our country.

Introduction

Eggs are an important part of the human diet because of their high nutritional value, versality, affordability and accessibility. World egg day, celebrated annually on second Friday of October month, provides opportunity to recognize the nutritional, economic and cultural importance of eggs. Global egg production has increased substantially over the past several decades, reflecting the growing demand for affordable, nutrient-dense animal source foods. According to the FAO, global egg production surged from 33.6 to 87.6 million tons during 1960 to 2020. India ranks 2nd in the world in terms of total egg production and the total egg production in the country is 149.11 billion in 2024-25. Egg production increased by 4.44% compared to the previous year. The per-capita availability of egg is 106 eggs per annum in India. The top five egg producing states are Andhra Pradesh, Tamil Nadu, Telangana, West Bengal and Karnataka and together they contribute 64.37% of India's total egg production.

Nutritional value of eggs

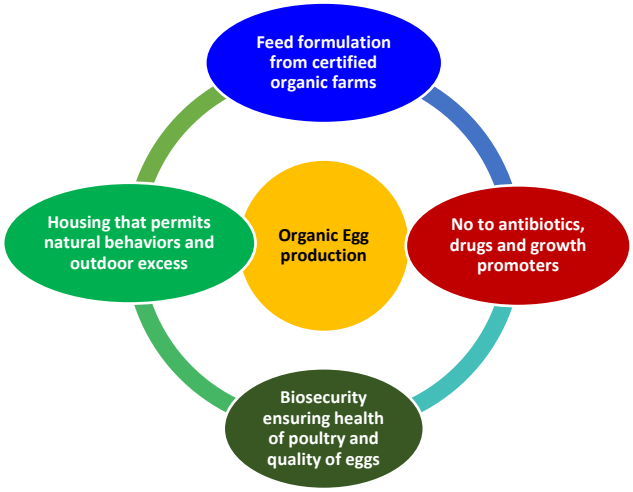
Poultry eggs are considered as rich source of high-quality proteins, essential fatty acids, vitamins and minerals. These nutrients contribute to several physiological functions, including growth and development, maintenance of tissues, immune function, vision and normal cellular activity. A single large egg provides 6-6.5 grams of high-quality protein, 4.57 g fat and energy of 70-75 kcal/egg depending on its size. Egg white (albumen) contributes approximately half of the egg's protein and is particularly rich in proteins such as ovalbumin, ovotransferrin and lysozyme. The egg yolk, in contrast, contains mostly fats, fat soluble vitamins and minerals. Egg protein contains all nine essential amino acids in proportions that support human nutritional requirements. It is therefore frequently used as a reference protein when evaluating the quality of other dietary proteins. Eggs are also sources of



Vitamins: A, D, E, K and several B-complex vitamins including riboflavin, folate and vitamin B12.

- Minerals: Iron, Calcium, Magnesium, Selenium, Sodium, Zinc and Phosphorous.
- Essential amino acids: Lysine and sulfur-containing amino acids such as methionine and cysteine.
- Lipids: Phospholipids and other biologically important fatty acids
- Bioactive compounds: Carotenoids such as lutein and zeaxanthin

Organic egg production



There is growing demand for organic eggs due to better taste, nutritional quality and production without chemical additives. Organic eggs come from chickens or ducks that are fed certified organic feed or organically grown feed. Birds must have access to outdoor areas. There is devoid of use of pesticides, growth promoters and antibiotics for healthy and safe egg production. However, the production of organic eggs is more expensive than conventional production systems because of the higher cost of organic feed, certification and management requirements.

The power of egg

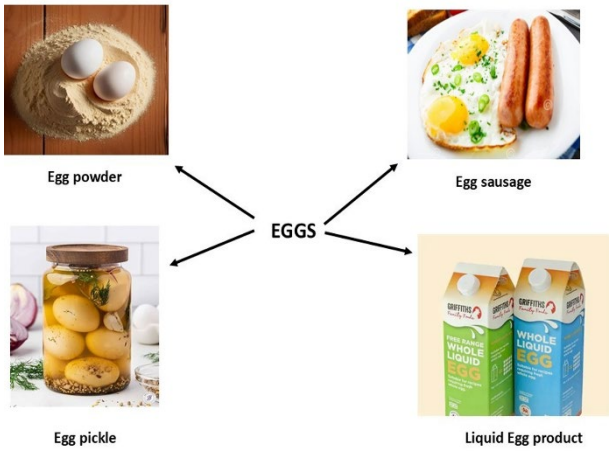
Eggs are powerhouse of nutrition, providing health benefits economically. Eggs increase good HDL cholesterol in body. As a rich source of protein, they keep you full for longer, helping in weight management. Properly cooked eggs are safe and are a good source of essential nutrients for immunity. Eggs have a low glycemic index and can be a part of a healthy diet for people with diabetes. Eggs also provide nutrients that contribute to immune function, muscle growth, tissue repair, brain and heart health. Eggs improve eyesight and make stronger bones and teeth.

Value added egg products

Value added egg products are processed foods prepared from fresh eggs to improve their shelf life, convenience, taste, marketability and economic value. Egg processing utilizes excellent functional properties of egg proteins, including emulsification, foaming, gelation and water binding capacity. Common value-added egg products are

- Egg powder: Egg powder is a dehydrated egg product prepared from whole egg, egg yolk or egg white.
- Liquid egg products: Fresh eggs are broken under hygienic conditions, followed by filtration and separation into yolk and albumen for pasteurization to reduce pathogen load.
- Frozen egg products: Liquid whole egg, yok, or egg white can be frozen to extend storage life while retaining much of the functional quality of egg.
- Egg sausage: Egg sausage is a processed product prepared from egg ingredients along with suitable seasonings and stabilizers, followed by shaping and thermal processing.
- Pickled eggs: Pickled eggs are prepared by immersing cooked eggs in an acidified brine containing vinegar, salt, and spices. The reduction in p^H, together with refrigeration

and hygienic handling, helps inhibit the growth of microorganisms and extend shelf life.



Duck eggs vis-à-vis chicken egg

Duck eggs generally contain more total nutrients per egg than chicken eggs because of large in size and higher yolk-to-white ratio. There is less chance of breakage due to thicker shell. Yolk is larger, deeper yellow/orange in colour and relatively rich in fat and nutrient dense. Albumen is more viscous and firm which makes it more useful in bakery products. Moreover, duck eggs provide more vitamin B12, vitamin D, iron, phosphorous, fat-soluble vitamins and antioxidants than chicken eggs. However, chicken eggs have more advantages in terms of greater commercial availability, consumer acceptance and production efficiency.

Awareness on eggs

The Government of India has undertaken various initiatives to create awareness and promote egg as the best source of animal protein. Awareness has been promoted through World Egg Day programmes, nutritional campaigns in school and community. Eggs and milk are introduced through Mid-Day Meal scheme in schools.

Concerns and challenges

Despite their high nutritional values, some issues need to be addressed through research and improved management practices.

- Antibiotic residue: Inappropriate or excessive use of antibiotics in poultry production may produce antibiotic residues in eggs, highlighting the need for less use of antibiotics or organic egg production.
- Chemicals and contaminants: Eggs may be exposed to environmental contaminants,

Best egg laying breeds in India

Sl No.	Name of Breed	Performance
1	White Leghorn	• It produces 280-320 eggs per year • Light body weight and low feed consumption
2	ISA Brown	• Hybrid breed with very high productivity • Produces more than 300 eggs per year • Early maturity and uniform production
3	Rhode Island Red	• Dual purpose breed • Produces 150-250 eggs per year • Highly adaptable to climatic conditions of India
4	Kadaknath	• Indigenous black chicken with medicinal value • Produces an average of 120-130 eggs per year
5	Vanaraja	• Developed for rural backyard farming • Produces 160-180 eggs per year
6	Gramapriya	• Produces more than 200 eggs per year • Disease resistant and hardy
7	Khaki Campbell	• Prolific duck breed for high egg production • Produces 280-300 eggs per year
8	Kuzi	• Improved indigenous duck population with high yielding • Produces 220 eggs per year

pesticides, heavy metals, requiring regular testing and improved production practices.

- Shelf life: Eggs are perishable and their quality can deteriorate during storage. Therefore, it demands research interventions to improve the shelf life.
- Egg allergy: Some children find egg as allergen.
- Cholesterol and dietary concerns

Conclusion

Eggs are considered as vegetarian food. Because of its easier availability, low price and balanced nutrition, it is a popular animal protein source than chicken and fish. In India, 86% eggs are produced from commercial layer, whereas 12.6% and 1% eggs are produced from indigenous chicken and ducks. Therefore, it necessitates to improve the backyard poultry and duck production in India. Moreover, biosecurity, hygiene, nutrition and health management at the farm level are essential for achieving optimum productivity and good quality eggs.

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Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 06

Crop Residue Management: A Key Strategy for Improving Soil Fertility and Reducing Air Pollution

Krishi Vigyan Kendra, Bhadradri Kothagudem (PJTAU),

Introduction

Crop residues are the leaves, stems, husks, stalks, roots and other plant materials left in the field after harvesting. In India, large quantities of residues are generated from **rice, wheat, maize, cotton, sunflower, pulses and sugarcane**. Traditionally, some farmers burn these residues to clear fields quickly for the next crop. Although burning is fast and inexpensive, it causes serious **air pollution, nutrient loss, soil degradation and greenhouse-gas emissions**. Instead of treating crop residues as waste, farmers can consider them a valuable **soil and farm resource**. Proper crop residue management through mulching, incorporation, composting, livestock feeding, biochar production and conversion into useful products can improve soil health while reducing pollution.

Why Crop Residue Burning Is a Problem

Open burning of crop residues releases smoke containing **particulate matter (PM2.5 and PM10), carbon monoxide and other pollutants**, which can deteriorate air quality. Large-scale residue burning can contribute to seasonal episodes of poor air quality, particularly when weather conditions trap pollutants near the ground. Burning also removes valuable nutrients from the farm. A considerable proportion of the nutrients contained in residues—particularly **nitrogen, phosphorus, potassium and sulphur**—can be lost through volatilization or remain in ash that is susceptible to removal. Repeated burning can therefore create a cycle in which farmers lose organic material from the soil and become increasingly dependent on external nutrient inputs.

Crop Residues: A Natural Source of Soil Fertility

Crop residues contain organic carbon and plant nutrients. When residues are retained or properly recycled, they gradually decompose and contribute to **soil organic matter**.

Major benefits include:

1. Increase in soil organic carbon

Returning residues to the soil adds carbon and organic matter. Higher soil organic matter improves soil structure, aggregation and biological activity.

2. Better nutrient cycling

Microorganisms decompose residues and gradually release nutrients that can be taken up by subsequent crops. Residue recycling can therefore complement mineral fertilizers.

3. Improved water-holding capacity

Organic matter acts like a sponge. Soils containing more organic matter can generally hold and supply more water to crops, which is particularly useful during periods of rainfall gaps.

4. Reduced soil erosion

Residue mulch protects the soil surface from the direct impact of raindrops and wind. This reduces detachment and movement of soil particles.

5. Improved soil structure

Residue decomposition contributes to aggregation, improving soil porosity and conditions for root growth.

6. Increased biological activity

Crop residues provide food for earthworms, fungi, bacteria and other soil organisms. A biologically active soil supports nutrient cycling and decomposition.

How Crop Residue Management Reduces Air Pollution

The simplest way to prevent pollution from residue burning is **not to burn the residue**. Instead, residues can be managed through several approaches:

1. In-situ residue incorporation

Crop residues can be chopped and incorporated into the soil using appropriate farm machinery. For example, after harvesting rice or maize, residues can be incorporated and allowed to decompose before the next crop.

2. Surface mulching

Residues can be retained on the soil surface as mulch. Mulching helps:

- Reduce evaporation
- Moderate soil temperature
- Suppress weeds
- Reduce erosion
- Increase infiltration
- Add organic matter over time

3. Zero-tillage and residue retention

Under conservation agriculture, crops can be established with minimum soil disturbance while residues remain on the soil surface. The combination of **minimum soil disturbance + residue retention + crop diversification** is particularly important for long-term soil health.

4. Composting

Crop residues can be mixed with animal dung and other biodegradable materials to produce compost. Compost returns organic matter and nutrients to agricultural fields and reduces the quantity of residues available for burning.

5. Livestock feed

Some residues, such as **maize stover, sorghum stover and certain pulse residues**, can be used as livestock feed after appropriate processing or treatment.

6. Biochar

Crop residues can be converted into biochar under controlled conditions and applied to soil. Biochar can contribute to long-term carbon storage and, depending on soil type and application conditions, improve certain soil properties.

7. Biomass and industrial utilization

Rice straw, cotton stalks, maize cobs and other residues can be utilized for products such as:

- Briquettes and pellets
- Bioenergy
- Paper and boards
- Mushroom cultivation
- Compost
- Biochar
- Biogas and other bio-based products

This converts agricultural waste into an economic resource.

Crop Residue Management in Major Crops

Crop	Important residues	Possible management
Rice	Straw, husk	Mulching, incorporation, composting, biomass utilization
Wheat	Straw	Mulching, incorporation, livestock feed
Maize	Stalks, leaves, cobs	Mulching, livestock feed, composting, bioenergy
Cotton	Stalks, leaves	Shredding, composting, biomass utilization
Sunflower	Stalks, heads	Chopping, composting, incorporation
Pulses	Straw and pods	Incorporation, livestock feed, compost
Sugarcane	Trash/leaves	Trash mulching, composting, bioenergy

Case Study 1: Rice Residue Management in the Indo-Gangetic Plains

Rice–wheat farmers in northwestern India have historically faced difficulties managing large quantities of rice straw between the rice and wheat seasons. Short turnaround time between harvesting rice and sowing wheat has encouraged some farmers to burn residues. The development and adoption of technologies such as **Happy Seeders, Super Seeders, straw choppers and other residue-management machinery** has provided alternatives.

Residue retention can provide soil-cover benefits, reduce erosion and contribute organic material to the soil. At the same time, avoiding burning reduces smoke and particulate emissions. This experience demonstrates that **appropriate machinery, timely operations, farmer training and access to custom-hiring services** are essential for large-scale residue management.

Case Study 2: Maize Residue Management

Maize produces substantial quantities of stalks, leaves and cobs. In many areas, these residues are burned or removed after harvest. An alternative is to **chop maize residues and retain them as surface mulch or incorporate them into the soil**.

For example, maize residues retained under conservation agriculture can:

- Protect the soil from erosion
- Reduce evaporation
- Increase organic matter
- Improve soil aggregation
- Provide habitat and food for soil organisms

In rainfed areas, residue mulch is particularly valuable because conserving soil moisture can help crops withstand short dry periods.

Case Study 3: Cotton Residue Management in Telangana

Cotton cultivation generates substantial stalk and plant residues after harvest. Farmers sometimes remove or burn cotton residues to prepare fields for the following crop. Instead, cotton stalks can be **chopped and incorporated or composted**, depending on the cropping system and pest-management requirements.

A practical approach is:

Cotton harvest → collection/removal of diseased material → shredding/chopping → incorporation or composting → decomposition → next crop

Proper residue management should also be combined with **field sanitation and integrated pest management**, particularly where residues could harbour pests or disease-causing organisms.

Crop Residues and Soil Carbon

One of the most important long-term benefits of residue recycling is its contribution to **soil organic carbon**. When crop residues are continuously removed or burned, less carbon is returned to the soil.

Crop residue → decomposition → soil organic matter → improved soil structure → better water and nutrient management

Increasing soil organic matter is therefore an important component of **climate-resilient agriculture**.

Crop Residue Management and Water Conservation

Residue mulch can significantly influence the soil-water relationship. A layer of residue on the soil surface can reduce direct exposure of soil to sunlight and wind, thereby reducing evaporation. It also protects the soil surface during intense rainfall.

Residue retention → less evaporation + improved infiltration + reduced runoff → better soil moisture availability

This is especially relevant to **rainfed agriculture and drought-prone regions of Telangana**.

Crop Residue Management and Fertilizer Efficiency

Crop residues should not be viewed as a complete replacement for fertilizers. Rather, they are an important component of **integrated nutrient management**.

Combining:

Crop residues + farmyard manure/compost + biofertilizers + balanced fertilizers

can improve nutrient cycling and soil health. Farmers should also understand the **carbon-to-nitrogen ratio** of residues. Materials with high carbon content, such

as mature straw, may temporarily immobilize available nitrogen during decomposition. Proper management, adequate soil moisture and balanced nutrient application can help overcome this issue.

Role of Farmers, KVKs and Farmer Groups

Crop residue management cannot be successful through individual action alone. **Krishi Vigyan Kendras (KVKs), agricultural universities, farmer producer organizations, custom-hiring centres and local farmer groups** can play an important role.

KVKs can organize:

- Frontline demonstrations
- Method demonstrations
- Training programmes
- Machinery demonstrations
- Composting demonstrations
- Village-level awareness programmes
- Soil-health monitoring
- Farmer field days

Custom-hiring centres can make expensive residue-management machinery accessible to small and marginal farmers.

From Waste to Wealth

Crop residue management can also create rural employment and additional income.

Residue → Burning → Smoke → Pollution

Residue → Collection → Processing → Compost/Mulch/Feed/Bioenergy → Soil fertility + Income + Clean air

This approach supports the concept of a **circular agricultural economy**, where agricultural by-products are returned to the production system rather than treated as waste.

Conclusion

Crop residues are not merely agricultural waste; they are an important **natural resource for maintaining soil fertility, conserving water and protecting the environment**. The continued burning of residues results in the loss of valuable biomass and contributes to air pollution. In contrast, residue retention, mulching, incorporation, composting, livestock utilization and biomass conversion can recycle nutrients and carbon back into the agricultural system. The future of sustainable agriculture should therefore move from **"burning residues" to "recycling residues."**

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 07

Beyond Protein: Why Pulses Are the Future of Sustainable Agriculture

Abstract

Modern agriculture is confronted with multiple and interconnected challenges, including declining soil fertility, climate change, shrinking water resources, rising production costs, and the growing demand for nutritious food. Addressing these challenges requires crop-based solutions that simultaneously enhance agricultural productivity, environmental sustainability, and human nutrition. Among such crops, "pulses" hold a unique place. Beyond being an affordable source of high-quality plant protein, they naturally enrich soils through biological nitrogen fixation, improve soil organic matter and microbial activity, reduce dependence on synthetic fertilizers, and strengthen the resilience of farming systems. Their ability to perform well under rainfed and resource-limited conditions makes them an essential component of climate-smart and sustainable agriculture.

India, the world's largest producer and consumer of pulses, has made remarkable progress in increasing domestic production and moving towards self-reliance. Recognizing their strategic importance, the Government of India and NITI Aayog have placed pulses at the heart of efforts to achieve nutritional security, sustainable agriculture, higher farmer incomes, and the vision of Atmanirbhar Bharat. Today, pulses are no longer viewed merely as food crops; they are increasingly recognized as strategic crops that support healthy soils, resilient farming systems, rural livelihoods, and long-term agricultural sustainability. This article highlights the diverse role of pulses in improving nutrition, restoring soil health, enhancing climate resilience, and building a sustainable and self-reliant agricultural future.

Introduction

Agriculture today stands at a critical crossroads. Feeding a growing global population while conserving natural resources has become one of the greatest challenges of the 21st century. Climate change, declining soil fertility, water scarcity, rising input costs, small and marginal landholdings, and the need to produce more nutritious food are placing unprecedented pressure on agricultural systems. The search is no longer simply for crops that produce higher yields, but for crops that can simultaneously improve soil health, strengthen climate resilience, enhance human nutrition, and sustain farmers' livelihoods. In this changing agricultural landscape, pulses have emerged as one of nature's most powerful yet underappreciated solutions (FAO, 2025)

Pulses such as chickpea, pigeonpea, greengram, blackgram, lentil, field pea, and cowpea, have nourished civilizations for thousands of years. Traditionally valued as affordable sources of plant-based protein, these crops are now increasingly recognized for the wide range of ecosystem services they provide. Through their symbiotic association with Rhizobium bacteria, pulses naturally fix atmospheric nitrogen, improve soil fertility, enhance soil microbial diversity, increase soil organic matter, reduce dependence on synthetic fertilizers, and contribute to more resilient and sustainable farming systems

Their ability to thrive under rainfed and resource-constrained conditions further makes them indispensable for climate-smart agriculture, particularly in semi-arid and dryland regions (FAO, 2024).

India occupies a unique position in the global pulses sector. The country is the world's largest producer, consumer, and cultivator of pulses, accounting for approximately 38% of the global pulse-growing area, 28% of global production, and 27% of global consumption. After a decline in production to 16.35 million tonnes in 2015–16, coordinated policy interventions, technological advancements, and improved crop management helped increase production to 26.06 million tonnes by 2022–23, substantially reducing import dependence. Building on this progress, the Government of India has launched the Mission for *Aatmanirbharta* in Pulses (2025–26 to 2030–31), aiming to strengthen domestic production, improve productivity, and achieve long-term self-sufficiency in pulses. These initiatives underscore the strategic importance of pulses not only for food and nutritional security but also for the broader vision of Atmanirbhar Bharat (NITI Aayog. 2025).

The significance of pulses extends far beyond the farm. They contribute to healthier diets, restore degraded soils, conserve water, support biodiversity, reduce greenhouse gas emissions associated with fertilizer use, and provide stable incomes for millions of smallholder farmers. As the world moves toward more sustainable, regenerative, and climate-resilient agricultural systems, pulses are no longer viewed merely as traditional food crops. They are increasingly recognized as strategic crops capable of addressing some of the most pressing challenges facing agriculture, nutrition, and environmental sustainability.

More Than a Source of Protein: A Nutritional Powerhouse

Pulses are often called the "poor man's protein," but modern nutritional science shows they are far more than that. They are nutrient-dense foods that provide high-quality plant protein, complex carbohydrates, dietary fibre, essential vitamins, minerals, and several health-promoting bioactive compounds. With a protein content ranging from 18–28%, pulses contain nearly two to three times more protein than most cereals, making them indispensable for improving dietary quality, particularly in predominantly vegetarian populations (FAO, 2016).

Unlike cereals, pulses are rich in lysine, an essential amino acid, while cereals provide methionine. Together, they form a complementary protein, scientifically validating traditional Indian diets such as rice with dal and millets with pulses. In addition, pulses are excellent sources of iron, zinc, magnesium, potassium, folate, and B-complex vitamins, helping combat protein deficiency, anaemia, and micronutrient malnutrition.

Beyond nutrition, pulses contribute significantly to preventive healthcare. Their high dietary fibre, resistant starch, and low glycaemic index (GI) promote gut health, improve blood sugar regulation, lower cholesterol, and reduce the risk of obesity, type 2 diabetes, and cardiovascular diseases. Regular pulse consumption is therefore associated with healthier diets and improved long-term health outcomes.

As the demand for nutritious and environmentally sustainable foods continues to grow, pulses have emerged as one of the most sustainable sources of plant-based protein. Recognizing their dual role in human nutrition and sustainable food systems, the Food and Agriculture Organization (FAO) has identified pulses as key crops for achieving global food and nutritional security.

Nature's Soil Fertility Managers

Healthy soils are the foundation of sustainable agriculture, and pulses are among nature's most effective soil improvers. Unlike non-leguminous crops, pulses establish a symbiotic association with *Rhizobium* bacteria in their root nodules, which convert atmospheric nitrogen into plant-available forms through **biological nitrogen fixation (BNF)**. This natural process reduces the dependence on synthetic nitrogen fertilizers while improving soil fertility **(Herridge et al., 2008; Peoples et al., 2009).**

Depending on the crop species, growing conditions, and management practices, pulses can fix **30–200 kg nitrogen ha^{-1}**, with a substantial proportion benefiting

subsequent crops through residual nitrogen and improved nutrient availability **(Herridge et al., 2008; Peoples et al., 2009).**

The benefits of pulses extend well beyond nitrogen fixation. Their root systems stimulate beneficial soil microorganisms, improve nutrient cycling, and enhance soil structure, porosity, and water infiltration. Crop residues further contribute organic matter, supporting long-term soil fertility and biological activity **(FAO, 2016; Peoples et al., 2009).**

An additional advantage of pulses is their **rotational effect**. Cereal crops grown after pulses often produce higher yields due to improved soil fertility and better soil health. Studies have shown that cereals following pulses can yield **up to 1.5 t ha^{-1} more**, an effect comparable to applying about **100 kg nitrogen fertilizer per hectare (FAO, 2016).**

By naturally enriching soils, reducing fertilizer requirements, and improving the productivity of subsequent crops, pulses have become indispensable components of **sustainable, regenerative, and climate-smart agricultural systems (FAO, 2025).**

Building Healthy Soils Beyond Nitrogen Fixation

Healthy soils are essential for sustaining agricultural productivity, and pulses contribute to soil health in multiple ways beyond biological nitrogen fixation. Their extensive root systems improve **soil structure, porosity, and aggregation**, allowing better root penetration, aeration, and water infiltration **(FAO, 2016; Lal, 2015).**

Pulse crop residues and root biomass enrich the soil with **organic matter**, which enhances soil organic carbon (SOC), improves nutrient cycling, and supports diverse microbial communities. Increased soil organic matter also improves the soil's water-holding capacity, making crops more resilient to short-term droughts, particularly in rainfed farming systems **(Lal, 2015; FAO, 2024).**

Pulses also stimulate beneficial soil microorganisms, including bacteria, fungi, and earthworms, creating a biologically active soil ecosystem. These organisms accelerate the decomposition of organic residues, improve nutrient availability, and contribute to long-term soil fertility and ecosystem stability **(FAO, 2016; ICAR-IIPR, 2023).**

Instead of burning crop residues, incorporating pulse residues into the soil through mulching or composting recycles valuable nutrients, increases soil organic carbon, and reduces greenhouse gas emissions. Such practices are increasingly promoted under **regenerative and conservation agriculture** as effective strategies for restoring degraded soils and improving long-term productivity **(FAO, 2024; Lal, 2015).**

By improving the **physical, chemical, and biological properties of soil**, pulses help build resilient farming systems that require fewer external inputs while maintaining productivity, making them indispensable for sustainable agriculture **(FAO, 2016).**

Pulses and Climate Resilience: Farming in a Changing Climate

Climate change is increasingly threatening agricultural productivity through rising temperatures, erratic rainfall, prolonged droughts, and frequent extreme weather events. Developing farming systems that can withstand these challenges has become a global priority, and pulses have emerged as one of the most resilient crops for climate-smart agriculture **(IPCC, 2023; FAO, 2024).**

Nearly **80% of India's pulse-growing area is rainfed**, highlighting their natural adaptation to moisture-limited environments **(NITI Aayog, 2025).** Compared to many cereal crops, pulses generally require less water and fewer external inputs, making them well suited to regions facing water scarcity and increasing climate variability **(FAO, 2016).**

Pulses also contribute to **climate change mitigation**. By fixing atmospheric nitrogen biologically, they reduce the need for synthetic nitrogen fertilizers, whose production and application are major sources of greenhouse gas emissions. Their inclusion in crop rotations further improves soil health and promotes carbon storage, supporting climate-resilient and low-carbon agricultural systems **(Herridge et al., 2008; Lal, 2015).**

Integrating pulses into cropping systems through intercropping, crop rotation, and diversification enhances farm resilience by reducing production risks, improving resource-use efficiency, and stabilizing yields under variable climatic conditions **(FAO, 2024;**

ICRISAT, 2023). As climate uncertainty continues to intensify, pulses are no longer simply alternative crops—they are becoming **essential crops for building resilient and sustainable farming systems**.

Pulses: Driving Atmanirbhar Bharat

Pulses are no longer viewed merely as food crops—they have become **strategic crops** for strengthening India's food, nutritional, and economic security. As the **world's largest producer, consumer, and cultivator of pulses**, India plays a pivotal role in the global pulse sector, accounting for nearly **28% of global production, 27% of global consumption, and about 38% of the global pulse-growing area (NITI Aayog, 2025).**

Although India has made remarkable progress in increasing pulse production—from **16.35 million tonnes in 2015–16 to 26.06 million tonnes in 2022–23**—the country has continued to import selected pulses to bridge the domestic demand–supply gap **(NITI Aayog, 2025).** Recognizing this challenge, the Government of India launched the **Mission for Aatmanirbharta in Pulses (2025–26 to 2030–31)** to enhance productivity, improve seed systems, strengthen procurement, and reduce import dependence **(Government of India, 2025).**

Achieving self-sufficiency in pulses goes beyond reducing imports. It strengthens **nutritional security**, enhances **farmer incomes**, conserves valuable **foreign exchange**, and builds a more resilient food system capable of meeting the needs of a growing population. Expanding pulse cultivation, improving productivity, and promoting value addition through Farmer Producer Organizations (FPOs), processing industries, market linkages can generate employment and increase rural incomes **(NITI Aayog, 2025).** On the other hand investing in pulse research, quality seed production, climate-resilient varieties, and efficient value chains will not only improve agricultural sustainability but also ensure long-term food and nutritional security for future generations **(NITI Aayog, 2025; PMO, Government of India, 2025).**

The Way Forward: Unlocking the Full Potential of Pulses

Despite their immense contribution to nutrition, soil health, and environmental sustainability, the productivity of pulses in India remains lower than the global potential. Bridging this gap requires a combination of **scientific innovation, farmer-centric policies, improved production technologies, and stronger market support (NITI Aayog, 2025; ICAR-IIPR, 2023).**on the otherhand, improving access to **high-yielding, climate-resilient, and biofortified pulse varieties**, along with quality seed systems, timely availability of inputs, and adoption of improved agronomic practices, can substantially enhance productivity and farm profitability **(ICAR-IIPR, 2023).**

Equally important is strengthening the **pulse value chain** through Farmer Producer Organizations (FPOs), improved storage, processing, branding, and market linkages. Value addition not only reduces post-harvest losses but also creates rural employment, improves farmers' income, and enhances the competitiveness of Indian pulses in domestic and international markets **(NITI Aayog, 2025).**

Consumer awareness also plays a crucial role. Promoting regular pulse consumption through nutrition campaigns, school feeding programmes, and public distribution initiatives can improve dietary diversity while creating sustained demand for pulse production **(FAO, 2024).**

Therefore to witness increase pulse production, we requires coordinated efforts from **research institutions, extension agencies, policymakers, private enterprises, FPOs, and farmers**. By integrating science, policy, and market opportunities, pulses can become a cornerstone of sustainable agriculture, nutritional security, climate resilience, and rural prosperity in India **(NITI Aayog, 2025; FAO, 2024).**

The urgency to strengthen pulse production has never been greater. Increasing climate variability, characterized by delayed monsoons, erratic rainfall, prolonged dry spells, heat waves, and recurring **El Nino** events, has exposed the vulnerability of conventional cropping systems. In such situations, pulses serve as reliable **climate-smart alternatives** and are increasingly recommended in contingency crop planning because of their short duration, lower water requirement, and adaptability to rainfed

conditions. Promoting pulse-based cropping systems and integrating them into climate adaptation strategies will not only help farmers reduce production risks but also strengthen India's resilience to future climatic uncertainties **(ICAR–CRIDA, 2023; IPCC, 2023; FAO, 2024).**

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 08

Novel Traits: A New Direction in Dairy Cattle Breeding

Abstract

Dairy cattle breeding has traditionally placed strong emphasis on milk yield. Although this approach has greatly increased production, selection mainly for milk yield can be associated with poorer fertility, greater mastitis risk, lameness, metabolic problems and shorter herd life. Modern breeding therefore gives greater importance to functional and novel traits that support animal health, welfare, efficiency and longevity. Novel traits include direct health traits, feed efficiency, methane emission, hoof and claw health, behaviour and climate adaptation. Their recording has become easier through mid-infrared spectroscopy, sensors, biomarkers and pooled databases. Genomic selection, genome-wide association studies (GWAS) and total merit indices can then use these records to select animals for a balanced combination of production and functional performance.

Introduction

For many years, a good dairy cow was judged mainly by the amount of milk she produced. This focus increased milk production, but breeding decisions based mainly on production can create unfavourable relationships with fertility, udder health and longevity. A productive cow is more valuable when she can remain healthy, fertile and productive for a longer period. Because of this, breeding organizations have moved beyond milk yield alone and now consider functional and novel traits. Functional traits reduce the cost of maintaining a healthy and productive animal. Novel traits are traits that have always been biologically important but were difficult to measure on a large scale until recent advances in phenotyping and genomic technologies.

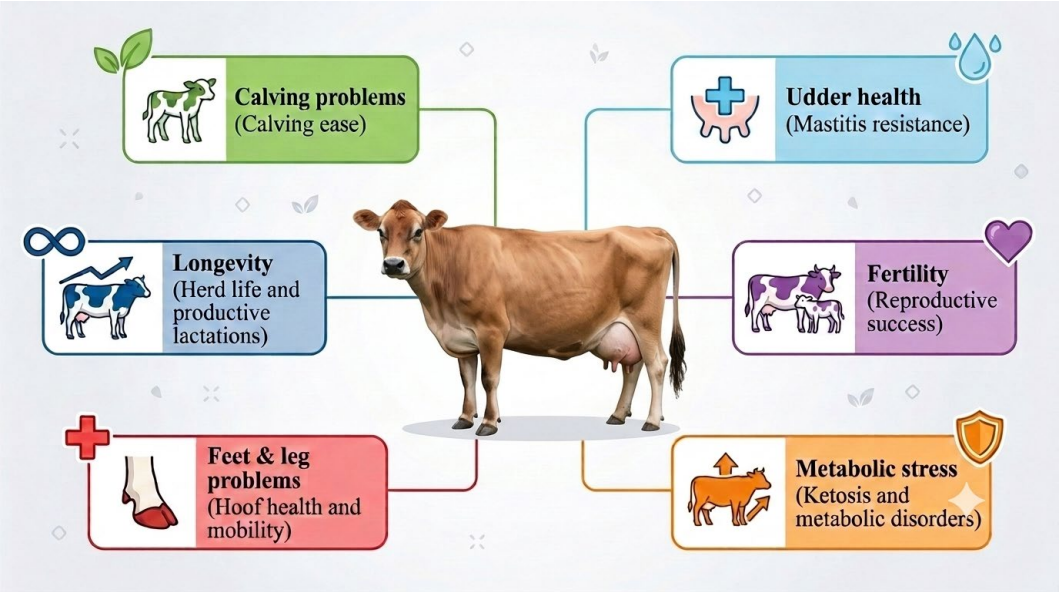


Figure 1. Classification of functional traits in dairy cattle (ICAR, 2019).

Functional Traits and Novel Traits

Functional traits do not directly increase milk output. Instead, they help maintain health, reproduction and productive life. For example, a cow that calves easily, resists mastitis and remains in the herd for six lactations rather than three can be more valuable because she requires fewer replacement and health-related costs. ICAR (2019) groups functional traits into six broad categories: calving problems, udder health, fertility, metabolic stress, feet and leg problems, and longevity.

Novel traits include direct health traits such as mastitis, reproductive and metabolic disorders and calving ease; feed efficiency; methane emission; milk components; hoof and claw health; cow behaviour; and climate adaptation. Their measurement has become more practical because of improved phenotyping systems, genomic tools and increasing attention to animal welfare and environmental sustainability.

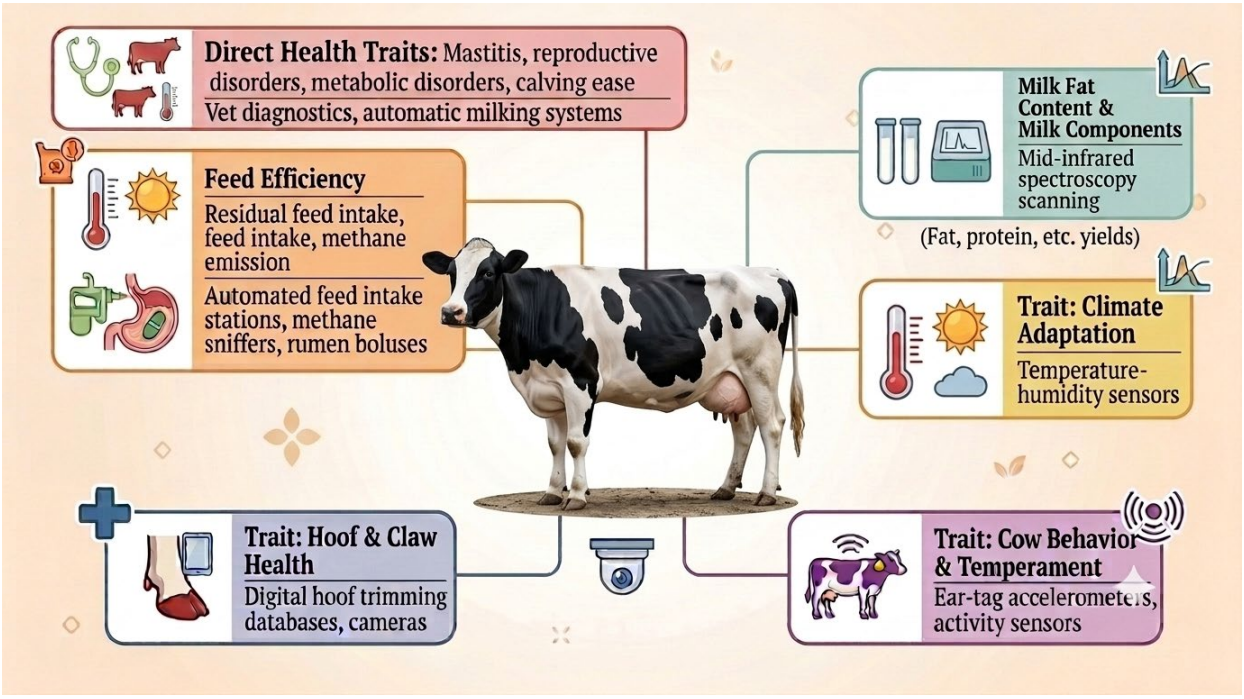


Figure 2. Examples of novel traits and their phenotyping approaches in dairy cattle.

Genetic Basis of Novel Traits

Most novel traits have low heritability, meaning that environmental and management effects account for a large part of the observed differences between animals. Reported heritability estimates in the article include 0.02–0.09 for clinical mastitis, 0.02–0.04 for lameness and 0.01–0.16 for ketosis. Low heritability does not mean that genetic improvement is impossible; it means that accurate phenotypes and sufficiently large datasets are important.

Genetic correlations are also important. Somatic cell count, which can be measured in milk, is strongly associated with mastitis and can therefore support indirect selection for udder health. Fertility and milk yield can show an unfavourable genetic relationship, whereas health, fertility and longevity can be improved together when breeding programmes use a balanced selection objective.

How Novel Traits Are Recorded?

Accurate recording is the foundation for genetic evaluation of novel traits. Several approaches can be combined:

- **Mid-infrared spectroscopy:** Milk samples can be scanned during routine milk testing. The information can support prediction of milk components, energy balance, ketosis risk, milk properties and indicators related to methane output.

- **Sensors and wearables:** Pedometers, ear-tag sensors and other devices can continuously record activity, oestrus, lameness and rumination. Rumen boluses can monitor pH and temperature, while cameras can assess movement and other animal characteristics.
- **Laboratory and biomarker testing:** Measurements such as progesterone, cortisol, NEFA and BHBA can provide useful information on reproductive and metabolic status, although laboratory testing can be expensive for routine use.
- **Pooled records:** Records from veterinarians, hoof trimmers, slaughterhouses and automatic milking systems can add valuable information and increase the number of phenotypic observations available for genetic evaluation.

Using Novel Traits in Selection

Modern breeding programmes combine phenotypic information with genomic information so that animals can be selected earlier and for more than one trait.

- **Genomic selection:** A reference population with genotypes and accurately recorded phenotypes is used to establish relationships between DNA markers and breeding values. Genotypes of young calves can then be used to estimate their genetic merit for novel traits, reducing the need to wait until they become adults and produce daughters.
- **GWAS:** Genome-wide association studies search for genomic regions associated with traits. The article identifies CARD11 and EIF3B in relation to feed efficiency, SLC18A2 in relation to temperament, and CYP19A1 in relation to oestrus behaviour.
- **Total merit indices:** A total merit index combines production, health, fertility, longevity and other economically important traits into one overall breeding objective. Examples described in the article include Germany's RZG/RZRobot, Australia's APR and the USA's NM$/TPI approaches.

Challenges in Recording Novel Traits

- **Observer variation:** Traits such as temperament and body condition can be affected by differences between observers.
- **Large datasets are required:** Some disorders are relatively uncommon, so many animals and records are needed to obtain reliable genetic information.
- **Cost of phenotyping:** Detailed feed-intake measurement, hormone assays and some disease-related tests can be expensive and are therefore more common in research herds.
- **Farmer and stakeholder participation:** Reliable information from farmers, veterinarians, hoof trimmers and other stakeholders is essential for maintaining large, high-quality databases.

Conclusion

The future of dairy cattle breeding is not simply about producing more milk. The aim is to breed cows that are productive, healthy, fertile, efficient and long-lived. Novel traits provide an opportunity to include these characteristics in breeding programmes. Mid-infrared spectroscopy, sensors, biomarkers, genomic selection, GWAS and total merit indices are making large-scale recording and selection increasingly practical. Continued participation of farmers and other stakeholders, together with accurate and standardised phenotyping, will be essential for successful genetic improvement.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 09

Beyond Crops: Building Better Livelihoods

Agriculture has always been the backbone of rural livelihoods, providing food, employment, income and raw materials for millions of farm families. However, farming is facing several challenges, including changing climate, irregular rainfall, rising input costs, declining profitability of some traditional crops, labour shortages, pest and disease problems and fluctuating market prices. In such a situation, depending entirely on a single crop or enterprise can increase the vulnerability of farm households. This has created a need to look beyond crops and develop diversified farming-based livelihood systems in which different farm enterprises complement each other and contribute to household income, food security and employment.

From Crop Production to Livelihood Diversification

A farming-based livelihood system is a combination of agricultural and allied activities undertaken by a farm family to meet its food, income and employment requirements. Crop production remains the foundation, but it can be supported by dairy, poultry, goat and sheep rearing, fisheries, horticulture, beekeeping, mushroom cultivation, agroforestry and other suitable enterprises. The choice of enterprises should depend on the availability of land, water, labour, capital, technical knowledge and market opportunities. Instead of depending on a single source of income, the farm family can develop several complementary sources of income.

Why Move Beyond Crops?

The major advantage of diversification is the possibility of spreading production and income across different enterprises and seasons. Crop income is often concentrated around harvesting periods, whereas dairy can provide relatively regular returns from milk sales. Vegetables may provide income within a shorter production cycle, while poultry and small ruminants can provide additional sources of earnings. Fruit trees and agroforestry may provide longer-term returns.

This does not mean that every farmer should adopt every possible enterprise. Instead, farmers should select enterprises that are technically feasible, economically suitable and compatible with their available resources. A small farmer with limited water may choose dairy, poultry, vegetables or goats rather than a water-intensive enterprise. A farmer with a suitable pond may consider fisheries. Thus, farm diversification should be location-specific and resource-based.

Integration: Making Every Farm Resource Count

One of the most important principles of a farming-based livelihood system is resource recycling. In an integrated system, the waste or by-product from one enterprise can become a useful input for another.

For example:

Crop residues → Livestock feed

Livestock manure → Compost/organic nutrient source
Farm pond → Fish production + suitable irrigation use
Vegetable residues → Livestock feed/compost
Poultry litter → Nutrient source after proper management

This circular flow reduces unnecessary wastage and improves the utilization of farm resources. It can also reduce the need for some external inputs, depending on the farming system and management practices.

The basic principle can be represented as:

Crops → Residues → Livestock → Manure → Soil fertility → Crops

This simple cycle demonstrates how different enterprises can support one another.

Crop Diversification: The First Step

Crop diversification is one of the simplest ways of moving beyond dependence on a single crop. Instead of growing only one crop repeatedly, farmers can include cereals, pulses, oilseeds, vegetables, fruits, fodder crops and other locally suitable crops. Including legumes in cropping systems can contribute to biological nitrogen fixation, while crop rotation can help break pest and disease cycles and improve the utilization of soil resources. Horticultural crops can provide high-value production opportunities, while fodder crops can support livestock enterprises. A diversified cropping system can therefore provide food, fodder, fibre, income and ecological benefits from the same farm.

Livestock: A Valuable Partner to Crop Farming

Livestock plays an important role in rural livelihoods. Dairy animals provide milk, while cattle and other livestock produce manure that can be incorporated into nutrient-management systems. Crop residues such as straw, stover and other suitable residues can provide feed resources. Small ruminants such as goats and sheep can also be integrated with crop production where suitable feed resources, housing and markets are available. Poultry provides another complementary enterprise through egg and meat production. Thus, livestock can contribute not only to income but also to **nutrient recycling and farm-level resource integration**.

Horticulture: Adding Value to the Farm

Horticultural crops such as fruits, vegetables, flowers and spices can provide opportunities for diversification. Vegetables with short production cycles can complement seasonal field crops, while fruit crops can provide longer-term returns.

However, horticultural production also requires careful attention to quality planting material, irrigation, pest management, harvesting, storage and marketing. Without proper market planning, higher production does not necessarily translate into higher profits.

Fisheries and Farm Ponds

Where water resources permit, farm ponds can become an important component of diversified farming systems. Fisheries can provide an additional farm enterprise while the pond itself can contribute to water management.

An integrated model may combine:

Fish + vegetables + livestock + crops

The feasibility of such a system depends on water availability, pond design, fish species, management skills, investment and local market demand.

Beekeeping and Pollination

Beekeeping is another enterprise that can be integrated with agriculture, particularly where flowering crops, horticultural crops or other suitable floral resources are available. Honey and beeswax provide products for sale, while bees contribute to pollination of many crops.

Thus, beekeeping represents an example of an enterprise that can provide both direct economic output and ecosystem services.

Mushroom Cultivation: Enterprise with Limited Land Requirement

Mushroom cultivation can provide an additional livelihood activity where suitable temperature, humidity, substrate materials, technical knowledge and markets are available. Agricultural residues can be used as growing substrates depending on the mushroom species and production method. Mushroom production is particularly interesting for livelihood diversification because it can be undertaken in a relatively small space. However, successful production requires good hygiene, appropriate environmental management and reliable market

access.

Agroforestry: Combining Trees and Agriculture

Agroforestry combines trees with crops and/or livestock on the same land-management unit. Trees can provide fruits, fodder, fuelwood, timber and other products, while also contributing to soil conservation and environmental benefits. A well-planned agroforestry system can provide short-, medium- and long-term products, helping farmers diversify their production base. Species selection should be based on local climate, soil, water availability, farm objectives and market demand.

From Farm Produce to Farm Enterprise

A major opportunity lies in transforming farmers from producers of raw commodities into participants in value addition and agribusiness.

Consider the difference:

Milk → Curd → Paneer → Packaged product

Tomato → Pulp → Sauce → Packaged product

Mango → Pulp → Juice/Pickle → Marketable product

Millet → Flour → Ready-to-cook product

Honey → Processing → Grading → Packaging → Branded product

Value addition can create employment and additional business opportunities, but its success depends on processing costs, product quality, food safety, packaging, consumer demand and market access.

Women and Youth in Farm-Based Livelihoods

A diversified farming system can provide opportunities beyond traditional field operations. Women can participate in dairy, poultry, vegetable cultivation, mushroom production, food processing, value addition and marketing. Young people can participate in farm mechanization, digital agriculture, nursery production, processing, logistics, agri-tourism and other agricultural enterprises. This changes the perception of agriculture from simply being a traditional occupation to becoming a field for entrepreneurship, innovation and rural business development.

Connecting Farmers with Markets

Production alone cannot ensure a successful livelihood. A farmer may produce a good-quality commodity but still face difficulties if there is no suitable market, storage facility or processing opportunity.

The livelihood chain can therefore be visualized as:

Farmer → Production → Aggregation → Grading → Processing → Packaging → Marketing → Consumer

Farmer Producer Organisations (FPOs), cooperatives, self-help groups and other collective approaches can help farmers improve aggregation, input access, processing and market connections where effectively organized.

Climate Change and Livelihood Resilience

Climate variability is increasing the uncertainty associated with agricultural production. Drought, excessive rainfall, heat stress, changing pest and disease patterns and other climate-related stresses can affect farm income. Diversification can help distribute exposure across different enterprises. For instance, if a particular crop experiences production problems, income from livestock, poultry, vegetables or other enterprises may continue. However, diversification itself involves costs and risks, so farmers need to select enterprises carefully and consider their water, labour, capital and market conditions.

The broader objective should therefore be:

Climate-resilient crops + Efficient water use + Livestock + Horticulture + Allied enterprises + Better markets

Challenges in Building Diversified Livelihoods

Although diversification offers opportunities, it is not free from challenges. Farmers may face:

- High initial investment
- Lack of technical knowledge
- Shortage of skilled labour
- Difficulty in accessing quality inputs
- Animal and crop diseases
- Storage and processing limitations
- Market price fluctuations
- Lack of cold-chain facilities
- Limited access to institutional credit
- Difficulty in managing multiple enterprises simultaneously

Therefore, diversification should be planned rather than simply adding more enterprises.

Conclusion

Beyond Crops represents a broader way of looking at agriculture. A successful farm is not necessarily one that grows the largest number of crops, but one that makes efficient and sustainable use of its available resources while creating diverse opportunities for the farm family. By integrating crops with livestock, horticulture, fisheries, agroforestry and other suitable enterprises, farmers can build a more diversified production system. When this is combined with value addition, entrepreneurship, collective marketing and appropriate technologies, farming can become more than a means of crop production—it can become a foundation for sustainable rural livelihoods and farm-family prosperity.

JUST AGRICULTURE®
THE FUTURE OF AGRI INNOVATION

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 10

FARMER PRODUCER ORGANIZATIONS (FPOS): EMPOWERING INDIAN FARMERS THROUGH COLLECTIVE ACTION

Indian agriculture is powered largely by small and marginal farmers, but their small landholdings, limited marketable surplus, weak bargaining power, high input costs, and dependence on intermediaries often reduce farm profitability. NABARD notes that small and marginal farmers constitute around 85% of total landholdings and face constraints such as inadequate extension services, limited capital, poor business skills, low market efficiency, and weak access to quality inputs, credit, technology, and assured markets. Farmer Producer Organizations, popularly known as FPOs, have emerged as one of India's most important institutional innovations to help farmers overcome these disadvantages through collective action.

An FPO is a collective of farmer-producers, owned, managed, and governed by farmers themselves, and registered as a legal entity under the Companies Act, Cooperative Societies Act, or other permitted laws. The basic idea is simple but powerful: when farmers come together, they can buy inputs in bulk, aggregate produce, reduce transaction costs, access credit, adopt better technologies, process and brand products, and negotiate better prices in markets. In this sense, FPOs are not merely farmer groups; they are rural business institutions that aim to convert scattered smallholders into organized market participants

EVOLUTION AND HISTORY OF FARMER PRODUCER ORGANIZATIONS IN INDIA

The roots of farmer collectivization in India go back to the cooperative movement, which began in 1904, but the focused promotion of FPOs as modern farmer-owned institutions began much later. A major turning point came when the Y.K. Alagh Committee, constituted by the Government of India in 2000, recommended new generation cooperatives combining cooperative principles with professional business management; subsequently, the concept of Farmer Producer Companies (FPCs) was introduced through amendments to the Companies Act in 2003.

The movement gained further policy momentum in 2011-12, when the Department of Agriculture and Farmers Welfare began promoting FPOs under schemes such as the Village Initiative for Urban Clusters and the Integrated Development of 60,000 Pulses Villages in Rainfed Areas. In 2013, the Government issued national policy and process guidelines for promoting FPOs, with the Small Farmers' Agribusiness Consortium (SFAC) as the central nodal agency. According to NAAS, SFAC and NABARD played major roles in implementing FPO promotion schemes, and by 2019 they had helped establish more than 7,000 FPOs.

The biggest push came in 2020, when the Government of India launched the Central Sector Scheme for the Formation and Promotion of 10,000 Farmer Producer Organizations with a budget outlay of ₹6,865 crore up to 2027-28.

This scheme shifted FPO promotion from scattered efforts to a mission-mode national programme, with structured support for formation, capacity building, credit linkage, market linkage, and professional handholding. As of January-February 2026, significant progress has been achieved under the scheme, with thousands of FPOs registered and supported across the country, reflecting the Government's commitment to strengthening farmer collectives and enhancing their market competitiveness (Figure 1).

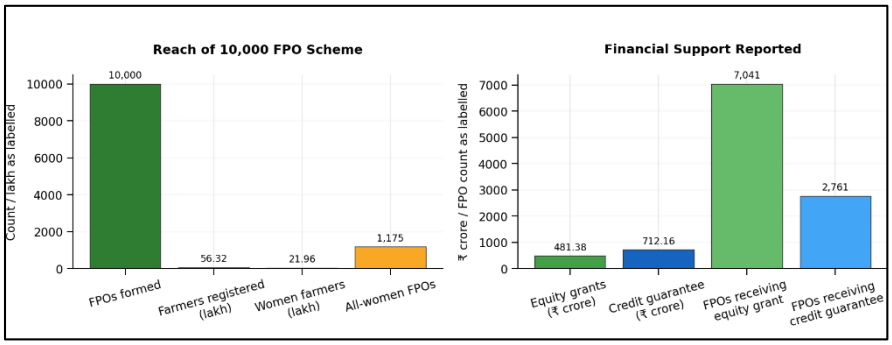


Figure 1: Current status snapshot of India's 10,000 FPO Scheme, based on official PIB data available for January-February 2026

The broader FPO ecosystem is even larger than the flagship 10,000-FPO scheme because many FPOs were promoted earlier by NABARD, SFAC, State Governments, NGOs, producer institutions, and private agencies. NAAS reports that the number of FPOs registered under the Companies Act reached 44,258 by 2024, while the Tata-Cornell Institute and BIRD reported that India had 44,547 Farmer Producer Companies (FPCs) and 214,797 agricultural producer companies (APCs) in their wider database, though such estimates depend on definitions and legal categories used. Therefore, while the government scheme's target of 10,000 FPOs is a clear milestone, the overall farmer-collective landscape is much wider and more diverse

MAJOR GOVERNMENT SCHEMES AND INSTITUTIONAL SUPPORT

The Government of India has played a crucial role in strengthening Farmer Producer Organizations (FPOs) through financial, technical, and institutional support. Under the Central Sector Scheme for Formation and Promotion of 10,000 FPOs, each newly formed FPO receives professional handholding support for five years. The scheme provides up to ₹18 lakh for management and operational activities, an equity grants up to ₹15 lakh, and credit guarantee support up to ₹2 crore to improve access to institutional finance and strengthen business operations.

The Small Farmers' Agribusiness Consortium (SFAC) serves as a key national agency promoting FPOs. It supports farmer collectives through Equity Grant and Credit Guarantee Fund Schemes, helping them mobilize capital, access credit, and expand agribusiness activities. SFAC also facilitates market access through initiatives such as the National Agriculture Market (e-NAM), enabling better price discovery and transparent marketing.

To further enhance FPO sustainability, various ministries have adopted a convergent approach. Support is provided for input dealership, market linkages, branding, processing, exports, and digital platforms such as ONDC. Recent policy initiatives emphasize FPO consolidation, professional management, market integration, digital registries, and value-chain development. These measures aim to transform FPOs into self-reliant, farmer-owned enterprises capable of increasing farm income, improving market competitiveness, and promoting inclusive rural development.

BENEFITS OF FPO'S FOR FARMERS

- **Collective Bargaining Power:** Farmers purchase inputs such as seeds, fertilizers, and pesticides in bulk at lower prices and sell produce collectively for better market returns.
- **Reduced Cost of Cultivation:** Bulk procurement lowers input costs and increases profitability.
- **Better Market Access:** FPOs connect farmers with larger markets, institutional buyers, processors, retailers, and exporters.
- **Improved Price Realization:** Collective marketing reduces distress sales and strengthens farmers' negotiating power.

- **Lower Marketing and Transaction Costs:** Shared transportation, storage, grading, sorting, and packaging facilities reduce expenses.
- **Access to Technology and Services:** FPOs facilitate farm machinery hiring, extension services, quality inputs, and modern agricultural technologies.
- **Financial Inclusion:** Easier access to credit, insurance, government schemes, and institutional finance.
- **Value Addition and Entrepreneurship:** Processing, branding, packaging, and direct marketing help farmers earn higher profits and create rural enterprises.
- **Reduced Post-Harvest Losses:** Improved storage and handling infrastructure minimizes wastage.
- **Social and Gender Inclusion:** FPOs actively support small, marginal, women, SC/ST, and economically weaker farmers. As of February 2026, India had 1,175 all-women FPOs and 1,084 FPOs with 50-99% women members, highlighting their role in women's empowerment and inclusive rural development.
- **Employment Generation:** FPOs create local jobs and strengthen rural livelihoods through collective agribusiness activities.

ACHIEVEMENTS AND IMPACT SO FAR

The 10,000 FPOs Scheme has evolved beyond farmer aggregation and is increasingly creating commercially viable, market-oriented producer enterprises. Enhanced capitalization through equity grants and credit guarantee support has improved the ability of FPOs to access formal finance, invest in infrastructure, and scale business operations. Simultaneously, integration with digital marketplaces, institutional procurement channels, exporters, and food processing value chains has strengthened market participation and improved farmers' bargaining power.

A key indicator of this transition is the strong business growth achieved by FPOs, which generated an estimated ₹9,000 crore turnover during FY 2024-25, with total business volume projected to surpass ₹10,000 crore, directly benefiting around 52 lakh farmers. Evidence from women-led FPOs further demonstrates that effective governance, financial discipline, and professional management can significantly enhance organizational performance. Collectively, these developments position FPOs as strategic institutions for improving farm profitability, accelerating value-chain integration, fostering rural entrepreneurship, and building a more resilient and inclusive agricultural economy.

CHALLENGES AND LIMITATIONS

Despite rapid growth, many Farmer Producer Organizations (FPOs) continue to face structural, financial, and operational constraints that hinder their evolution into competitive agribusiness enterprises. Limited professional management capacity, weak equity capital, inadequate working capital, and restricted access to institutional credit often undermine business expansion and long-term sustainability. Market-related challenges, including insufficient market intelligence, weak branding, fragmented supply chains, and inadequate storage, processing, and logistics infrastructure, further constrain value realization and profitability. Many FPOs remain concentrated in basic aggregation and input distribution activities, with limited participation in higher-value processing and marketing segments. In addition, complex regulatory and compliance requirements can be burdensome for newly established organizations with limited administrative capacity. Addressing these constraints requires stronger financial support mechanisms, professional managerial expertise, improved infrastructure, digital integration, streamlined compliance frameworks, and deeper linkages with industries, exporters, and institutional buyers to enhance competitiveness, resilience, and long-term viability.

WAY FORWARD

1. **Shift from formation-focused to business-focused FPO development**, emphasizing profitability, sustainability, and long-term growth rather than registration numbers alone.
2. **Strengthen professional management and governance**, including trained Boards, qualified CEOs, and transparent financial systems to improve operational efficiency.
3. **Ensure access to working capital and institutional credit**, as financial strength is

fundamental for procurement, value addition, and business expansion.

4. **Promote value-chain integration through processing, branding, packaging, and market linkages**, enabling FPOs to capture higher value and improve farmer incomes.
5. **Build strong market ecosystems through digital platforms, industry partnerships, and institutional procurement**, transforming FPOs into competitive, farmer-owned agribusiness enterprises.
6. Enhance integration with e-NAM, ONDC, APEDA, AIF, MIDH, NBHM, and institutional procurement systems.

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JUST AGRICULTURE®
THE FUTURE OF AGRI INNOVATION

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 11

From farm productivity to sugar supply security

Breaking the sugarcane supply chain cycle – An Agronomic perspective

Abstract

Sugarcane is often viewed merely as a raw material for sugar production. However, it is the starting point of a larger supply chain connecting farmers, sugar mills, markets, and consumers. Decisions made at the farm level, including variety selection, planting, irrigation, nutrient management, and harvesting, directly influence cane yield, sugar recovery, production costs, and the quality of sugar. The sugar industry also faces a cyclical challenge: increased sugarcane production can lead to a surplus of sugar and lower market prices, affecting mill profitability and farmers' income. This may influence farmers' decisions on whether to continue sugarcane cultivation or shift to other crops, eventually affecting future cane supply and sugar prices. Therefore, the key challenge is not simply to increase sugarcane production, but to improve farm productivity and profitability while maintaining sustainable cultivation practices and ensuring a consistent supply of quality sugarcane to the sugar industry.

The cycle begins in the field

The supply chain for sugar starts long before the cane is delivered to the factory. A farmer must first decide what to grow and how much to invest in the crop. Cane productivity can rise dramatically with improved agronomic practices. Higher yields can be achieved by improved crop protection, balanced nutrition, timely planting, better varieties, high-quality planting material, and effective irrigation. However, the overall cane supply can rise significantly when these advancements are implemented throughout a broad command area. Increased production is beneficial, but the industry may experience a sugar excess if supply outpaces demand.

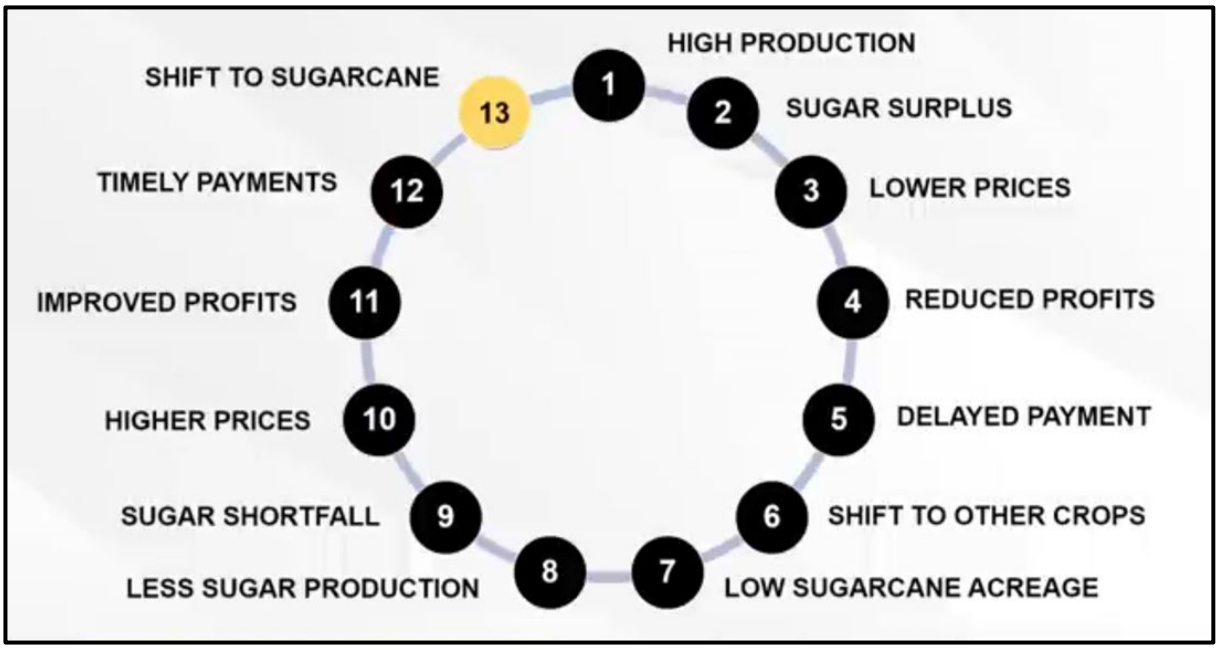
Increased cane productivity typically translates into increased sugar production. But there isn't always a straight line between market demand and agricultural yield. Inventory can accumulate when sugar production surpasses market prospects and consumption. This could put pressure on sugar prices and have an impact on the industry's overall economy. This is a crucial distinction for the farmer: more output does not always translate into higher profits. Instead of concentrating just on the tons of cane produced, the true goal must be to increase the economic value created from each acre.

The farmer is at the centre of the cycle

In the whole sugarcane supply chain, farmer profitability is arguably the most important link. In addition to cane yield, a farmer also takes into account labour needs, crop duration, water availability, cultivation costs, payment schedules, and the profitability of rival crops. Farmers may progressively reduce cane acreage if sugarcane starts to lose appeal in comparison to other crops. This goes beyond just a shift in cropping preferences. It is a logical financial choice based on resource availability, risk, and return. Therefore, sustaining the long-term supply of sugarcane depends on farmer profitability.

From surplus to shortage—and back again

The effects of farmers cutting back on sugarcane acreage due to decreased profitability may first be felt only at the farm level. Reduced area, however, may eventually result in less cane being available for sugar mills, which would diminish sugar production. Market prices could rise if there is less sugar available. Increased acreage can be encouraged by improved prices, which can make sugarcane growing more appealing.



The Agronomic answer: more value, not just more cane

Agronomists believe that increasing cane production on a constant basis is not always the answer. Rather, the emphasis should be on increasing the value per acre while utilizing less resources. This entails raising resource efficiency, lowering cultivation expenses, and increasing cane production while also enhancing sugar recovery. Farmers can attain sustainable productivity by using high-quality planting materials, appropriate types, an ideal plant population, integrated nutrition management, efficient irrigation, improved ratoon management, and prompt crop protection.

The objective should gradually move from: **"How many tonnes of cane can I produce?"** to **"How much profitable sugar value can I produce from my acre?"**

Every drop must produce more sugar

The sustainable cultivation of sugarcane will depend more and more on water. Increasing irrigation application is not a sustainable option as groundwater supplies are under stress. The industry must concentrate on increasing water productivity, or the amount of recoverable sugar and cane produced per unit of water. Crop productivity can be maintained while reducing needless water use via the use of drip irrigation, irrigation scheduling, soil-moisture monitoring, waste management, mulching, and better root-zone development.

The future question is therefore not simply **"How much water does sugarcane require?"**, but **"How efficiently can sugarcane convert water into cane and sugar?"**

Healthy soil, healthy supply chain

Soil health is one of the most crucial but less obvious aspects of the security of the sugarcane supply. Root development and the efficiency of using water and nutrients can be gradually diminished by declining soil organic carbon, compaction, poor structure, and nutritional imbalance. Although the effects might not be apparent in a single season, they can lead to decreased productivity and rising production costs over the course of subsequent crop cycles. Maintaining soil productivity can be aided by techniques including crop-residue recycling, green manuring, suitable organic additions, and balanced

nutrient management. A fertile soil is a long-term supply-chain asset as well as an agronomic asset.

The missing link: Timely farm services

Effective agronomy is only useful when it can be applied at the appropriate moment. Trash shredding, planting, intercultural management, earthing-up, and harvesting are examples of operations that frequently have limited operating windows. Farmers may be unable to implement recommended procedures due to a lack of equipment, labor, or qualified operators. This is where rural business owners and providers of agricultural services may be very helpful. Farmers can obtain machinery and technical assistance through a service-based model without having to purchase pricey equipment on their own. As a result, both farmers and rural business owners benefit from timely services and lasting business prospects.

From farm gate to factory gate

The farm and the plant must work together to create a robust sugar supply chain. Production must be sustainable and profitable for farmers. The practicality and economic viability of innovations must be guarantyd by agronomists. Timely knowledge must be provided by extension systems. Service suppliers must guaranty operational assistance. Sugar mills require reliable supplies of high-quality cane and effective procurement. The industry is better equipped to handle changes in production, resources, and markets when these connections cooperate.

The future is about sugar per acre

Tons of cane per acre have historically been the primary indicator of sugarcane success. However, a more comprehensive approach is needed for a sustainable sugar sector. Cane production, sugar recovery, water productivity, input efficiency, and farmer profitability should be the main priorities for the future. This signifies a change from maximizing production to maximizing value. Compared to a high-yielding crop produced at high expense, a somewhat lower-yielding crop with much reduced cultivation costs and improved water-use efficiency may offer greater economic value.

Building a resilient sugarcane future

The sugar industry cannot eliminate market cycles, but it can become more resilient to them. The **key lies in strengthening the economics and sustainability of every acre.**

Farmers are more inclined to keep growing sugarcane when they receive higher profits. Productivity may be sustained throughout several crop cycles when soil and water resources are preserved. Adoption of better technologies is facilitated by timely farm services. Additionally, the entire value chain is strengthened when mills receive reliable supplies of high-quality cane.

The supply chain starts with one acre

aThe quantity of sugar produced in a given season won't be the only factor influencing the sugar industry's destiny. It will depend on the industry's ability to design a system that ensures farmers continue to make money, soils continue to be productive, water is used effectively, and the mill consistently receives high-quality cane. Although sugar may reach the consumer at the end of the supply chain, it actually started much earlier in the farmer's field.

Conclusion

"Building a secure future from the ground up"

A transition from production-led growth to sustainable, farmer-centered value creation is necessary to break the cycle of the sugarcane supply chain. Although market swings are inevitable, they can be reduced by increasing farm profitability, improving soil health, increasing water-use efficiency, and ensuring prompt access to agronomic technologies and farm services. The future of the sugar industry rests not just on increasing cane production, but on growing high-quality cane efficiently and sustainably while supporting farmers' livelihoods. The security of the sugar supply ultimately starts with agricultural productivity, is maintained by farmer profitability, and is reinforced by prudent resource management. The industry can create a robust supply chain that benefits farmers, sugar mills, and consumers equally by linking agronomic excellence with economic viability on every acre.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 12

Post-Harvest Loss and Management In Fruit Crops: A Comprehensive Overview

ABSTRACT

Post-harvest management plays a crucial role in maintaining the quality, nutritional value, safety and marketability of fruit crops from harvesting until consumption. Fruits are highly perishable commodities and are particularly vulnerable to physical damage, microbial infection, physiological deterioration, improper storage, pest infestation and unsuitable transportation conditions. These factors can result in substantial quantitative and qualitative losses, thereby reducing farmers' income and increasing food waste. Effective post-harvest management involves appropriate harvesting, cleaning, sorting, grading, packaging, storage, transportation, processing and marketing practices. The adoption of improved technologies such as cold storage, modified atmosphere packaging, controlled atmosphere storage and efficient transportation can considerably extend shelf life and reduce losses. At the same time, factors such as high initial investment, inadequate infrastructure, energy requirements, lack of technical knowledge and limited access to technology remain major constraints, particularly for small and marginal farmers. This article discusses the major causes of post-harvest losses in fruit crops, the advantages and challenges of post-harvest management, and important strategies for reducing losses and improving the efficiency and sustainability of the fruit supply chain.

Keywords: *Post-harvest management, fruit crops, post-harvest loss, storage, packaging, transportation, shelf life, food waste*

INTRODUCTION

Post-harvest management refers to the series of operations performed after agricultural produce is harvested and before it reaches the final consumer. In fruit crops, these operations include harvesting, handling, cleaning, sorting, grading, packaging, storage, transportation, processing and marketing. The primary objective of post-harvest management is to maintain the quality and freshness of fruits while minimizing quantitative and qualitative losses.

Post-harvest loss (PHL) can be defined as the reduction in the quantity, quality, nutritional value or economic value of agricultural produce occurring between harvesting and consumption. Fruits are particularly vulnerable to post-harvest losses because of their high moisture content, active metabolism, delicate tissues and susceptibility to mechanical injury and microbial attack. Poor harvesting practices, rough handling, unsuitable packaging, inadequate storage facilities, improper temperature and humidity management, pest infestation and delays in transportation can accelerate deterioration. Consequently, a significant portion of the harvested produce may lose its market value before reaching consumers. An efficient post-harvest management system can help farmers obtain better prices, reduce wastage, maintain food quality, improve market access and increase the overall efficiency of the agricultural value chain. Therefore, post-harvest management should be considered an integral component of fruit production rather than a separate activity after production.

IMPORTANCE OF POST-HARVEST MANAGEMENT

Fruit production does not end with harvesting. The economic success of fruit cultivation largely depends on how effectively the harvested produce is handled and marketed. Proper post-harvest management helps maintain the physical, chemical, nutritional and sensory qualities of fruits.

The major objectives include:

- Minimizing quantitative and qualitative losses.
- Maintaining freshness and nutritional quality.
- Extending the shelf life of fruits.
- Protecting fruits from mechanical injury and microbial infection.
- Improving sorting, grading and market presentation.
- Facilitating transportation and storage.
- Improving farmers' income and profitability.
- Reducing food waste throughout the supply chain.
- Meeting quality and safety requirements of different markets.
- Supporting sustainable and efficient utilization of agricultural resources.

ADVANTAGES OF POST-HARVEST MANAGEMENT

3.1 Reduction in Post-Harvest Losses

Appropriate harvesting, handling, packaging, storage and transportation practices reduce physical damage, spoilage and deterioration. As a result, a greater proportion of harvested fruits reaches consumers in marketable condition.

3.2 Extension of Shelf Life

Technologies such as refrigeration, controlled atmosphere storage, modified atmosphere packaging and appropriate humidity management can slow down physiological processes and microbial deterioration, thereby extending the storage life of fruits.

3.3 Improved Marketability

Sorting, cleaning and grading help separate fruits according to size, maturity, colour and quality. Properly graded and attractively packaged fruits have better consumer acceptance and market value.

3.4 Maintenance of Nutritional Quality

Appropriate post-harvest handling and storage conditions help preserve vitamins, minerals, antioxidants and other nutritional components of fruits. Minimizing unnecessary delays and exposure to unsuitable conditions is therefore important.

3.5 Increased Profitability

Reducing post-harvest losses increases the quantity of produce available for sale. Better quality, longer shelf life and improved market presentation can provide farmers and other stakeholders with better returns.

3.6 Improved Market Access

Compliance with quality, safety, packaging and handling requirements can facilitate access to organized retail, processing industries, distant domestic markets and export markets.

3.7 Employment Generation

Post-harvest operations such as grading, sorting, packaging, processing, storage and transportation generate employment opportunities, particularly in rural and semi-urban areas.

3.8 Contribution to Sustainable Agriculture

Reducing losses means that the resources used for production—such as land, water, labour, fertilizers and energy—are utilized more efficiently. Effective post-harvest management therefore contributes to reducing food waste and improving resource-use efficiency.

CHALLENGES AND LIMITATIONS OF POST-HARVEST MANAGEMENT

Although post-harvest management provides several benefits, its adoption is associated with certain challenges.

4.1 High Initial Investment

Cold storage, refrigerated vehicles, pack houses, ripening chambers and other modern facilities require considerable capital investment. This can be difficult for small and marginal farmers.

4.2 Requirement of Technical Knowledge

Modern post-harvest technologies require trained personnel for their appropriate operation and maintenance. Lack of technical knowledge may result in ineffective use of technology.

4.3 Energy Requirements

Refrigeration and controlled atmosphere storage require continuous energy. High energy consumption

can increase operating costs, particularly where reliable and affordable electricity is not available.

4.4 Inadequate Infrastructure

Poor rural roads, insufficient pack houses, limited cold-chain facilities and inadequate transportation infrastructure can result in substantial losses between the farm and the market.

4.5 Environmental Concerns

Certain packaging materials, particularly single-use plastics, can contribute to environmental pollution. Therefore, the adoption of recyclable, biodegradable and environmentally friendly packaging materials is desirable.

4.6 Limited Access to Technology

Farmers in remote areas may have limited access to cold storage, grading facilities, packaging materials and other post-harvest technologies.

4.7 Resistance to Adoption

Some farmers may continue using traditional practices because of limited awareness, perceived risks, lack of technical support or uncertainty regarding the economic benefits of new technologies.

4.8 Market Fluctuations

Even when post-harvest management is efficient, fluctuations in market prices, demand, transportation costs and trade conditions can influence profitability.

MAJOR CAUSES OF POST-HARVEST LOSSES IN FRUIT CROPS

Post-harvest losses occur due to a combination of biological, physical, physiological, technological and environmental factors.

5.1 Physical Damage

Fruits can suffer bruises, cuts, abrasions, cracks and crushing during harvesting, sorting, packing, loading and transportation. Mechanical injuries damage fruit tissues and create entry points for microorganisms, accelerating decay.

Careful harvesting and handling are therefore essential for reducing mechanical damage.

5.2 Microbial and Pathogen Infection

Fungi and bacteria are major causes of fruit deterioration. Injured or overripe fruits are particularly susceptible to microbial infection. High humidity, poor sanitation and inadequate ventilation can further promote pathogen development.

Maintaining hygiene throughout the post-harvest chain is therefore critical.

5.3 Improper Storage Conditions

Temperature and relative humidity have a major influence on fruit quality. Excessively high temperatures accelerate respiration and ripening, while unsuitable humidity can result in excessive water loss or microbial growth.

Proper storage conditions must therefore be selected according to the specific requirements of each fruit crop.

5.4 Ethylene Exposure

Ethylene is a naturally occurring plant hormone associated with fruit ripening and senescence. Exposure to ethylene can accelerate ripening in susceptible fruits. Storing ethylene-producing fruits together with ethylene-sensitive fruits without appropriate management may therefore shorten storage life.

5.5 Pest Infestation

Insects, rodents and other pests can damage fruits during storage and transportation. Pest damage not only reduces the physical quality of fruits but can also facilitate secondary microbial infection.

5.6 Lack of Appropriate Technology

Limited access to cold storage, pack houses, ripening chambers, refrigerated transportation and suitable packaging can significantly increase post-harvest losses.

5.7 Improper Harvesting Time

Harvesting fruits at an inappropriate stage of maturity can negatively affect their storage life, quality, flavour and marketability. Therefore, maturity indices should be considered when determining the appropriate harvesting stage.

POST-HARVEST MANAGEMENT STRATEGIES FOR FRUIT CROPS

6.1 Scientific Harvesting Practices

Harvesting should be carried out at the appropriate stage of maturity. Sharp and clean harvesting tools should be used where required, and fruits should be handled gently to avoid bruising and other injuries. Harvesting during cooler parts of the day can also help reduce field heat in many situations. Harvested fruits

should not be thrown, dropped or subjected to unnecessary pressure.

6.2 Cleaning and Sanitation

Clean harvesting equipment, containers, storage rooms and handling surfaces are important for minimizing contamination.

Workers involved in harvesting and handling should maintain proper personal hygiene. Damaged, diseased and decaying fruits should be removed promptly to prevent the spread of infection.

6.3 Sorting and Grading

Sorting involves removing damaged, diseased and undesirable fruits. Grading classifies fruits according to characteristics such as size, colour, maturity and quality.

Proper grading improves uniformity and facilitates better packaging, transportation and marketing.

6.4 Pre-Cooling

Pre-cooling involves removing field heat from freshly harvested produce soon after harvest. Reducing the temperature of fruits at the appropriate stage can slow respiration and deterioration and may help maintain quality during subsequent storage and transportation.

The appropriate pre-cooling method depends on the fruit crop and its characteristics.

6.5 Temperature and Humidity Management

Temperature and relative humidity should be maintained according to the requirements of the specific fruit crop. Proper environmental control helps reduce respiration, water loss and microbial deterioration.

Cold-chain management is particularly important for highly perishable fruits intended for distant markets.

6.6 Proper Packaging

Packaging protects fruits from mechanical injury, contamination, moisture loss and other adverse environmental conditions. Packaging materials should provide adequate ventilation, cushioning and strength.

The selection of packaging should consider fruit type, size, weight, transportation distance, storage conditions and marketing requirements.

6.7 Modified and Controlled Atmosphere Technologies

Modified atmosphere packaging and controlled atmosphere storage can regulate the concentrations of oxygen and carbon dioxide around stored fruits. Such technologies can slow physiological deterioration and extend shelf life when applied appropriately.

However, the required atmospheric conditions differ among fruit crops and must be carefully managed.

6.8 Efficient Transportation

Transportation should minimize vibration, compression, excessive temperature fluctuations and delays. Properly packed produce should be transported using suitable vehicles and handling systems.

For temperature-sensitive fruits, refrigerated transportation can help maintain the cold chain from the storage facility to the market.

6.9 Storage Management

Storage facilities should be clean, well-ventilated and appropriate for the crop being stored. Temperature, humidity and air circulation should be monitored regularly.

Fruits should be inspected periodically and deteriorated produce should be removed promptly.

6.10 Processing and Value Addition

Processing provides an alternative when fresh fruits cannot be marketed immediately. Fruits can be converted into products such as:

- Pulp and juice
- Jam and jelly
- Squash and beverages
- Dried fruits
- Dehydrated products
- Pickles
- Fruit-based confectionery
- Purees and processed food products

Value addition can reduce wastage and create additional income-generating opportunities.

6.11 Farmer Training and Capacity Building

Training farmers and other stakeholders is one of the most important components of reducing post-harvest losses. Extension agencies, agricultural universities, research institutions, Krishi Vigyan Kendras, government departments and private organizations can contribute through demonstrations, training programmes, advisories and capacity-building activities.

ROLE OF DIFFERENT STAKEHOLDERS

Reducing post-harvest losses requires coordinated

efforts among different stakeholders.

Farmers

Farmers should adopt scientific harvesting, sorting, grading, packaging and storage practices and use appropriate technologies according to the crop and market.

Extension Agencies

Extension agencies can create awareness and provide practical training on post-harvest technologies and management practices.

Researchers and Agricultural Universities

Research institutions can develop affordable, crop-specific and locally suitable post-harvest technologies.

Government Agencies

Government support can facilitate infrastructure development, training, financial assistance, cold-chain development and market linkages.

Private Sector

Private companies can contribute through investment in storage, transportation, processing, packaging and value-chain infrastructure.

Farmer Producer Organizations

Farmer Producer Organizations (FPOs) can help farmers collectively access grading, packaging, storage, transportation, processing and marketing facilities. Collective action can improve the efficiency and bargaining capacity of producers.

FUTURE PROSPECTS

The future of post-harvest management lies in integrating scientific knowledge, affordable technology and efficient value-chain management. Digital technologies can support monitoring of storage conditions, transportation and market information. Solar-powered cold storage and energy-efficient technologies may provide useful options in areas with energy constraints. The development of biodegradable packaging, low-cost storage structures, improved handling equipment and small-scale processing technologies can particularly benefit small and marginal farmers. Greater emphasis should also be placed on crop-specific post-harvest protocols because different fruits vary considerably in their maturity, respiration rate, ethylene sensitivity, temperature requirements and storage behaviour.

CONCLUSION

Post-harvest losses in fruit crops represent an important challenge for farmers, consumers and the agricultural economy. Because fruits are highly perishable, inappropriate harvesting, handling, storage, packaging and transportation can rapidly reduce their quality and market value. Effective post-harvest management provides an opportunity to minimize these losses, extend shelf life, maintain nutritional quality, improve marketability and increase farmers' profitability. Scientific harvesting, careful handling, sanitation, sorting, grading, pre-cooling, appropriate packaging, temperature and humidity management, efficient transportation, proper storage and value addition are essential components of an effective post-harvest system. However, successful implementation requires addressing constraints such as inadequate infrastructure, high investment costs, energy requirements, limited technical knowledge and restricted access to modern technologies. Strengthening extension services, farmer training, collective action, research and development, infrastructure and market linkages can help overcome these constraints. A coordinated approach involving farmers, researchers, extension agencies, policymakers, FPOs and the private sector is therefore essential. By strengthening post-harvest management throughout the fruit value chain, it is possible to reduce food waste, improve resource-use efficiency, increase economic returns and contribute to a more sustainable and resilient agricultural system.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 13

Agricultural Waste for Sustainable Fashion: A Review of Materials and Applications

Abstract

The global fashion and textile industry faces urgent pressure to transition toward circular economic models to mitigate pollution from synthetic materials and toxic wet processing. Over 1.3 billion tons of agricultural residues—including sugarcane bagasse, banana pseudostems, rice straw, citrus peels, and tea biomass—are generated annually, with large volumes burned or landfilled. This article presents a concise review of agricultural waste as a scalable source for sustainable fashion. It examines cellulosic fiber extraction, natural bio-dye extraction, and mycelium leather bio-composites. The study details extraction technologies, fabric application techniques (surface cationization, exhaust dyeing, and fiber blending), and environmental benefits such as carbon footprint reduction, lower chemical water demand, and economic valorization of rural wastes.

Keywords: Agricultural waste, sustainable fashion, natural dyes, sugarcane bagasse, mycelium leather, circular bioeconomy.

1. Introduction

The global textile industry is a major driver of resource depletion, accounting for 8–10% of global carbon emissions and over 20% of industrial water pollution. Traditional textile manufacturing relies heavily on synthetic petroleum-based polymers (such as polyester and nylon) and resource-intensive crops like conventional cotton. Additionally, synthetic textile dyeing releases hazardous heavy metals, aromatic amines, and non-biodegradable synthetic effluents into aquatic habitats.

Valorizing agricultural residues offers a viable strategy to replace petroleum feedstocks with biodegradable alternatives. Globally, agriculture produces over 1.3 billion tons of organic waste annually. Rechanneling crop stalks, fruit peels, and fungal biomass into textile production eliminates waste incineration, captures embodied carbon, and promotes a closed-loop fashion bioeconomy.

Agricultural waste materials can be systematically categorized based on their structural composition and ultimate functional application in sustainable fashion. The primary biomass streams utilized in bio-based fashion innovation include:

- Sugarcane Bagasse Residues
- Banana Pseudostem Waste
- Rice Straw and Crop Residues for Fungal Growth
- Agro-Food Residues and By-Products for Natural Dyes

2. Uses and Sources of Agricultural Waste in Fashion

Agricultural waste streams supply three primary functional categories of sustainable textile materials:

Lignocellulosic Fibers: Crop residues such as sugarcane bagasse (40–50% cellulose), banana pseudostems, and pineapple leaves (PALF) provide high-purity cellulose fibers suitable for apparel and technical textiles.



Bio-Dyes and Pigments: Agro-food residues like onion skins, pomegranate rinds, spent coffee grounds, and tea waste contain high concentrations of tannins, flavonoids, and anthocyanins used for non-toxic fabric dyeing.

Mycelium Leather Substrates: Fungal mycelium grown on rice straw or sawdust creates dense 3D fibrous mats that serve as biodegradable alternatives to bovine and synthetic leathers.

3. Processing Technologies and Conversion Pathways

Converting agricultural biomass into textile-grade materials involves targeted mechanical, chemical, and biological processing pipelines:

Cellulose Fiber Extraction: Biomass undergoes decortication and mild alkaline pulping (10–18% NaOH at 90–120°C) to remove lignin and hemicellulose. Ultrafine cationic cellulose fibers are isolated via electrospinning or acid hydrolysis for spun yarn production.

Natural Bio-Dye Extraction: Natural colorants are extracted via solid-liquid extraction, microwave-assisted extraction (MAE), or ultrasound-assisted extraction (UAE) using aqueous or ethanol solvents to preserve dye purity.

Mycelium Bio-Composite Synthesis: White-rot fungal strains (e.g., Trametes sp.) are cultivated on straw or bagasse substrates over 14–21 days, yielding a thick mycelial mat that is plasticized with natural polyols (glycerol) for flexibility.

4. Application Methods on Textile Fabrics

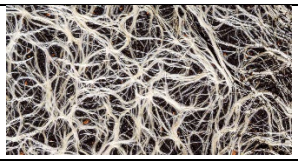
Agricultural materials are applied to textiles using specialized finishing and color-fixation methods:

Surface Cationization and Mordanting: Cellulosic fibers like cotton lack natural affinity for bio-dyes. Pre-treating fabrics with natural bio-mordants (such as pomegranate rind tannin extract or alum) or eco-friendly cationizing agents introduces positive surface charges that bond strongly with dye molecules.

Exhaust Dyeing and Pad-Curing: Bio-dyes are applied via exhaust dyeing or pad-dry-cure methods under controlled temperatures (60–90°C) and neutral-to-mildly acidic pH (4.5–7.0) to ensure high wash and rub fastness.

Comparative Technical Performance of Agricultural Waste Materials

Table 1: Chemical composition, extraction/processing methods of primary agricultural waste.

Material Source		Primary Biomass Content	Processing Method
Sugarcane Bagasse Fiber		Cellulose 34–47% Lignin 14–23%	Alkali-H2O2 (10 g/L NaOH, 12 g/L H2O2) + Silicone Softener
Banana Pseudostem (Layer 1)		Cellulose 60–65% Hemicellulose 19–27%	Semi-automatic mechanical raspador scraping + mild chemical scouring
Rice Straw Mycelium Leather		Rice straw substrate + Trametes sp. SW25-2	Solid-state fermentation + Ethylene glycol post-treatment + Hot press (120 °C, 1 MPa)
Superfine Mycelium Fiber/WPU		Ganoderma lucidum + Poplar sawdust/WPU	Substrate growth + defibrillation + waterborne polyurethane casting

Fiber Blending and Coating: Bagasse and banana micro-cellulose fibers are blended with organic cotton or viscose during spinning to create high-tenacity hybrid yarns for woven apparel.

5. Advantages and Ecological Impact

Utilizing agricultural waste in textiles provides key environmental and economic advantages:

- **Carbon Reduction & Biodegradability:** Diverting biomass from open-field burning mitigates black carbon and CO2 emissions while producing 100% biodegradable textiles.
- **Toxic Chemical Elimination:** Natural dyes and plant fibers eliminate toxic synthetic fixatives, heavy metals, and microplastic pollution, reducing wastewater toxicity.
- **Rural Economic Valorization:** Monetizing crop residues generates secondary revenue for farming communities while lowering raw material costs for textile manufacturers.

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JUST AGRICULTURE®
THE FUTURE OF AGRI INNOVATION

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 14

Pomegranate Peel as a Natural Textile Dye

Abstract

This critical review synthesizes empirical research and craft frameworks regarding the utilization of pomegranate (Punica granatum) peel and rind as an eco-friendly natural textile dye. Derived from agricultural fruit waste, pomegranate peel contains high concentrations of natural polyphenols and hydrolysable tannins, notably ellagic acid, punicalagin, and punicalin derivatives. These compounds function as both high-affinity chromophores and effective self-mordanting agents across proteinaceous (silk, wool) and cellulosic (cotton, Tencel) substrates. This article review evaluates extraction methodologies (aqueous decoction vs. ethanol-water solvent systems), thermodynamic dyeing parameters, metallic and natural mordant complexations (ferrous sulphate, alum, copper sulphate, gum rosin), spectral color strength (K/S), and wash/light fastness ratings. Furthermore, it highlights functional value-added properties, specifically Ultraviolet Protection Factor (UPF 15–24) performance on cotton fabrics.

Keywords: Pomegranate peel, Natural textile dye, Sustainable textile dyeing, Agricultural fruit waste.

1. Introduction

The textile dyeing and finishing sector is globally recognized as a resource-intensive industry that relies heavily on synthetic, petroleum-derived colorants. While synthetic dyes offer high tinctorial strength and batch-to-batch reproducibility, their effluent discharge introduces non-biodegradable aromatic compounds, heavy metals, and toxic residues into aquatic ecosystems. In response to stringent environmental regulations and heightened consumer demand for sustainable fashion, bio-resource utilization and natural colorant engineering have re-emerged as essential domain priorities.Among various bio-waste substrates, pomegranate (Punica granatum) peel—an abundant byproduct of fruit juice processing and agricultural waste—serves as an exceptional raw material for sustainable textile coloration. Pomegranate rinds are naturally rich in hydrolysable tannins, specifically ellagic acid, alongside polyphenolic compounds such as punicalagin and punicalin. The molecular structure of ellagic acid acts as the primary yellow-to-brown chromophore, while the dense tannin content enables the extract to function as a self-mordanting agent, forming strong hydrogen and coordination bonds with proteinaceous (silk, wool) and cellulosic (cotton, Tencel) fibers without strictly requiring synthetic chemical fixatives.Among various bio-waste substrates, pomegranate (Punica granatum) peel—an abundant byproduct of fruit juice processing and agricultural waste—serves as an exceptional raw material for sustainable textile coloration (Satyanarayana & Chandra, 2013). Pomegranate rinds are naturally rich in hydrolysable tannins, specifically ellagic acid, alongside polyphenolic compounds such as punicalagin and punicalin (Otaviano et al., 2022; Yang et al., 2023).

The molecular structure of ellagic acid acts as the primary yellow-to-brown chromophore, while the dense tannin content enables the extract to function as a self-mordanting agent, forming strong hydrogen and coordination bonds with proteinaceous (silk, wool) and cellulosic (cotton, Tencel) fibers without strictly requiring synthetic chemical fixatives (Otaviano et al., 2023; Rehman et al., 2017; Yang et al., 2023)

2. Extraction Methodologies and Dyeing Parameters

The efficiency of natural dye extraction directly dictates color yield, tinctorial strength (K/S), and environmental viability. Literature documents two main extraction pathways: aqueous decoction and organic solvent extraction.

- **Aqueous Decoction Methods:** Practitioners and researchers (Botanical Colors; Cedar Dell Designs; Folk Fibers) demonstrate that drying and crushing pomegranate peels into small pieces, followed by boiling and simmering in water for 45 to 60 minutes, effectively releases the water-soluble tannins and ellagic acid pigments into the dye bath solution.
- **Solvent Extraction Optimization:** Satyanarayana and Chandra (2013) evaluated an ethanol-water solvent mixture for extracting natural colorants from pomegranate peel. Their findings confirmed that solvent mixture extraction improves pigment yield and color uniformity when applied to cotton cloth.
- **Thermodynamic & Kinetic Optimization on Silk:** Yang et al. (2023) systematically optimized silk dyeing parameters, establishing that optimum dye performance occurs at pH 9, 60°C, and a duration of 60 minutes. Incorporating natural fixing agents such as gum rosin dramatically increased color strength to a K/S value of 11.74 and achieved exceptional color fastness up to level 5.
- **Substrate Optimization on Tencel:** Rehman et al. (2017) investigated regenerated cellulosic Tencel fabric, establishing that pre-mordanting with ferrous sulphate achieved the highest color strength (K/S 4.72) and superior fastness properties.

3. Mordanting Chemistry and Color Spectrum Shifts

Although unmordanted pomegranate peel yields natural golden-yellow, khaki, and yellow-brown shades due to its inherent tannin content, introducing metallic salts and natural fixing agents expands the achievable color palette while enhancing fiber-dye affinity.

Inorganic Metallic Mordants



Figure:1 Dying process



Figure: 2 Boiling peel

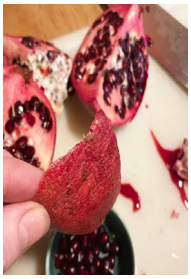


Figure: 3 Pomegranate peel

- **Ferrous Sulphate (Iron):** Iron salts react synergistically with polyphenolic tannins to form dark iron-tannate complexes. This induces a bathochromic color shift, transforming golden-yellow tones into deep olive, brown, dark grey, and slate shades across cotton, silk, wool, and Tencel.
- **Alum (Aluminum Potassium Sulfate):** Alum pre-mordanting brightens the natural yellow hue, generating luminous yellow-gold shades with clean visual clarity (Folk Fibers; Cedar Dell Designs).
- **Copper Sulphate:** Rehman et al. (2017) compared copper sulphate against ferrous sulphate on Tencel fabric across pre-, post-, and simultaneous mordanting methods, proving that ferrous sulphate pre-mordanting provided superior shade depth and fastness.

Bio-Based Fixing Agents

Yang et al. (2023) demonstrated that bio-based fixatives, specifically gum rosin, combined with natural mordants provide a 100% sustainable alternative to heavy metals. This treatment stabilizes the ellagic acid molecules on silk fibers, achieving maximum wash fastness (level 5).

Table 1: Key experimental parameters, substrates, mordants, and primary performance.

Study Reference	Substrate	Mordant / Fixative	Key Findings (K/S & UPF)	Color / Fastness Outcome
Yang et al. (2023)	 Silk	Natural Mordant + Gum Rosin	Optimum pH 9, 60°C, 60 min; K/S = 11.74	High color strength; Level 5 fastness
Rehman et al. (2017)	 Tencel	Ferrous Sulphate (Pre-mordant)	Ferrous sulphate pre-mordanting K/S = 4.72	Grades 4–5 wash, light & rub fastness
Otaviano et al. (2022)	 Cotton	Unmordanted / Aqueous extract	UPF values between 15 and 24	Yellowish shades; Good UV protection
Otaviano et al. (2023)	 Cotton	Pomegranate extract + ZnO	Physicochemical characterization	ZnO gave minimal incremental UV gain
Satyanarayana (2013)	 Cotton	Ethanol-water solvent extract	Solvent optimization for uniform yield	Improved dye durability & shade clarity

4. Functional Properties and Photoprotective UV Rating

A major breakthrough in natural textile dye research is the discovery of multi-functional performance traits imparted by pomegranate peel extract, elevating it from a simple aesthetic colorant to a bio-functional textile finish.

Otaviano *et al.* (2022, 2023) investigated the ultraviolet (UV) photoprotective properties of cotton fabrics dyed with aqueous pomegranate peel extract. Due to the high density of phenolic rings, ellagic acid, and punicalagin derivatives, the treated cotton fabrics exhibited substantial UV-absorbing capacity, achieving Ultraviolet Protection Factor (UPF) values between 15 and 24 (categorized as good to very good photoprotection). Crucially, the researchers observed that incorporating zinc oxide (ZnO) nanoparticles did not yield statistically significant improvements over the raw pomegranate extract alone, proving that the agricultural byproduct itself acts as a potent natural UV shield.

5. Conclusion

The pomegranate peel (Punica granatum) is a highly viable, eco-friendly, and multi-functional alternative to synthetic textile colorants. By upcycling an abundant agricultural waste product, textile manufacturers can eliminate toxic synthetic effluent while achieving a rich color palette spanning golden yellow, olive, brown, and dark grey. Under optimized

thermodynamic conditions (pH 9, 60°C, 60 minutes) and bio-mordanting treatments (such as gum rosin or pre-mordanted ferrous sulphate), dyed substrates achieve outstanding color strength (K/S values up to 11.74) and top-tier wash, light, and rubbing fastness (grades 4 to 5) across silk, cotton, and Tencel fibers.

Future perspectives for commercial adoption require addressing key industrial challenges: (1) standardizing raw material collection to eliminate seasonal variation in tannin content, (2) developing scaled continuous extraction technologies (such as ultrasound- or enzyme-assisted extraction), and (3) expanding long-term wash fastness testing across synthetic-natural fiber blends. Addressing these areas will facilitate the transition of pomegranate peel dye from laboratory and craft experimentation into mainstream circular fashion manufacturing.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 15

Popcorn: The Science Behind the Pop

Summary

Popcorn is a kind of maize that is prized for its kernels ability to burst into large tender flakes. The market price of popcorn depends on how the kernels pop, not just on how heavy the grain is. This article explains the structure of a popcorn kernel how popping happens, the main types of kernels and flakes the measures used to judge popping quality and the popcorn varieties and hybrids that are now available to growers in India.

Introduction

Popcorn (*Zea mays* L. Var. Everta) is a specialty maize whose value comes from one trait: the quality of its popping. A farmer can harvest a crop and still earn little if the kernels pop poorly because traders and processors grade popcorn on how much it expands and on the percentage of kernels that actually pop. Demand for ready-to-eat popcorn is growing in India with multiplexes, packaged snacks and microwave popcorn. Yet Indian productivity remains around 3.71 t/ha against about 5.83 t/ha in leading producing countries and part of the domestic demand is still met through imports. Popcorn is grown mainly in the dry belts of Rajasthan and Madhya Pradesh, the hills of Himachal Pradesh and Uttarakhand and as a *rabi* crop in Telangana and Karnataka.

The Popcorn Kernel

A popcorn kernel is built like a small pressure vessel. It belongs to the family Poaceae and is an extreme flint type of maize. Three of its parts decide whether it pops well:

- **Pericarp (hull):** a hard, low-porosity outer layer of cellulose. It resists moisture and holds the steam pressure in until the kernel bursts. A damaged pericarp leaks steam and the kernel fails to pop.
- **Endosperm:** most of the kernel is hard, translucent (vitreous) endosperm, with tightly packed starch granules in a protein matrix. This hard starch expands into the white foam of a popped flake.
- **Embryo (germ):** sits at the base of the kernel, surrounded by the starch core.

The moisture held inside the kernel is the fuel for popping. The ideal internal moisture is about 13.5–14.5% (Sweley *et al*., 2013). Nutritionally, popcorn is a whole grain that supplies carbohydrates, protein, dietary fibre and minerals and it is low in fat when popped with hot air instead of oil (United States Department of Agriculture, FoodData Central, 2024).

How a Kernel Pops

A kernel pops when the steam pressure inside it becomes greater than the strength of the hull. The process takes only a few seconds:

1. **Heating:** the kernel is heated in oil, hot air or a microwave oven.
2. **Steam formation:** water trapped in the endosperm turns to steam at around 180 °C and the tough pericarp stops it from escaping.
3. **Gelatinisation:** heat and steam soften the starch granules into a hot, gel-like mass.
4. **Rupture:** pressure builds until the hull bursts suddenly.
5. **Expansion:** the gelatinised starch puffs into a foam as the pressure drops, then cools and sets into a crisp, white flake.

This is why moisture matters much. Little water gives too little steam and small flakes; too much water softens the kernel and lets steam leak before pressure can build. Broadly field management does not change the heating process itself. It changes the kernel that enters it: how well it is filled, how sound its hull. How much moisture it carries (Sweley *et al.*, 2012).

Kernel Types and Flake Shapes

Popcorn is classified twice: once by the shape of the raw kernel (Table 1) and once by the shape of the popped flake (Table 2).

Table 1. Popcorn types based on kernel shape

Trait	Pearl type	Rice type
Kernel shape	Round, smooth top	Pointed, elongated tip
Common colour	Yellow	White
Expansion	Very high	Moderate to variable
Genetic base	Narrow, highly standardised commercial lines	Wider genetic diversity

Source: Johnson (1991)

Table 2. Popcorn types based on flake shape

Trait	Butterfly (snowflake)	Mushroom
Flake shape	Irregular, with several protruding "wings"	Round, compact ball
Texture	Light and tender	Dense and sturdy
Main use	Cinemas and fresh salted snacking	Caramel or chocolate coating, packaged snacks

Source: Kaur *et al.* (2021)

Most traditional cultivars produce a mix of both flake types. Dedicated mushroom hybrids have been developed since the late 1990s for the coating industry, where flakes must not break during handling.

Measuring Popping Quality

Three measurements decide the market value of a popcorn lot (Gopinath *et al.*, 2024):

- **Popping expansion volume (PEV):** the volume of popped flakes per unit weight or volume of raw kernels, expressed in cm^3/g or ml/ml. A higher PEV gives lighter, more tender flakes and is the main trait in commercial grading.
- **Popping percentage:** the share of kernels that pop. It is the mirror image of unpopped kernels, the hard "old maids" left at the bottom of the bowl that consumers dislike.
- **Total flake volume (TFV):** the total volume produced by a fixed lot of kernels. Processors use it to plan packaging and to judge the economic yield of a lot.

Flake size and the ratio of butterfly to mushroom flakes are also recorded in many field trials. Under the All India Coordinated Research Project (AICRP) on Maize, a new hybrid must reach at least 85% popping and an expansion of at least 15 ml/ml to qualify against the national checks.

Table 3. Popcorn varieties and hybrids available in India

Variety / hybrid	Year	Key feature	Expansion ratio	Popping (%)
APCH 3 (Pusa Hybrid Popcorn 2)	2021	Bred for processing; matures in about 103 days	1:19	96.7
APCH 2 (Pusa Hybrid Popcorn 1)	2021	Bred for processing; stable yields in the North Western and Peninsular Zones	1:18	98.3
LPCH 2	2020	High yield; moderately resistant to *Curvularia* leaf spot	1:16.6 (up to 1:23)	86.1 (up to 95)
LPCH 3	2020	High yield; recommended for 14 states	1:14.6 (up to 1:20)	89.8 (up to 96)
DMRHP 1402	2017	Bred by ICAR-Indian Institute of Maize Research; national check	≥ 1:15	≥ 85
BPCH-6	2016	Developed by Professor Jayashankar Telangana State Agricultural University; national check	≥ 1:15	≥ 85
LPCH 1	–	Early hybrid (75–80 days); responds well to inputs	–	90–95
VL Amber Popcorn	–	Hill-adapted composite; long-standing check	≥ 1:15	≥ 85
Pant Popcorn 1	–	Grown in *kharif*, *rabi* and spring seasons at Pantnagar (irrigated)	–	–

Source: ICAR-Indian Institute of Maize Research cultivar catalogue; AICRP on Maize. Values marked ≥ are the minimum AICRP standard, not variety-specific measurements.

Popcorn Varieties and Hybrids in India

Indian growers now have a range of hybrids that combine higher yield with good popping (Table 3). VL Amber Popcorn, BPCH-6 and DMRHP 1402 serve as the national reference checks in AICRP trials and newer hybrids must out-yield them while meeting the popping standard.

Conclusion

A popcorn kernel pops well when a sound hull, a well-filled hard endosperm and the right moisture (about 14 %) come together. Accordingly genetics sets the upper limit of popping quality and modern hybrids such as APCH 2 APCH 3 LPCH 2 and LPCH 3 have raised that limit to above 95 % popping. Whether a crop reaches that limit depends on how it's grown, harvested and stored. I believe that growers and processors should therefore judge popcorn, by its expansion volume and popping percentage not by grain yield.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 16

Digital Agriculture: How Drones, AI and Sensors Are Changing the Future of Farming

Abstract

Indian agriculture is facing shrinking landholdings, water scarcity, climate change, rising input costs and labour shortages. By supplying inputs at the appropriate time, location, and quantity, digital technologies like drones, artificial intelligence (AI), sensors, remote sensing, and smartphone apps can increase productivity and save expenses. The main digital technologies, their advantages, institutional and governmental initiatives, difficulties, and future directions are covered in this article.

Keywords: Digital agriculture, precision farming, agricultural drones, artificial intelligence, remote sensing, smart farming

Introduction

A sizable portion of India's people still makes their living from agriculture. The majority of farmers are marginal and small-scale, and the size of holdings is continuously decreasing due to land division from generation to generation. The only choice is to increase production from each unit of land, water, and input as the area under cultivation cannot be increased any further. Digital agriculture, which uses information and communication technologies across the entire farming process—from planting to harvesting, storing, and marketing—was born out of this necessity. In the past, farming relied on estimation and expertise. Digital farming relies on data-driven decisions. It is also called Precision Agriculture or Smart Farming. The core idea is simple. No two parts of a field are identical. In one corner the soil may be short of moisture, in another of nutrients, and in a third a pest attack may already have begun. Digital technologies help the farmer see and measure these differences and act accordingly.

Agricultural Drones: Watching the Farm from the Sky

Drones are now the most visible face of digital agriculture. Their main uses are as follows.

Spraying: Drones can spray pesticides, herbicides, liquid fertilizers and nano fertilizers on an acre in just a few minutes. Compared with conventional knapsack sprayers, they save considerable time, labour and water. The biggest advantage is that the farmer avoids direct contact with chemicals, which matters greatly for health. Drones are especially useful in tall crops such as sugarcane and maize, and in flooded paddy fields where walking is difficult.

Crop monitoring: Drones fitted with multispectral or thermal cameras reveal crop conditions invisible to the naked eye. Plant health, nutrient deficiencies, water stress and early pest or disease outbreaks can be detected in time, so treatment is possible before the damage spreads.

Land survey and mapping: Drones can produce accurate maps of field boundaries, slope, drainage and uneven patches. This information helps with land records, irrigation planning and the design of water conservation structures.

Crop damage assessment: Losses from floods, hailstorms or drought can be assessed quickly and transparently from drone imagery, which can speed up the settlement of crop insurance claims.

The government's **Namo Drone Didi** scheme links this technology to the empowerment of rural women. It aims to provide training and drones to women's self-help groups so that they become entrepreneurs offering drone services to farmers.

Sensors and the Internet of Things (IoT)

Sensors installed in the field collect data continuously and send it to a mobile phone or computer, so the farmer can check field conditions from home. The main types are:

Soil moisture sensors: They show the moisture available in the soil, so irrigation is applied only when and as much as needed. This is highly valuable in water-scarce regions.

Soil nutrient sensors: They report pH, electrical conductivity and levels of nutrients such as nitrogen, phosphorus and potassium, forming the basis of balanced fertilizer use.

Automatic weather stations: They measure temperature, humidity, rainfall and wind speed at the field level.

Automated irrigation systems: Drip or sprinkler systems switch on and off automatically on sensor signals.

Livestock and storage sensors: They monitor animal health and activity, and the temperature and humidity of warehouses, reducing post-harvest losses.

The strength of IoT is that it automates decision-making. The sensor collects the data, software analyses it, and the machine acts.

Artificial Intelligence and Machine Learning

The power of AI lies in finding patterns hidden in huge volumes of data and turning them into useful advice for the farmer.

Pest and disease identification: The farmer photographs a leaf or fruit and sends it to an app. AI identifies the disease or pest and suggests treatment, without waiting to reach an expert.

Yield forecasting: Expected production is estimated from weather, soil, sowing date and satellite imagery. This information is useful to farmers, storage agencies and policymakers alike.

Market forecasting: By analysing price trends, AI can indicate when selling the crop would be most profitable.

Multilingual voice advisory: In a country as linguistically diverse as India, the ability to ask questions and hear answers in one's own language can be transformative, because even farmers with limited literacy can use the technology.

Computer vision: Some modern machines identify weeds with cameras and spray herbicide only on them, greatly reducing chemical use.

Remote Sensing and Geographic Information Systems (GIS)

Satellite images make it possible to monitor crop condition, sown area, drought risk and water resources across large regions. Vegetation indices such as NDVI

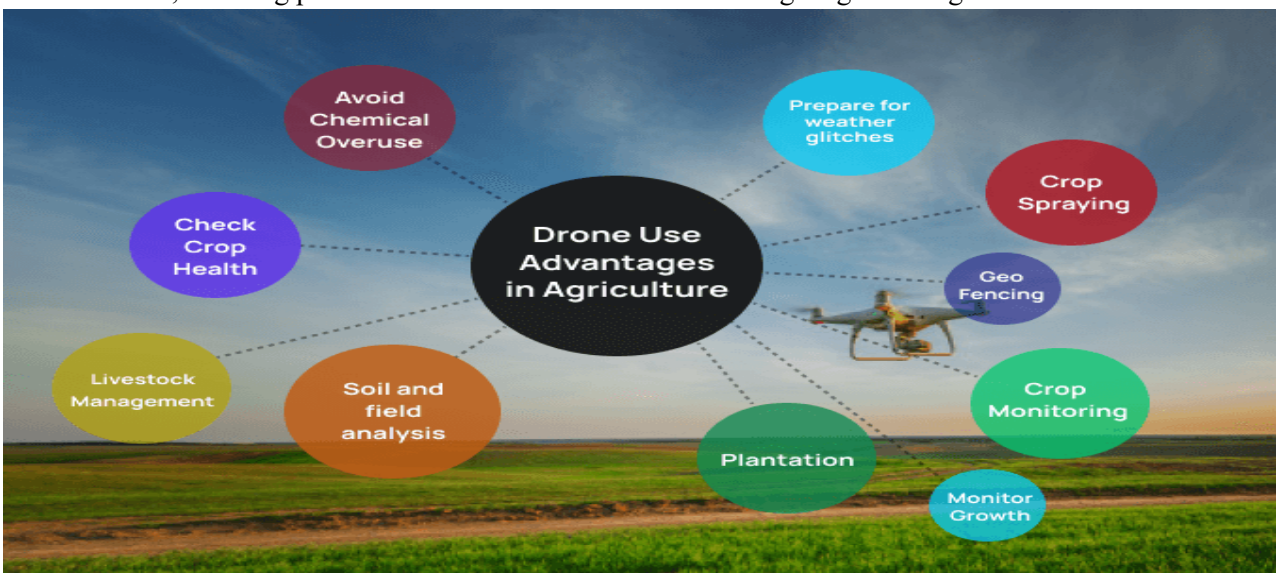
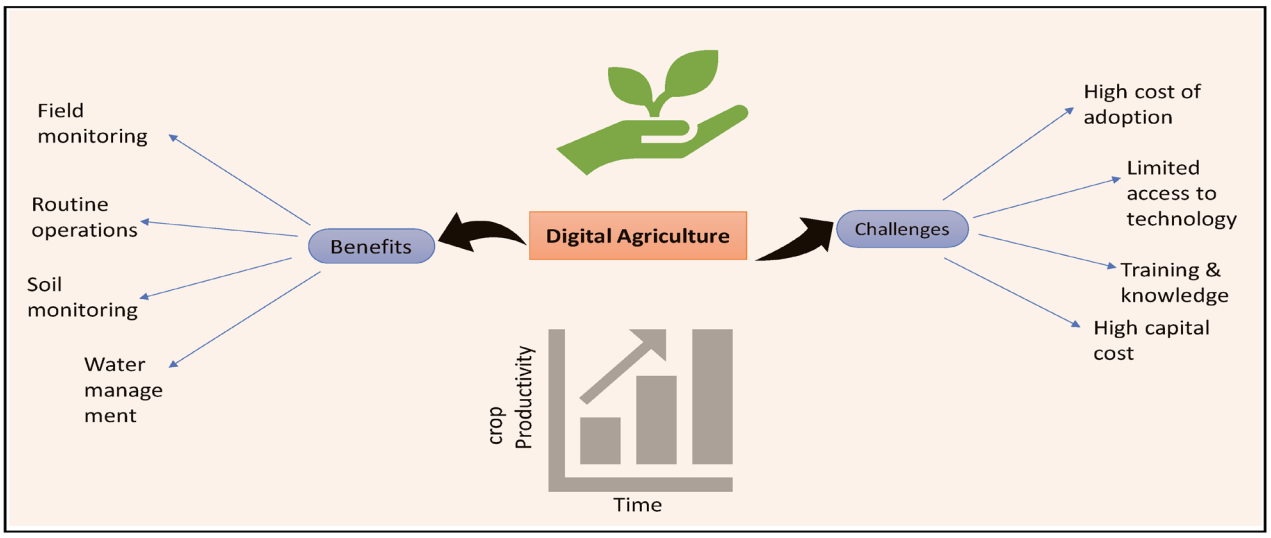


Figure 1. Different uses of drone in agriculture



give a scientific measure of crop greenness and health. These data are used in crop area estimation, drought monitoring, crop cutting experiments and insurance schemes. With GIS, soil, climate and crop data can be layered on maps to prepare crop plans suited to a particular area.

Precision Machinery and GPS

GPS-guided tractors sow in straight, uniform rows, saving seed, fuel and time. Variable Rate Technology (VRT) equipment changes the quantity of fertilizer or seed according to the needs of different parts of the field. Laser land levellers save irrigation water and bring uniformity to germination and yield.

Mobile Apps and Digital Platforms

Several digital channels are available to bring information to farmers.

- **Meghdoot:** Agro-meteorological advisories.
- **Kisan Suvidha:** Weather, market prices, plant protection and input dealer information.
- **e-NAM:** An online trading platform linking mandis.
- **Kisan Call Centre:** Expert advice on a toll-free number.
- **ICAR apps and portals:** Crop-specific production technologies, pest and disease management and information on improved varieties.

Benefits of Digital Farming

The benefits of digital technologies are many-sided.

Higher productivity:

Figure 2. A schematic representation of the benefits and challenges of digital agriculture.

Timely and precise decisions ensure the crop receives the right input at the right stage, improving both yield and quality.

Lower costs: Savings in seed, fertilizer, pesticide, water and labour raise net income.

Resource conservation: Water and soil health are protected, and fertilizer wastage is reduced.

Risk management: Early warnings about weather, pests, diseases and markets help farmers avoid losses.

Environmental protection: Lower chemical use reduces groundwater pollution and greenhouse gas emissions.

Conclusion

Digital agriculture is not a vision of the future but a need of the present. Drones, AI and sensors do not replace the farmer; they combine his experience and traditional knowledge with the power of data, enabling better decisions. The measure of success for any technology, however, is whether it is affordable, simple, local and trustworthy for the farmer. This requires research institutions, government, industry and the farming community to work together. If these technologies reach small and marginal farmers, the goal of "lower cost, higher production, a safer environment and increased income" can become a reality.

Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 17

Nematode Survival Strategies under Environmental Extremes: From Structural Adaptations to Climate Change Responses

Abstract

Nematodes occupy almost every environment on Earth, from soils and plant tissues to deserts, polar regions and animal hosts, and many species regularly face drought, extreme temperatures, oxygen shortage, salinity or the absence of a host. They survive through combined structural, behavioural, physiological, biochemical and developmental adaptations, including protective eggshells, cysts and cuticles, coiling and aggregation, cryptobiosis, trehalose and stress proteins, and diapause or dauer arrest. Notable examples include survival of intracellular freezing, about 46,000 years of cryptobiosis in permafrost, and tolerance of arsenic-rich lakes. Climate change is reshaping nematode communities, but responses vary among species and ecosystems. Understanding these strategies helps predict plant-parasitic nematode behaviour and improve entomopathogenic nematodes as biocontrol agents.

Keywords: Nematodes, anhydrobiosis, cryptobiosis, desiccation tolerance, diapause.

Introduction

Nematodes are among the most widely distributed multicellular organisms on Earth, occurring in soils, sediments, freshwater and marine habitats, plant tissues and animal hosts. Despite their microscopic size, they face wide variation in temperature, moisture, oxygen, osmotic conditions and food supply, and for parasitic species survival through unfavourable periods is essential because hosts are not always available (Perry, 1999; Perry and Moens, 2011).

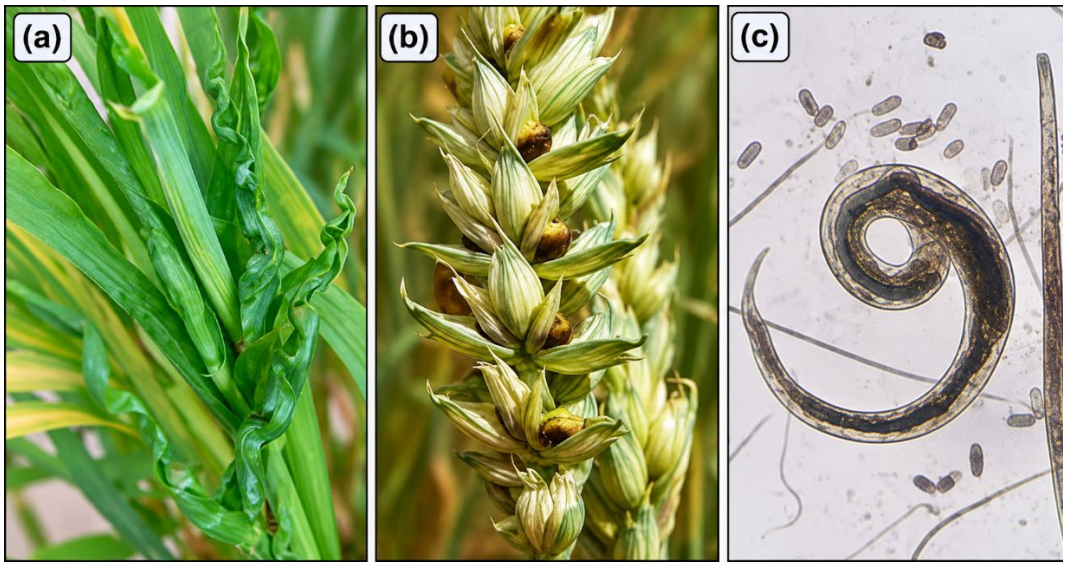


Fig. 1. Infected wheat leaves (a), spike (b) with *Anguina tritici* and (Left) Female coiled ventrally, (Right) Male, and some second-stage juvenile and eggs (c), (Abdelfattah A. Dababat, Adnan Tülek)

Dormancy, Cryptobiosis and Related States

The ability of nematodes to revive after drying was recognised as early as 1743, when John Needham observed organisms emerging from dried, blighted wheat after water was added (Needham, 1743). Research since then shows that survival is not controlled by a single mechanism; species combine structural protection, behavioural adjustment, metabolic suppression and developmental change according to the type and duration of stress (Evans and Perry, 1976; Perry, 1999).

Several overlapping terms describe inactive states in nematodes. **Hypobiosis** refers to reduced development and metabolism, whereas **cryptobiosis** is a more extreme condition in which metabolism becomes extremely low or undetectable; when induced by water loss it is called **anhydrobiosis**. Cold, oxygen deficiency and osmotic stress may similarly induce cryobiosis, anoxybiosis and osmobiosis. **Diapause** is a regulated developmental arrest tied to a particular life-cycle stage that may persist even after conditions improve, while **quiescence** is triggered directly by an adverse condition and is reversed once the stress is removed (Glazer et al., 2005). Nematodes therefore do not simply become inactive under stress; they actively alter their developmental programme to survive it.

Structural Protection

Eggs, cysts and cuticles act as physical barriers that provide a first line of defence against water loss and temperature change. The lipid-rich eggshell of *Ascaris* reduces water movement and protects the embryo during dehydration, although higher temperatures can still accelerate water loss (Wharton, 1980). In cyst nematodes such as *Heterodera* and *Globodera*, the dead female body becomes a cyst that shelters eggs and juveniles and lets the population persist in soil between crops. Some nematodes also retain moulted cuticles; young adults of the reniform nematode, *Rotylenchulus reniformis*, stay enclosed in earlier cuticular layers that slow water loss in dry soil (Gaur and Perry, 1991). Structural protection thus often buys time rather than preventing damage altogether.

Behavioural Responses and Long-Term Survival

Nematodes also change behaviour as conditions dry. Under desiccation, species such as *Ditylenchus myceliophagus* and *R. reniformis* contract into a tight coil that reduces exposed surface area and water loss, a response that is rapid and reversible when moisture returns (Treonis and Wall, 2005; Perry and Moens, 2011). Aggregation gives further protection, because individuals at the centre of a dense mass experience a buffered microenvironment. *Ditylenchus dipsaci* forms such masses, known as “nematode wool”, and has survived about 23 years in dried plant material, while second-stage juveniles of *Anguina tritici* tolerate severe desiccation inside protected plant tissues (Evans and Perry, 1976; Perry, 1999). Repeated drying and rewetting, however, imposes stress and gradually reduces survival (Perry, 1999).

Biochemical Mechanisms of Desiccation Tolerance

Severe dehydration destabilises membranes and proteins, and rehydration generates oxidative stress, so anhydrobiotic nematodes need molecular protection during both phases (Erkut et al., 2013). The best-studied protectant is **trehalose**, a non-reducing sugar that accumulates during drying; in *Caenorhabditis elegans*, trehalose metabolism is closely linked to the ability of dauer larvae to survive extreme desiccation (Erkut et al., 2011). Heat-shock proteins and late embryogenesis abundant (LEA)-type proteins help maintain protein stability, and antioxidant systems limit oxidative damage (Erkut et al., 2013). In entomopathogenic nematodes, acclimation to heat or dehydration also triggers broader tolerance through changes in membrane lipids, sugars, polyols and stress proteins (Glazer et al., 2005). Anhydrobiosis is therefore not simply drying and becoming inactive, but a coordinated process of metabolic suppression and cellular protection.

Developmental Arrest, Diapause and Dauer Stage

Some nematodes survive stress by pausing development rather than by extreme dehydration tolerance. Eggs of cyst nematodes contain pre-parasitic second-stage juveniles that stay inactive until conditions and host availability suit them, keeping development synchronised with the host plant (Perry, 1999). When food is scarce or conditions deteriorate, *C. elegans* larvae enter the dauer stage, with morphological, metabolic and behavioural changes that allow prolonged survival without food (Vlaar et al., 2021). The advantage is that the nematode avoids

the energetic cost of growth and reproduction until favourable conditions return.

Nematodes in Extreme Environments

The Antarctic nematode *Panagrolaimus* sp. DAW1 (formerly *P. davidi*) is among the best-documented animals able to survive intracellular freezing, tolerating freezing at about −10 °C, a state generally lethal to animal cells (Raymond and Wharton, 2013; Thorne et al., 2017). Even more striking is *P. kolymaensis* from Siberian permafrost, which radiocarbon dating suggests remained in cryptobiosis for about 46,000 years and which shares survival mechanisms with the *C. elegans* dauer larva (Shatilovich et al., 2023). Nematodes from the saline, arsenic-rich Mono Lake in California, including *Auanema* species, show exceptional arsenic tolerance, indicating that some nematodes become specialised inhabitants of chemically stressful habitats rather than merely surviving temporary stress (Shih et al., 2019).

Nematode Responses to Climate Change

Climate change brings rising temperature, altered rainfall, more frequent drought and extreme weather, which affect nematode survival, development, reproduction and distribution, but the effects are not uniform (Bozbuğa et al., 2026; Chi et al., 2026). A 2026 meta-analysis of 106 experimental sites found that warming raised plant-feeding nematode abundance by about 37.8% in temperate farmland but reduced several trophic groups by 44.5–65.2% in arid grasslands and deserts; reduced rainfall caused strong declines in arid ecosystems, and elevated CO_2 increased total nematode abundance by 23.2% in temperate farmland (Chi et al., 2026). For plant-parasitic nematodes, warming can speed development and allow more generations per season, rainfall and soil moisture alter movement and infection, and elevated CO_2 modifies root growth and plant defence, yet temperatures beyond a species' optimum reduce survival and reproduction (Bozbuğa et al., 2026). Climate change is thus reshaping the conditions under which species survive rather than making nematodes uniformly more adaptable: species with effective dormancy, anhydrobiosis or broad host ranges may persist, whereas those with narrow requirements may decline or shift range. The same stresses can also reduce the field persistence of beneficial entomopathogenic nematodes (Glazer et al., 2005; Glazer et al., 2025).

Agricultural Significance

Plant-parasitic nematodes persist in soil, residues and roots, and their tolerance of drought, temperature swings and long periods without feeding makes them hard to manage (Perry, 1999). Under climate change, warmer conditions may accelerate development while severe heat or drought may exceed tolerance limits, so management must consider local climate, soil, species and cropping system rather than assume a universal response (Bozbuğa et al., 2026). The same knowledge benefits biocontrol: infective juveniles of *Steinernema* and *Heterorhabditis* must survive production, storage, transport and application, and desiccation, temperature and ultraviolet radiation strongly affect their field performance, so understanding stress tolerance is essential for better formulations (Glazer et al., 2005; Glazer et al., 2025). Survival research therefore serves two goals: reducing the persistence of harmful plant-parasitic nematodes while improving that of beneficial entomopathogenic nematodes.

Conclusion

Nematode survival rests on the interaction of structural protection, behavioural adjustment, metabolic suppression, biochemical defence and developmental flexibility, which operate in sequence: environmental stress → behavioural adjustment → physical protection → metabolic suppression → biochemical protection → recovery. Freezing tolerance in *Panagrolaimus* sp. DAW1, the roughly 46,000-year cryptobiosis of *P. kolymaensis* and arsenic tolerance in *Auanema* show their remarkable flexibility, while climate change is creating context-dependent responses that already alter nematode communities. Future work should test multiple stresses together across ecosystems, which will help predict plant-parasitic nematode persistence, guide climate-sensitive management and make entomopathogenic nematode biocontrol more reliable.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 18

Banana Fiber: From Agricultural Waste to Sustainable Fashion

Abstract

Global banana cultivation generates over 110 million tonnes of agricultural biomass waste annually, predominantly comprised of discarded pseudostems after fruit harvest. Traditionally burned or left to rot, banana pseudostems represent a highly potent lignocellulosic resource capable of supplying eco-friendly natural fibers for the global textile industry. This paper evaluates the technical, mechanical, and ecological dimensions of transforming banana pseudostem waste into high-value textile fibers. We analyze the morphological structure, chemical composition (60–65% cellulose, 10–15% hemicellulose, and 5–10% lignin), mechanical extraction methodologies (decortication and bio-enzymatic retting), physical properties, yarn blending behavior, and life-cycle environmental metrics. Comparative evidence indicates that banana fiber processing requires less than 5% of the water demanded by conventional cotton while yielding a high specific tenacity (~793 MPa·cm³/g) and excellent moisture regain (~10.6%). Integrating banana fiber into circular fashion supply chains offers dual benefits: reducing synthetic fiber dependency and empowering rural agricultural communities through agro-waste valorization.

Keywords: banana pseudostem, lignocellulosic fiber, eco-friendly extraction, enzymatic retting, sustainable fashion, circular economy, natural fiber blending.

Introduction

The global textile industry is undergoing a critical transition driven by ecological necessity. Conventional natural fibers like cotton impose extreme environmental costs—including excessive water consumption (~10,000 liters per kilogram of lint) and heavy pesticide dependency—while synthetic fibers like polyester contribute to microplastic pollution and petroleum depletion (Cherian et al., 2021). Consequently, research has intensified toward identifying non-conventional lignocellulosic fibers derived from agricultural residues. Among these, the banana plant (Musa acuminata and Musa balbisiana) stands out as one of the most abundant yet underutilized agricultural waste streams.

Bananas are cultivated across more than 130 tropical and subtropical countries, occupying over 5 million hectares of agricultural land (Food and Agriculture Organization, 2022). Because each banana plant fruits only once in its lifecycle, the parent stem (pseudostem) must be felled post-harvest to allow suckers to grow. This agronomic practice generates approximately 200 kilograms of wet pseudostem biomass per tonne of harvested fruit, resulting in over 110 million tonnes of waste annually worldwide (Subagyo & Chafid, 2018). Disposing of this massive volume poses significant challenges; field burning releases greenhouse gases and particulates, while uncontrolled field decomposition creates breeding grounds for agricultural pests and fungal pathogens.



Figure 1: Banana Tree with its part

Morphological and Chemical Architecture of Banana Pseudostem

The banana pseudostem consists of concentric leaf sheaths surrounding a floral axis. Fiber distribution varies significantly across the concentric sheaths, categorized into three distinct morphological zones: the outer sheath, middle sheath, and inner sheath. The outer sheath yields coarser, highly lignified technical fibers suitable for industrial applications and technical textiles, whereas the inner sheaths contain finer, more pliable fibers optimal for fine apparel yarns (Preethi & Balakrishnan, 2020).

From a biochemical standpoint, banana pseudostem fiber is a natural composite material consisting of crystalline cellulose micro fibrils embedded in an amorphous matrix of hemicellulose, lignin, pectin, and plant waxes. Table 1 outlines the comparative chemical composition of banana fiber against conventional commercial natural fibers.

Note. Data adapted from Subagyo & Chafid (2018) and Ray et al. (2022). Values represent dry weight percentages.

Extraction and Processing Methodologies

Extracting high-quality textile fiber from green pseudostems involves a multi-stage sequence: mechanical decortication, biological or enzymatic retting, and chemical degumming/softening (Ray et al., 2022).



Figure 2: Extraction Process of Banana Fiber

(1. Tree, 2. Bark, 3.Fibre, 4. Fabric)

Mechanical Decortication

Fresh pseudostems are split longitudinally into strips (tuxies) and fed into mechanical decorticators consisting of rotating scrapers or bladed rollers. The scrapers crush the parenchymatous tissue and squeeze out excess sap, leaving raw fiber strands. Mechanical extraction yields 1.5% to 2.5% dry fiber from total pseudostem weight. While efficient, mechanical decortication leaves residual pectins and gums that require further processing.

Table 1: Biochemical Composition of Banana Fiber vs. Standard Natural Fibers

Fiber Type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Moisture (%)
Banana Fiber	60.0 – 65.0	10.0 – 15.0	5.0 – 10.0	3.0 – 5.0	10.5 – 11.5
Cotton	88.0 – 92.0	5.0 – 8.0	0.5 – 1.0	0.8 – 1.2	7.5 – 8.5
Jute	61.0 – 71.5	13.6 – 20.4	12.0 – 13.0	0.2 – 0.5	12.5 – 13.5
Sisal	65.0 – 78.0	10.0 – 14.0	10.0 – 14.0	10.0 – 12.0	10.0 – 11.0
Flax (Linen)	71.0 – 78.0	18.6 – 20.6	2.2 – 3.0	2.2 – 2.3	8.0 – 10.0

Bio-Enzymatic Retting and Degumming

To isolate individual ultimate fibers from technical fiber bundles, decorticated strands undergo retting. Traditional water retting requires 14–21 days and can pollute local water bodies. Modern processing uses eco-friendly enzymatic retting employing pectinases and hemicellulases derived from Bacillus or Aspergillus strains. Microbial enzymatic treatments selectively digest binder gums in 24–48 hours without degrading microfibrillar cellulose, improving fiber softness and fineness (Preethi & Balakrishnan, 2020).

Physical and Mechanical Fiber Properties

Banana fiber exhibits notable mechanical attributes characterized by high tensile strength, low elongation at break, and strong moisture absorption capability. Table 2 summarizes its mechanical benchmarks alongside conventional apparel fibers.

Table 2: Mechanical and Physical Performance Metrics

Property	Banana Fiber	Cotton	Jute	Polyester
Tensile Strength (MPa)	520 – 780	287 – 597	393 – 773	400 – 700
Young's Modulus (GPa)	20.0 – 32.0	5.5 – 12.6	13.0 – 26.5	8.0 – 14.0
Elongation at Break (%)	1.5 – 3.0	7.0 – 8.0	1.5 – 1.8	15.0 – 30.0
Moisture Regain (%)	10.5 – 11.5	7.5 – 8.5	12.5 – 13.8	0.4 – 0.5

Note. Compiled from Cherian et al. (2021) and Preethi & Balakrishnan (2020).

Yarn Spinning, Blending, and Textile Engineering

Due to its higher bending rigidity compared to cotton, 100% pure banana fiber presents challenges during high-speed ring spinning. Consequently, textile engineers utilize strategic blending. Combining banana fiber with organic cotton (e.g., 30/70 or 20/80 banana/cotton blend) or silk yields yarns with excellent tensile strength, enhanced breathability, and favorable fabric drape suitable for woven shirtings, denim, and home furnishings (Ray et al., 2022).

Dyeing Mechanics and Coloration Processes

Because banana fiber possesses a rich cellulosic backbone (~63-65% alpha-cellulose) abundant in primary and secondary hydroxyl (-OH) functional groups, its dyeing behavior is closely analogous to cotton and linen, modified by residual surface lignin (Subagyo & Chafid, 2018). The primary dye classes and chemical mechanisms used include:

Reactive Dye Covalent Bonding: Vinyl sulfone and monochlorotriazine reactive dyes form permanent covalent bonds with the cellulose hydroxyl groups under mild alkaline conditions. Reactive dyes yield vibrant shades with superior wash fastness (Grade 4-5) and light fastness on banana yarns (Cherian et al., 2021).

Natural Bio-Dyeing Systems: For 100% biodegradable sustainable apparel, bio-dyes derived from botanical sources—such as Indigo (Indigofera tinctoria), Madder Root (Rubia tinctorum), Marigold (Tagetes erecta), and Turmeric (Curcuma longa)—are widely utilized. Non-toxic bio-mordants like potash alum or ferrous sulfate are pre-applied to form coordination complexes that anchor natural pigments to the cellulosic matrix.

Direct Dyes: Applied in neutral to weakly alkaline dye baths assisted by electrolyte salts. Direct dyes offer economical, uniform coloration with excellent levelness, though post-dyeing cationic fixing agents are recommended to prevent bleeding during washing.

Post-Dyeing Finishing Treatments ("After Finish")

Raw and dyed banana fibers inherently possess high flexural rigidity and surface coarseness attributable to residual lignin (~5-10%) and coarse multi-cellular bundles. To make banana textiles viable for commercial apparel and skin-contact garments, specialized post-dyeing finishing treatments are applied:

1. **Silicone Softening Finishes:** Applied via padding or exhaust bath methods during final rinsing. Silicone molecules deposit a thin

lubricative film over the fiber exterior, dramatically reducing inter-fiber friction coefficient. This imparts a silky, supple hand feel, enhances drape, and improves fabric flexural recovery (Preethi & Balakrishnan, 2020).

2. **Enzymatic Biopolishing:** Dyed fabrics are treated with acidic or neutral cellulase enzymes in a temperature-controlled bath (45-50°C, pH 4.8). Cellulase selectively hydrolyzes protruding surface micro-fibrils and loose fiber ends without sacrificing core yarn tensile strength. This removes surface fuzz, prevents pilling, and brightens color clarity.
3. **Eco-Friendly Crease Resistance:** Natural cellulose chains readily form intra-molecular hydrogen bonds when bent, causing creasing. Non-toxic polycarboxylic crosslinking agents—such as citric acid—are applied to form durable ester crosslinks between cellulose chains, giving banana linen excellent wrinkle recovery angles.
4. **Functional Hydrophobic Finishes:** For outdoor or structural garment applications, atmospheric cold plasma or natural carnauba wax emulsions are applied. Plasma etched micro-roughness creates superhydrophobic surface characteristics without synthetic fluorocarbons

Life-Cycle Environmental Assessment and Socio-Economic Impact

Life-Cycle Assessment (LCA) studies highlight banana pseudostem fiber as a standout sustainable alternative. Because the pseudostem is a byproduct of food production, banana fiber incurs zero dedicated agricultural land or fertilizer footprint. Water required during eco-enzymatic extraction is under 500 liters per kilogram—a 95% reduction compared to cotton. At end-of-life, 100% pure banana textile products fully biodegrade in soil within 60 to 90 days.

In addition to ecological benefits, decentralizing banana fiber extraction creates vital socio-economic opportunities for rural farming clusters in developing nations. Processing units established near banana plantations allow farming cooperatives to earn supplementary income from agricultural waste, driving rural economic development and circular industrial symbiosis (Cherian et al., 2021).

Conclusion

Banana pseudostem fiber represents a compelling convergence of agricultural waste valorization and sustainable fashion engineering. By converting over 110 million tonnes of annual post-harvest waste into high-performance natural textiles, the fashion sector can reduce its reliance on water-intensive cotton and petroleum-based synthetics. Overcoming current spinning throughput constraints through enzymatic softening and modern fiber blending will accelerate commercial adoption across global apparel markets.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 19

Residual effect of Integrated Nutrient Management on the growth and yield of *rabi* buckwheat (*Fygopyrum esculentum)* under rice-buckwheat cropping sequence

Abstract

A field experiment was conducted during *kharif* and *rabi* seasons of 2016-17 and 2017-18 at Krishi Vigyan Kendra (KVK) Farm of Kokrajhar district under Lower Brahmaputra Valley Zone (LBVZ) of Assam to study the residual effect of integrated nutrient management in *kharif* rice on production potential of succeeding buckwheat crop under rice- buckwheat cropping sequence. The integrated nutrient management treatments *viz.,* T_1 (Control), T_2 (100% RDF), T_3 (100% RDF + FYM @ 10 t ha^{-1}), T_4 (75% RDF + 25% N through FYM), T_5 (75% RDF + 25% N through vermicompost), T_6 (50% RDF + 50% N through FYM), T_7 (50% RDF + 50% N through vermicompost) and T_8 (FYM @ 1 t ha^{-1} + mixture of *Azospirilium amazonens* A-10 and *Bacillus megaterium* P-5 @ 4 kg ha^{-1} + Rock phosphate @ 10 kg, MOP@ 40 K_2O ha^{-1}) were applied to rice in *kharif,* 2016 and 2017 as main- plot treatments and replicated three times in randomized block design. In succeeding *rabi* season, 2016-17 and 2017-18, on the same field buckwheat was grown for which each main plot treatment was splitted into three sub plot treatments with three levels of recommended dose of fertilizers (RDF) *i.e.* levels of NPK *viz.*, B_1 (0% RDF), B_2 (50% RDF) and B_3 (100% RDF) to buckwheat resulting into twenty four treatment combinations replicated three times in split plot design. Results revealed that the application of 100% RDF through chemical fertilizer + FYM @10t ha^{-1} to *kharif* rice reported the significant effect on growth, yield attributes, and seed yields of succeeding buckwheat crop followed by 75% RDF through chemical fertilizer + 25% RDN through vermicompost. The result of the experiment revealed that 100% NPK through chemical fertilizer + 10t FYM/ha recorded maximum plant height at 30,60,90 DAS (52.08 cm) and at harvest (75.07 cm), maximum number of branches per plant at harvest (5.00), dry matter accumulation per plant (26.56 g), seed index (3.39 g), seed yield (991 kg/ha) and stover yield (2513 kg/ha) in buckwheat. Thus, application of 100% RDF i.e. 60 kg N, 20 kg P_2O_5 and 40 kg K_2O through chemical fertilizer along with 10 t FYM ha^{-1} reported the promising residual effect on growth, yield and yield attributing characters of succeeding buckwheat in rice-buckwheat cropping sequence under Lower Brahmaputtra valley Zone (LBVZ) of Assam.

Keywords: FYM, Vermicompost, inorganic fertilizer, INM, Cropping sequence, rice, buckwheat, Seed yield, LBVZ, Assam

1. Introduction:

Rice is cultivated in about 165 million hectares globally with a production of 756 million tonnes and Asian countries produce about 90 per cent of this production (Anon., 2018a). India is one of the leading rice producing countries of the world along with China, Thailand, Vietnam, Indonesia and Bangladesh.

India is the second largest producer of rice after china and it is cultivated on an area of 43.80 million hectares and annual production of about 112.91 million tonnes with average productivity of 2578 kg per hectare (Anon., 2018a). Rice accounts for about 42 per cent of total food grain production and 55 per cent of cereal production in the country. It plays a vital role in our national food security and is a means of livelihood for millions of rural households.

Rice is the principal crop in Assam and prevailing farming system are basically rice based. Out of a total 40.87 lakh hectares cropped area in Assam, *kharif* rice locally known as *sali* rice, occupies an area of 17.94 lakh hectares. Rice production in the state is 52.84 lakh tonnes with average productivity of 2171 kg ha^{-1} (Anon., 2018b).

The theme of the present day agriculture is to achieve the targeted production to meet the increasing food demand with sustaining soil productivity. The most limiting factor that has affected the production of crops and productivity is fertilizer through imbalanced and indiscriminate use on one hand and withdrawal of organic matter from the schedule of inputs on the other (Kumar and Singh, 2008). Therefore, integrated nutrient management (INM) has been an increasing necessity especially for the tropical Indian soils. Cultivation in this area is largely rain fed. Hence, improving agricultural productivity of this large area seems to be an important task that needs to be imparted through low input sustainable and profitable cropping system on the fatigued natural resource base (Ladha *et al*., 2003). Selection of crops and cropping pattern is an important factor for maintaining productivity of a soil. The other aspect is INM which needs framing for a crop sequence and soil type. Boosting yield, reducing production cost and improving soil health are three inter-linked components of the INM (Singh *et al*., 2008). Numerous reports of INM revealed that higher crop yield could be achieved through certain amount of substitution of inorganic fertilizers with organic manures (OM) and /or addition of OM with 100% chemical fertilizers, e.g., 50% substitution of NPK with OM was as good as 100% chemical fertilizers for grain yields in rice (Mandal and Adhikari, 2005).

The *kharif* rice or *sali* rice is the major category of rice grown in Assam during June-October/ November which occupies about 90 per cent of the total rice area of the region. After harvest of *kharif* rice, vast areas remain vacant due to late harvest and lack of irrigation facility. Therefore, attempts are to be made to utilize those rice lands. There is a vast scope to grow buckwheat as second crop successfully after the harvest of the *kharif* rice like other crops such as rice-rapeseed, rice- lentil, rice- niger etc.

Buckwheat (*Fagopyrum esculentum* Moench) is an ancient Asian crop, now widely grown around the world. Even though, it is an underutilized crop, it remains important for food security in the temperate and hilly regions of countries in East Asia, East Europe and the Himalayan region (Arora, 1995). Buckwheat is grown mainly for human consumption and as animal feed, although it can also be used as a vegetable, a green manure crop, medicinal purpose, fodder, as a smother crop to control weeds and as a source of buckwheat honey. Buckwheat locally known as '*Dhemshi*' received importance in the state of Assam as a *rabi* crop in recent years because of its productivity and economic importance. It is quick growing crop, rich in protein and carbohydrates and almost at par with common wheat. Moreover, it is a suitable crop for poor soils and has excellent tolerance to acid condition. Although, buckwheat is underutilized crop but it is nutritionally better than other food crops and are resilient crop in respect to biotic and abiotic stresses.

At present, studies on nutrient utilization in cropping system of different crops are available but effect of organic sources with different levels of inorganic fertilizer applied to kharif rice on the performance of succeeding buckwheat especially on the aspects of residual effect, growth and yield is very meagre. Hence the present study on the residual effect

of integrated nutrient management applied to *kharif* rice on growth and yield of succeeding buckwheat under rice-buckwheat cropping sequence is the need of time.

Materials and Methods:

A field experiment entitled "Integrated Nutrient Management in rice-buckwheat cropping sequence" was conducted at Krishi Vigyan Kendra (KVK) Farm, Gossaigaon under Lower Brahmaputra Valley Zone (LBVZ) of Assam during *kharif,* 2016 - 17 and *rabi* 2017-18 to study the effect of integrated nutrient management (INM) on *kharif* rice and the residual effect on the succeeding buckwheat crop. The soil of the experimental field was sandy loam in texture, acidic in reaction (pH 5.40), low in organic carbon (0.47%), low in available nitrogen (170.5 kg ha^{-1}), medium in available phosphorus (23.45 kg ha^{-1}) and low in available potassium (115.15 kg ha^{-1}). The treatment consisted of integrated nutrient management *viz.,* T_1 (Control), T_2 (100% RDF), T_3 (100% RDF + FYM @ 10 t ha^{-1}), T_4 (75% RDF + 25% N through FYM), T_5 (75% RDF + 25% N through vermicompost), T_6 (50% RDF + 50% N through FYM), T_7 (50% RDF + 50% N through vermicompost) and T_8 (FYM @ 1 t ha^{-1} + mixture of *Azospirilium amazonens* A-10 and *Bacillus megaterium* P-5 @ 4 kg ha^{-1} + Rock phosphate @ 10 kg, MOP@ 40 K_2O ha^{-1}) applied to rice in *kharif* 2016 and 2017 as main- plot treatments replicated three times in randomized block design. Organic manures (FYM and vermicompost) were applied to kharif rice as per treatments and evenly spread and mixed in that particular plot. The kharif rice was fertilized as per treatments. The nitrogen was applied through urea (46% N) whereas phosphorus was applied through single superphosphate (16% P_2O_5) and potasium was applied through potash (60 % K_20). The 50% dose of nitrogen and a full dose of phosphorus and potasium were applied at the time of transplanting and the remaining 50 % dose of nitrogen was applied as top dressing at 30 days after transplanting. After the harvesting of *kharif* rice, buckwheat was grown as succeeding crop on 19th November, 2016 and 16th November 2017. In succeeding rabi season, each main plot was split into three sub plots with three levels of recommended dose of fertilizer viz. B_1- control (0), B_2-50% RDF, and B_3-100% RDF to buckwheat resulting into twenty four treatment combination replicated three times in split plot design. The experiment was conducted on the same site without changing the randomization of the treatment for the successive year to assess the residual effects. The data recorded were statistically analyzed using MSTATC software..

During *rabi* 2017-18, each main plot treatment was splitted into three sub plot treatments with three levels of recommended dose of fertilizers of buckwheat (RDF) *i.e.* levels of NPK *viz.*, B_1 (0% RDF), B_2 (50% RDF) and B_3 (100% RDF) to buckwheat resulting into twenty four treatment combinations replicated three times in split plot design. The experiment was conducted on the same site without changing the randomization of the treatments for the next year to assess the residual effects. The data in respect of growth,

yield attributes, yield and nutrient uptake of rice and buckwheat crops were recorded. The cropping sequence of rice-buckwheat was also assessed through rice equivalent yield, monetary returns and benefit cost ratio. The changes in physical and chemical properties of soil were also assessed.

RESULTS AND DISCUSSION

Growth:

In order to quantify the response observed due to integrated nutrient management to the preceding *kharif* rice on succeeding buckwheat, the plant growth and development was assessed on pooled basis in terms of plant height (Table 1). At 40DAS, 60 DAS and at harvest, treatment receiving application of 100% RDF + FYM @ 10 t/ha) to preceding rice crop had resulted in significantly taller plants and further it remained at par with the treatment T_5 (75 % RDF+ 25% N through Vermi compost)on the basis of mean of two years. From the data, it could be seen that the mean plant height of buckwheat increased with the advancement of crop age during both the years of experimentation and reached to its maximum at harvest. further it remained at par with treatment T_3 (75% RDN through chemical fertilizer + 25% RDN through vermicompost) at harvest.

Table1: Residual effect of integrated nutrient management in *kharif* rice on the growth of *rabi* buckwheat (2 years pool data)

Treatment	Plant height (cm)				No. of branches/plant	Dry matter accumulation (g/m^2)			
I)Main plot treatment(T)	**20DAS**	**40 DAS**	**60 DAS**	**At harvest**	**At harvest**	**20DAS**	**40DAS**	**60DAS**	**At harvest**
T_1- Control (No fertilizer & FYM application)	21.80	57.40	71.88	83.05	**3.91**	**64.38**	**124.34**	**257.06**	**333.82**
T_2-100% RDF	22.88	61.33	76.21	86.30	**4.43**	**65.45**	**133.37**	**281.46**	**358.50**
T_3-100% RDF + FYM @10t/ha (As per AAU recommendation)	24.75	64.12	78.88	90.21	**5.62**	**68.23**	**140.18**	**295.90**	**379.38**
T_4-75% RDF + 25% N through FYM	23.60	61.57	76.63	87.08	**4.67**	**66.95**	**136.67**	**281.90**	**354.48**
T_5-75 % RDF+ 25% N through Vermi compost	24.60	62.88	77.91	88.17	**5.01**	**67.18**	**137.96**	**283.91**	**360.67**
T_6-50% RDF + 50 % N through FYM	22.44	60.75	75.74	85.35	**5.06**	**63.38**	**133.78**	**272.32**	**348.98**
T_7-50% RDF + 50% N through Vermi compost	22.73	61.57	76.50	85.80	**5.30**	**65.36**	**137.07**	**279.77**	**358.15**
T_8- FYM @ 1 t/ha + mixture of Azospiriliumamazonens A-10 and Bacillus megaterium P-5@4kg/ha,+ Rock phosphate@ 10kg MOP@ 40k$_2$0/ha	22.38	60.52	75.65	84.73	**4.75**	**61.98**	**132.39**	**263.67**	**338.69**
Sm +	0.33	0.88	0.81	0.97	0.18	0.89	2.35	5.98	5.13
CD (P=0.05)	1.03	2.70	2.48	2.97	0.55	2.73	7.19	18.31	15.72
CV (%)	**4.37**	**4.32**	**3.19**	**3.38**	**11.15**	**4.10**	**5.24**	**6.47**	**4.35**
II Sub plot treatment (B)									
B_1- 0% RDF	22.2	57.9	72.7	82.79	**4.02**	**61.63**	**119.53**	**240.82**	**292.90**
B_2- 50% RDF	23.1	61.5	76.2	86.84	**4.82**	**66.47**	**139.08**	**290.33**	**367.29**
B_3- 100% RDF	24.2	64.4	79.5	89.39	**5.69**	**68.00**	**144.80**	**299.84**	**402.06**
S.Em+	0.21	0.42	0.46	0.45	0.10	0.64	1.28	2.71	2.91
CD (P=0.05)	0.61	1.21	1.32	1.31	0.29	1.84	3.70	7.84	8.41
CV (%)	**4.44**	**3.34**	**2.93**	**2.56**	**10.18**	**4.77**	**4.66**	**4.79**	**4.02**
Interaction (T x B)									
Between two B means at the same level of T									
S.Em+	0.59	1.53	1.40	1.68	0.31	1.55	4.07	10.36	8.89
CD (P=0.05)	**NS**	**NS**	**NS**	**NS**	NS	**NS**	**NS**	**NS**	**NS**
CV									
Between two T means at the same or different level of B									
S.Em+	0.59	1.31	1.33	1.43	0.29	1.72	3.77	8.65	8.45
CD (P=0.05)	**NS**	**NS**	**NS**	**NS**	NS	**NS**	**NS**	**NS**	**NS**

Table 2: Residual effect of integrated nutrient management in *kharif* rice on the yield of *rabi* buckwheat (2 years pooled data)

Treatment						
I)Main plot treatment(T)	**No. of spikes /plant**	**No. of seeds per spike**	**Test weight (g)**	**Seed yield (q/ha)**	**Stover yield (q/ha)**	**Harvest Index (%)**
T_1- Control (No fertilizer & FYM application)	**16.68**	**8.27**	**23.75**	7.45	14.21	34.03
T_2-100% RDF	**18.34**	**9.93**	**24.86**	10.40	19.21	35.09
T_3-100% RDF + FYM @10t/ha (As per AAU recommendation)	**20.19**	**11.10**	**26.06**	13.21	24.50	35.25
T_4-75% RDF + 25% N through FYM	**18.94**	**10.12**	**24.91**	10.94	20.49	34.74
T_5-75 % RDF+ 25% N through Vermi compost	**19.72**	**10.71**	**25.56**	11.88	22.19	34.76
T_6-50% RDF + 50 % N through FYM	**17.55**	**9.67**	**24.59**	9.55	17.47	35.27
T_7-50% RDF + 50% N through Vermi compost	**17.91**	**9.81**	**24.73**	10.13	18.61	35.09
T_8- FYM @ 1 t/ha + mixture of Azospiriliumamazonens A-10 and Bacillus megaterium P-5@4kg/ha,+ Rock phosphate@ 10kg MOP@ 40k_20/ha	**16.84**	**9.10**	**24.36**	8.98	16.55	35.11
Sm +	0.427	0.265	0.312	0.335	0.579	0.297
CD (P=0.05)	1.308	0.811	0.955	1.025	1.774	**NS**
CV (%)	**7.01**	**8.06**	**3.76**	**9.72**	**9.07**	**2.55**
II Sub plot treatment (B)						
B_1- 0% RDF	**16.19**	**8.7**	**23.8**	**8.6**	**17.3**	**33.2**
B_2- 50% RDF	**18.11**	**9.9**	**25.0**	**10.1**	**18.8**	**35.1**
B_3- 100% RDF	**20.51**	**10.9**	**25.8**	**12.2**	**21.4**	**36.4**
S.Em+	0.318	0.176	0.199	0.183	0.328	0.128
CD (P=0.05)	0.919	0.510	0.576	0.529	0.948	0.370
CV (%)	**8.51**	**8.77**	**3.93**	**8.68**	**8.38**	**1.79**
Interaction (T x B)						
Between two B means at the same level of T						
S.Em+	0.740	0.459	0.540	0.580	1.003	0.514
CD (P=0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Between two T means at the same or different level of B						
S.Em+	0.849	0.486	0.555	0.538	0.953	0.419
CD (P=0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

Application of 100 % RDF + FYM @ 10 t/ha (T_3) recorded significantly higher number of branches per plant at harvest and was found at par with treatment T_5 (75% RDF through chemical fertilizer + 25% RDN through vermicompost). At 60 DAS and at harvest, significantly maximum dry matter accumulation per square meter was recorded with application of T_3 (100% RDF + FYM @ 10 t/ha) which was remained at par with treatment T_5 (75% RDF through chemical fertilizer + 25% RDN through vermicompost). The higher nutrient availability under INM treatments resulted into increased conversion of carbohydrates into protein which in turn elaborated into protoplasm and cell wall material increased the size of the cell, which expressed morphologically in terms of plant height, number of branches and ultimately dry matter accumulation. Cellulose is a highly persistent composition material, which requires longer time for decomposition. Thus, FYM and vermicompost have not been fully utilized by the *kharif* rice crop in first crop season and notably benefitted the succeeding buckwheat crop. Similarly, the beneficial residual effect of addition of FYM along with inorganic fertilizers under cropping system on growth attributes was reported by Singh *et al*. (2002) in rice-lentil, Gaud (2004) in rice-mustard, Maiti *et al.* (2006) in *kharif* hybrid rice-summer hybrid rice, Imade (2014) in rice-green gram cropping sequence as well as Mansuri (2016) in rice-chickpea cropping sequence.

Yield and yield attributes

Yield is a function of various yield attributes. Most of the yield contributing characters viz., number of spikes per plant, number of seeds per spike, test weight (100 g seed weight) and seed yield per plant (Table 2) were significantly influenced in buckwheat due to residual effect of integrated nutrient management applied in kharif rice. Significantly maximum values of number of seeds per spike, and seed yield per plot were recorded with the application of 100% RDF + FYM @ 10 t/ha) over all the treatments. Such effect may be owing to increased availability of nutrient in soil from native pool as well as their residual effect through mineralization and improvement of physico-chemical properties of soil and thereby improving water and nutrient holding capacity of soil, which result in to more growth of crop and resulted in adequate food supply to sink and ultimately reflected in to better yield attributes. Significantly higher seed and stover yields of buckwheat (Table 2) was recorded under application of T_3 (RDF + FYM @ 10 t/ha) in average of two years. It may be ascertained to the increased availability of nutrients due to mineralization of organic materials, release of CO_2 increasing fertilizer use efficiency, accumulation of organic carbon and improvement of soil physical properties. The increased buckwheat seed yield might be due to addition of FYM or vermicompost to preceding *kharif* rice resulting in improvement in soil structure which reduced the soil crusting and also serves as a source of energy for soil microflora which resulted in better root nodulation and nitrogen fixation. Significantly, higher stover yield under above treatments might be due to increase in vegetative growth in terms of plant height, number of branches and dry matter accumulation.

Similar results were reported earlier by Jeyabal and Kuppuswamy (2001) in rice-legume, Singh *et al.* (2002) in rice-lentil, Gaud (2004) in rice-mustard, Pillai *et al.* (2007) in rice based crop sequence, Gogoi *et al*. (2010) in rice-niger and Paul *et al.* (2013) in rice - buckwheat cropping sequence. The farm yard manure not only the store house of large number of macro and micro nutrients but also helps considerably to improve the physical, chemical and biological properties of the soil. Thus, application of 10 t FYM per hectare gave residual effect of 25 kg N per hectare (Bandopadhyay and Puste, 2002) in terms of inorganic fertilizer. This might be ascribed to the mineralization of un-decomposed FYM left out in the soil after the harvest of rice crop. The persistent material in FYM requires more time for its decomposition, hence, about 25 to 30% of nitrogen and small fraction of phosphorus and potassium in FYM may be available to immediate crop i.e. *kharif* rice and rest to subsequent crops (Inoko,1984) which sustain the productivity.

CONCLUSION:

On the basis of experimental results, rice crop

grown with 100% RDF @ 60-20-40 kg NPK ha^{-1} through chemical fertilizer along with 10t/ha FYM reported promising residual effect on yield and yield attributing characters of succeeding *rabi* buckwheat crop in rice-buckwheat cropping sequence under under Lower Brahmaputtra Valley Zone of Assam state.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 20

Natural Dyes from Agricultural Crops for Eco-Friendly Textiles: A Review

1. Introduction

The global textile wet processing sector is recognized as one of the most environmentally intensive industrial activities, consuming substantial quantities of non-renewable petrochemicals, water, and synthetic dyestuffs (Kumari & Juneja, 2023; Pizzicato et al., 2023)[1]. Annually, approximately 800,000 tons of synthetic dyes are produced globally, with nearly 75% utilized in textile manufacturing (Pizzicato et al., 2023)[5]. The discharge of untreated effluent containing heavy metals, aromatic amines, synthetic salts, and toxic auxiliaries poses severe ecological and human health hazards, including aquatic photosynthesis inhibition, bioaccumulation, contact dermatitis, and carcinogenic risks (Kumari & Juneja, 2023; Pizzicato et al., 2023; Singh et al., 2020; Slama et al., 2021)[6]. In response to strict environmental regulations and growing consumer demand for sustainable fashion, natural dyes derived from agricultural crops, crop residues, and food-processing by-products have re-emerged as vital eco-friendly alternatives (Dansena et al., 2026; Kumari & Juneja, 2023; Saxena & Raja, 2014)[15]. This review provides a comprehensive analysis of plant-derived natural colorants, highlighting agricultural crop sources, advanced green extraction methods, sustainable bio-mordanting techniques, functional properties, circular economy benefits, and technical challenges hindering industrial scalability **(Kumari & Juneja, 2023; Pizzicato et al., 2023; Yadav et al., 2022).**

2. Agricultural Crops and Bio-Waste Sources for Natural Colorants

Plant-derived dyes represent approximately 90% of all natural dyes used in textile applications. These colorants are obtained from diverse crop tissues, including roots, leaves, flowers, seeds, barks, and agricultural waste residues. The primary bioactive chromophores present in dye-yielding crops include flavonoids, anthocyanins, carotenoids, tannins, quinones, anthraquinones, curcuminoids and indigoids.

2.1 Primary Cultivated Dye Crops

Extensively cultivated dye crops include Turmeric (Curcuma longa), rich in the polyphenolic diarylheptanoid curcumin, which imparts vibrant yellow hues; Indigo (Indigofera tinctoria), containing the glucoside indican that converts to insoluble indigotin blue; Madder (Rubia tinctorum), whose roots yield alizarin and purpurin for deep red shades; Marigold (Tagetes erecta), rich in lutein and carotenoids for orange-yellow tones; and Henna (Lawsonia inermis), which contains lawsone (naphthoquinone) for orange-brown shades.

2.2 Valorization of Agricultural Crop Waste and By-Products

To prevent land competition with food crops, recent research focuses on agro-industrial waste valorization. Substantial quantities of agricultural residues—such as onion skins (flavonoids), pomegranate rinds (tannins and polyphenols), tea waste, walnut husks containing juglone, avocado peels (catechins and condensed tannins), custard apple peels, and banana leaves—serve as abundant, low-cost sources of natural pigments.

Valorizing crop waste promotes circular economy practices, reduces landfill disposal, and generates supplementary income for farming communities.

3. Extraction Technologies and Green Processing

The extraction of natural dyes from agricultural crops is a critical step in determining pigment recovery, color intensity, process efficiency, and the overall economic feasibility of eco-friendly textile coloration. Conventional aqueous extraction, which involves boiling or heating powdered plant materials in water, remains widely used because of its simplicity, low cost, and relatively low environmental impact.



3.1. Advanced Green Extraction Technologies

To overcome the limitations of conventional extraction, several advanced techniques have been developed to improve pigment recovery under environmentally responsible processing conditions.

- **Ultrasound-Assisted Extraction (UAE):** This technique employs ultrasonic waves to generate cavitation bubbles in the extraction medium. Their collapse disrupts plant cell walls, enhances mass transfer, and facilitates the release of intracellular pigments. UAE can reduce extraction time, solvent consumption, and processing temperatures while improving dye yield.
- **Microwave-Assisted Extraction (MAE):** Microwave energy rapidly heats moisture within plant tissues, generating internal pressure that promotes cell-wall rupture and accelerates pigment release.
- **Enzyme-Assisted Extraction (EAE):** Enzymes such as cellulase, pectinase, and hemicellulase degrade structural components of plant cell walls under relatively mild conditions. This process facilitates the release of free and bound colorants, particularly phenolic compounds, while reducing the need for harsh chemicals and excessive heating.
- **Supercritical Carbon Dioxide Extraction:** Supercritical CO_2 provides a recyclable, low-toxicity extraction medium that can minimize the use of conventional organic solvents. It is particularly suitable for relatively nonpolar compounds, including certain carotenoids.

4. Mordanting Systems and Surface Modification

Mordanting is an important process in natural textile dyeing because it enhances the interaction between dye molecules and textile fibers, thereby improving dye uptake, shade development, and colorfastness. The effectiveness of natural dyes varies according to the chemical composition of both the colorant and the substrate. Cellulosic fibers, including cotton and linen, contain abundant hydroxyl groups but generally exhibit limited affinity for many natural colorants. In contrast, protein fibers such as wool and silk contain amino, carboxyl, and other functional groups that can interact more readily with several classes of natural dyes. Traditional mordants, including alum, ferrous sulfate, copper sulfate, and tin salts, promote dye fixation by forming coordination complexes with suitable functional groups in the dye and fiber. Growing interest in sustainable textile processing has encouraged the use of bio-mordants derived from agricultural by-products and renewable biological resources. Examples include pomegranate peel, myrobalan (*Terminalia chebula*), gallnuts, spent tea leaves, and tamarind-derived extracts. These materials contain tannins, polyphenols, and other functional compounds capable of interacting with natural dyes and textile substrates. Chitosan, a renewable biopolymer, is also investigated as a surface-modifying and dye-fixation agent.

Table 1: Key Agricultural Crops and Residues for Natural Textile Dyeing

Crop / Waste Source		Primary Chromophore	Colour Obtained	Substrate Affinity
Turmeric (Curcuma longa)		Curcumin (Diarylheptanoid)	Bright Yellow	Cotton, Silk, Wool
Madder Root (Rubia tinctorum)		Alizarin & Purpurin	Crimson Red / Pink	Wool, Silk, Cotton
Indigo Leaves (Indigofera tinctoria)		Indican / Indigotin	Deep Blue	Denim, Cotton, Linen
Pomegranate Peel		Hydrolysable Tannins	Yellowish Brown	Cotton, Wool, Silk
Avocado & Custard Apple Peels		Catechins & Flavonoids	Pinkish Brown to Beige	Cotton, Silk, Linen

5. Functional Properties and Sustainability Impact

Beyond providing eco-friendly aesthetics, plant-derived dyes impart valuable functional biological attributes to textiles due to active phytochemicals:

• **Antimicrobial & Antibacterial Performance:** Polyphenolic compounds, tannins, and flavonoids inherent in plants like madder, pomegranate, and henna exhibit potent antibacterial activity against Gram-positive and Gram-negative bacteria.

• **UV Protection & Antioxidant Activity:** Dyeing cotton and wool with agricultural crop extracts (e.g., waste pomegranate rind or orange peel) achieves excellent Ultraviolet Protection Factors (UPF 50+), shielding human skin from harmful radiation.

• **Health & Consumer Safety:** Natural textiles infused with medicinal herbs form the basis of 'Ayurvastra' (curative wellness textiles), widely used for sensitive skin, infants, and medical apparel.

• **Environmental Footprint & UN SDGs:** Natural dyes possess a 40% lower carbon footprint and up to 80% lower Effluent Treatment Plant (ETP) costs compared to synthetic dyeing processes. Their implementation directly aligns with UN Sustainable Development Goals, including SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

6. Industrial Challenges

Despite compelling ecological benefits, natural dyes face several technical and economic barriers restricting large-scale industrial adoption:

1. Poor Colour Reproducibility: Variations in plant species, maturity stage, soil conditions, and harvest season cause shade inconsistencies across production batches.

2. Moderate Fastness Durability: Natural colorants often display lower light and wash fastness compared to synthetic counterparts, requiring optimized mordanting protocols.

3. Seasonal Raw Material Availability: Agricultural

crop availability is subject to seasonal cycles, necessitating efficient storage or reliance on continuous crop wastes and microbial fermentation.

4. Economic & Standardization Constraints: Higher raw material volumes, longer dyeing cycles, and lack of standardized global protocols increase total manufacturing costs.

7. Conclusion: Natural dyes extracted from agricultural crops and crop waste present a scientifically viable, environmentally responsible, and multifunctional pathway for modern sustainable textiles. By replacing petroleum-based synthetic dyes with biological colorants, the textile industry can drastically diminish toxic effluent discharge, carbon emissions, and health risks. Continued interdisciplinary research spanning green chemistry, biotechnology, process optimization, and standardized waste valorization will be pivotal in establishing cost-effective, scalable, and circular natural dyeing systems for the global textile sector.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 21

Pesticides in a Changing World: Rising use, global trade and the case for smarter crop protection

INTRODUCTION

Pesticides have become an important part of modern crop protection. They help farmers manage insects, weeds, fungi and other organisms that threaten crop health and yield. Yet their benefits come with responsibilities: poorly targeted or inappropriate use can contaminate soil and water, affect non-target organisms, reduce biodiversity and expose people to harmful substances. The challenge for agriculture is therefore not simply to decide whether pesticides are useful, but how to use them effectively while reducing avoidable risks.

The Food and Agriculture Organization of the United Nations (FAO) provides a clear picture of the scale of this challenge in its report, Pesticides use and trade 1990–2023. According to the FAO's latest analysis, global agricultural pesticide use reached 3.73 million tonnes of active ingredients in 2023. This was 2% lower than in 2022, but 14% higher than a decade earlier and approximately double the level recorded in 1990 (FAO, 2025). A single year's decline, in other words, does not reverse the longer-term growth in global use.

Global Trends in Pesticide Use and Application Intensity

Pesticide use has changed not only in volume but also in composition. Comparing the 1990s with 2014-2023, the FAO reports a 130% increase in herbicide use, a 58% increase in fungicides and bactericides, and a 48% increase in insecticides. Herbicides also expanded their share of total pesticide use from 40% to 51% while the shares of insecticides and fungicides/bactericides each fell from about 25–26% to 22% (FAO, 2025). These shifts reflect different pest pressures, production systems and crop-management choices across regions.

In 2023, pesticide use averaged 2.40 kilograms per hectare of cropland worldwide. The FAO also reports 0.88 grams per international dollar of agricultural production and 0.45 kilograms per person. Compared with 1990, the per-hectare indicator had risen by 96%, the per-person indicator by 31%, while use relative to the value of agricultural production had increased by 4% (FAO, 2025). These measures provide different perspectives: total tonnage describes scale, use per hectare indicates application intensity, and use relative to production value offers a rough view of pesticide inputs in relation to agricultural output. None alone, however, reveals whether applications were necessary, well timed or environmentally safe.

Trade connects the pesticide landscape

Pesticides are also part of a large international market. In 2023, global exports—measured as formulated products and used by the FAO as a proxy for trade—fell by 3% in volume to approximately 6.7 million tonnes. Their value declined by 12% to USD 42.8 billion. Over the preceding decade, however, export volume increased by 39% and export value by 27% (FAO, 2025).

Asia was the largest exporting region in 2023, with exports of about 3.6 million tonnes worth USD 17.1 billion, including 2.4 million tonnes shipped to other regions. The Americas recorded the largest imports from outside their region, at 1.97 million tonnes, narrowly ahead of Europe at 1.96 million tonnes (FAO, 2025). Trade figures should not be read as direct measures of agricultural application: imported products may be stored for later use, used in public-health programmes, or include formulation ingredients. The distinction matters when comparing trade volumes with pesticide use on farms.

Regional differences call for local solutions

Global averages can hide substantial differences. The Americas have been the largest pesticide-using region since the mid-1990s. In 2023, agricultural use there was 1.84 million tonnes, following a 3% decline from 2022, but still 202% above the 1990 level. Asia used 1.05 million tonnes in 2023, 75% more than in 1990. Europe's use was 444,000 tonnes in 2023 and had declined by 12% since 1990. Africa used 211,000 tonnes, while Oceania's reported use reached 190,000 tonnes (FAO, 2025).

Intensity tells a different story from total volume. Oceania recorded the highest use per hectare of cropland in 2023 at 5.64 kg/ha, whereas the Americas had the highest long-term average per hectare across the period examined. Such comparisons need context: crop mix, climate, pest pressure, cultivated area, reporting coverage and the types of products used can all influence the figures. The practical lesson is that pesticide policy and farmer support should be adapted to local cropping systems rather than based on a single global benchmark.

A new concern: antimicrobial resistance

The FAO brief also highlights azole-based fungicides, a group used to prevent and treat plant diseases. Some azoles can have bactericidal properties, and concern is growing that their use may contribute to antimicrobial resistance, with possible implications for human pathogens. Across data from 64 countries, azole-based fungicides represented an estimated 9% of total fungicides and bactericides. The median share was 13% in Europe, 7% in the Americas, 4% in Asia and 1% in Africa; recent data for Oceania were unavailable (FAO, 2025).

These figures are a starting point rather than a complete global assessment. Better and more consistent reporting would help researchers and decision-makers understand where these products are used, how patterns change, and where stewardship measures may be most useful. The issue also illustrates why pesticide management increasingly intersects with wider One Health concerns linking people, animals, plants and the environment.

From routine spraying to integrated pest management

The most promising response is not a blanket rejection of crop-protection tools, but a move towards more precise, preventive and evidence-based decisions. FAO promotes integrated pest management (IPM), which combines appropriate methods to keep pest populations below damaging levels while reducing reliance on chemical control where feasible. Measures can include resistant or tolerant varieties, clean planting material, crop sanitation, appropriate irrigation and fertilisation, pruning, and disinfection where relevant (FAO, 2025). Monitoring pest populations and applying treatments only when justified can further improve timing and targeting.

For farmers, this approach can mean identifying the pest correctly, checking whether damage warrants intervention, selecting a suitable product, following the label, using protective equipment, avoiding drift and runoff, and storing and disposing of pesticides safely. For governments and the agricultural sector, priorities include farmer training, access to non-chemical options, reliable residue and exposure monitoring, transparent data systems, and support for research into biological control and precision application.

The way forward

The latest global data present a mixed picture: pesticide use fell slightly in 2023, yet remains substantially higher than in earlier decades, and international trade continues at considerable scale. At the same time, regional patterns and emerging concerns such as antimicrobial resistance show that the issue cannot be managed through volume statistics alone. More sustainable crop protection requires better

information about what is applied, where, why and with what results.

A future with productive agriculture and healthier ecosystems depends on treating pesticides as one component of a broader pest-management strategy, not as an automatic first response. Stronger monitoring, practical IPM support and responsible use can help protect crops while reducing risks to farm workers, consumers and the environment.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 22

Unlocking the Nutritional Potential of Fermented Rice

For generations, Indian households have not treated cooked rice as mere leftovers. Instead, they often soak it in water and let it ferment. This straightforward process has produced a wide variety of traditional foods and beverages across India, such as pakhala in Odisha and many fermented rice-water preparations in other regions. These examples illustrate fermentation's integral role in the country's food culture. Traditional Indian fermented rice-based foods show extensive diversity and potential nutritional and functional attributes. Contemporary food science is increasingly investigating the biochemical and nutritional changes that occur during rice fermentation.

Microbial interactions during rice fermentation

Fermentation is a biological conversion in which microbes utilize the nutrients present in food and transform them into organic acids and other metabolites. In traditional fermented foods, these microbes originate from the food itself, the water, the vessel, or the surrounding environment. The composition of the microbial community and the specific fermentation conditions influence the final nutritional, sensory, and biochemical properties of the food (Ray et al., 2016). Traditional Indian fermented foods contain abundant microorganisms, predominantly lactic acid bacteria (LAB). LAB have been the focus of significant scientific research due to their roles in food fermentation and their potential functional properties (Kumar et al., 2013). During rice fermentation, microbes act on carbohydrates, proteins, and other grain components. Fermentation can also influence phytochemicals and mineral availability by modifying the compounds that bind minerals. Thus, fermentation serves not only as a preservation method but also as a process that alters the food's biochemistry.

Traditional practices examined through modern scientific analysis

A 2026 study investigated naturally fermented water from Kerala red rice using advanced analytical techniques. The researchers conducted a combined analysis of biochemicals, shotgun metagenomics, metabolomics, and mineral release to characterize the changes occurring during approximately 18 hours of natural fermentation. Under the experimental conditions, the fermented rice water exhibited a 22.7% increase in carbohydrates, a 163.52% increase in protein, and a 35.47% increase in free amino acids. A diverse range of microbes was detected, and phytase activity increased following fermentation (Hariharamohan et al., 2026). These results should be interpreted with caution, as they pertain to a specific experimental preparation of Kerala red rice water. The findings do not imply that all forms of fermented rice will exhibit identical changes in nutritional content.

Potential effects of fermentation on mineral availability

Cereals naturally contain phytate, which can bind minerals (iron, zinc and calcium) and reduce their availability for absorption. Fermentation can promote phytase activity (an enzyme which degrades phytate). The fermented rice water liberated significantly more calcium, iron, and zinc from the experimental phytate-mineral complexes in the in vitro digestion assay.

It suggests a possible explanation for the nutritional value of traditional fermentation, indicating that it may alter both the quantity and bioavailability of nutrients. Further research is needed to confirm these effects in real diets and across different rice types and fermentation methods.

Potential benefits of fermented rice for gut health

The growing interest in fermented foods is largely attributable to their microbial content and fermentation products. Traditional Indian fermented foods are a rich source of lactic acid bacteria, which have been extensively studied for their potential functional and probiotic applications (Kumar et al., 2013). However, it is important to avoid assuming that the presence of microbes in fermented food directly translates to improved gut health from consuming fermented rice. The health effects depend on the specific microbes present, their ability to survive digestion, the food matrix, the quantity consumed, and the individual's overall diet. Fermented rice is therefore more accurately characterised as a potentially functional traditional food rather than a probiotic in the strictest sense.

The role of resistant starch in fermented rice

A notable nutritional aspect of cooked and cooled rice is the alteration of starch structure due to cooling. Some starch becomes less digestible, forming resistant starch, which can reach the large intestine and be utilized by gut microbiota. Fermentation adds another dimension as the microbes can alter the starch and other carbohydrates. Research on fermented rice products shows that fermentation can affect the nutritional profile and functional properties, although the effect varies by rice variety, fermentation process, and microbes involved. India's traditional rice foods: beyond leftovers: more than leftover. A key aspect of fermented rice is how it integrates traditional knowledge with modern scientific understanding. Pakhala, a traditional Odia preparation, involves fermenting cooked rice in water and is particularly associated with the hot summer months. The recipe may include curd, cucumber, cumin, onion, and mint (Kumari et al., 2022). These foods were developed before terms such as probiotic, phytase, or metabolomics entered the scientific lexicon. Modern research does not suggest that traditional communities understood the molecular basis of these processes. However, traditional food systems offer valuable starting points for scientific investigation.

However is fermented rice always safe?

Fermentation is not the same as leaving cooked rice out at room temperature for an uncontrolled period. Cooked rice can contain *Bacillus cereus* spores (a microorganism that is associated with food poisoning). The spores can survive the cooking process and may germinate if the cooked rice is stored under conditions which are conducive to bacterial growth. The research indicates that temperature and storage time are the key factors in controlling the risk. Traditional fermentation may involve specific ingredients, temperatures, vessels, and durations, but these factors are not always standardised. Safe handling and temperature control remain essential. Contamination is a potential risk and may not always be detectable by sight, smell, or taste.

From leftover to functional food

Fermented rice is at the nexus of traditional knowledge, microbiology, nutrition, food chemistry and sustainability. Fermentation can alter rice's biochemical profile, affect the microbial community, and modify the food itself. The extent of these changes is demonstrated in recent work on Kerala red rice, where the application of modern techniques (metagenomics and metabolomics) has revealed a great deal of complexity. The immediate priority is not to replace traditional foods with laboratory-designed alternatives, but to understand them more thoroughly. Key questions include identifying the microbes responsible for beneficial changes, determining how rice variety and fermentation duration affect nutritional quality, and developing methods to standardize beneficial aspects of fermentation while managing food safety risks, real lesson of fermented rice is not that 'yesterday's rice is a superfood'. Rather, some of our oldest food traditions may contain

biological processes that we're only just beginning to understand through modern science.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 23

Scope of Vegetable Cultivation: Opportunities, Difficulties, and Prospects for the Nagaland Region

ABSTRACT

Nagaland is a northeastern Indian state with diverse agroclimatic conditions, hilly terrain, and abundant natural resources. The region offers significant potential for cultivating a wide range of vegetables, including cabbage, cauliflower, tomato, potato, brinjal, chilli, beans, peas, pumpkin, and indigenous leafy vegetables. Growing demand for fresh and nutritious vegetables, growing awareness of healthy diets, and opportunities for organic and sustainable farming have created promising prospects for vegetable production.

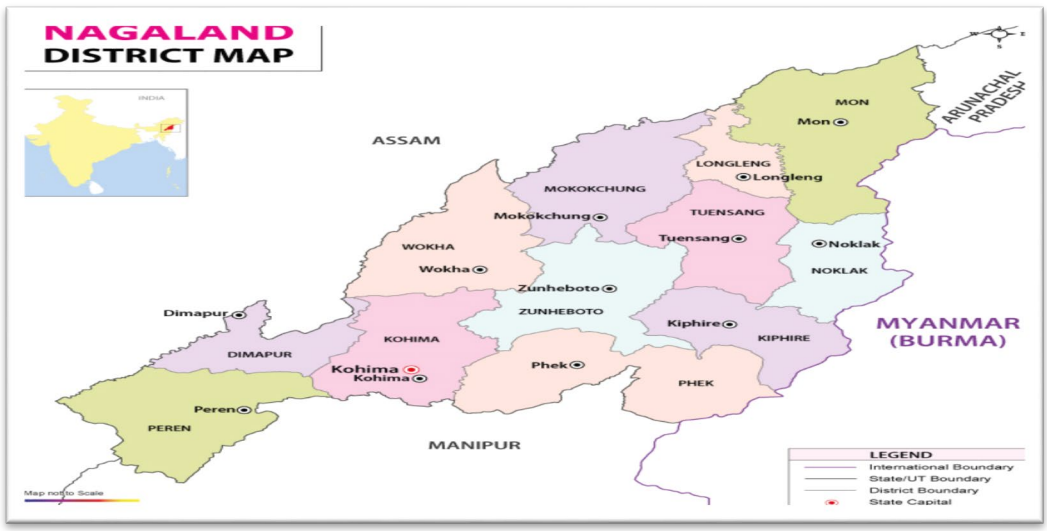
Keywords: Vegetable cultivation, Nagaland, livelihood security, market potential

Introduction

The Indian horticulture sector has experienced remarkable growth over the past decades and has become a significant source of revenue for the government and a vital contributor to the nation's economy. It also helps reduce poverty in agrarian communities (Jamir and Ezung, 2024). The Northeastern regions of India are located with sharing about 98% international border with Bhutan, China, Myanmar and Bangladesh between 21.5°N - 29.5°N latitude and 85.5°E – 97.3°E longitude. This region accounts for only 8% (2,62,230 km^2) of the total geographical area of the country.

The region is blessed by various agro-climatic zones which supporting the rich in flora, which is home to a diversity of underutilised fruits and vegetables (Behera and Dubey, 2023). Traditional farming methods here rely heavily on natural composting and organic practices, making local produce well suited to the growing market demand for organic food (Kumar and Konyak, 2023).

Present Status of Vegetable Production



Vegetable cultivation occupies an important position in Nagaland's horticultural sector. The farmers grow both commonly grown vegetables and locally preferred indigenous vegetables

Table 1: Area, Production and Productivity of vegetables

Year	Area (ha)	Production (MT)	Productivity(kg)
2022-23	42497.44	46479.00	294.72
2023-24	42515.48	456938.00	264.84
2024-25	42463.06	456027.31	286.98

Source: Government of Nagaland, *Nagaland Economic Survey*, 2025-2026.

Table 1 shows that the area under vegetables remained relatively stable during the three years. However, production and productivity fluctuated. The improvement in productivity during 2024–25 compared with 2023–24 indicates that there is scope to increase production through better management of existing cultivated land rather than relying only on expansion of area.

Agro-climatic conditions of Nagaland for Vegetable cultivation

Nagaland has a predominantly hilly landscape with considerable variation in altitude and climatic conditions. Such variation provides opportunities for growing different vegetables according to location and season. The researchers found that integrated nutrient management significantly improved growth, yield, quality and economic performance of French bean (Changkiri *et al*., 2024).

Geographical Indications (GI)

Identify agricultural products whose quality, reputation, or characteristics are essentially linked to a particular geographical region. In vegetable science, GI recognition is important because it can help protect indigenous vegetable varieties, traditional production systems, local knowledge, and farmers' market identity.

GI-tagged product	GI registration	When	Why it received GI recognition
Naga Mircha (Naga King Chilli/Raja Mircha)	Agricultural, Class 31	**2008** (certificate dated 2 Dec 2008)	Distinctive Naga origin, characteristic pungency/flavour and traditional cultivation/use in Nagaland.
Naga Tree Tomato	Horticultural product (Tomato), Class 31	**23 March 2015**	Traditionally grown across Nagaland and has distinctive organoleptic/quality characteristics associated with the region.
Naga Cucumber	Agricultural, Class 31	**14 September 2021**	Known for its distinctive **sweetness and green colour with a yellow tinge**, and its traditional cultivation in Nagaland.

Important Local Vegetable Varieties and Landraces of Nagaland

Nagaland is home to a wide variety of native vegetables, including traditional landraces, farmer-selected cultivars, and several regionally adapted kinds. They have developed under a variety of agroclimatic conditions and traditional farming practices. Significant regional vegetable types

Vegetable crop type or name	Local/indigenous
✓ Cucumber	Naga Cucumber
✓ Chilli (Naga Mircha)	Naga King Chilli

- ✓ Tree tomatoNaga Tree Tomato
- ✓ Brinjal Local Naga Brinjal
- ✓ French bean Naga Bean / Local Climbing Bean
- ✓ Pumpkin Local Naga Pumpkin
- ✓ Colocasia Local Naga Taro
- ✓ Bottle gourd Local Naga Bottle Gourd
- ✓ Bitter gourdLocal Naga Bitter Gourd
- ✓ Cowpea Local Naga Cowpea
- ✓ Yard-long bean Local Naga Yard-long Bean
- ✓ Amaranth Local Naga Amaranth
- ✓ Mustard greens Local Naga Mustard Greens
- ✓ Squash Local Naga Squash
- ✓ Tomato Local Naga Tomato

Protected Cultivation: Producing Beyond Natural Limitations

In order to lessen the negative impacts of climatic and environmental pressures, crops are produced in partially or totally controlled environments in a protected cultivation method. Farmers utilise inexpensive bamboo polyhouses that have UV films with a thickness of 200 microns. This keeps winter crops warm and shields crops that are susceptible to monsoon rains, like tomatoes. Structures that include greenhouses

i. Polyhouses
ii. shade-net homes
iii. low tunnels
iv. drip irrigation
v. mulching
vi. fertigation
vii. enhanced nursery systems
viii. controlled-environment production, and
ix. insect-proof nets

5. Off-season Vegetable Production

Cultivating crops during the off-season is one of the best opportunities available. Vegetable prices fluctuate based on supply; when production drops in major growing regions, vegetables cultivated elsewhere can fetch better prices. The climatic diversity in Nagaland creates the perfect conditions to capitalise on such opportunities. Examples of off-season varieties.

- ➢ Tomato: Arka Abhed, Rocky, Pusa Sheetal, Sheetal Hybrid
- ➢ Cabbage: Rareball, Pusa Ageti, Bajrang, Green Boy, Green Express
- ➢ Cauliflower: Pusa Early Synthetic
- ➢ Broccoli: Green Magic
- ➢ Pea: Arkel, Azad P-1
- ➢ Onion: N-53, Arka Kalyan, AFDR, Baswant-780
- ➢ Cucumber: Naga Sweet Cucumber

Jalwania *et al*. (2025) reviewed protected cultivation technologies for off-season vegetable production and identified greenhouses, polyhouses, net houses, low tunnels and other protected structures as important technologies for maintaining favourable crop environments.

5. Quality Planting Material: The First Link in the Value Chain

A high-performing vegetable industry begins with the seedling. Poor-quality planting material can limit productivity before the crop even enters the field. Its State Horticulture Nursery reports a semi-automated vegetable seedling production unit with a capacity of approximately 70,000 quality seedlings per batch. This creates scope for:

- ✓ Quality vegetable seedlings
- ✓ Disease-free planting material
- ✓ Commercial nurseries
- ✓ Youth entrepreneurship
- ✓ Cluster-based vegetable production

7. Organic and Low-input Vegetable Production

Nagaland has considerable scope for organic and ecological production systems. The state implements the Mission for Organic Value Chain Development for North-East Region (MOVCD-NER) alongside other horticultural programmes. For a premium market, farmers need some combination of:

- ✓ Credible production standards
- ✓ Traceability
- ✓ Certification or appropriate verification
- ✓ Quality consistency
- ✓ Branding
- ✓ Market access

Therefore, Nagaland should focus on organic value chains, not merely organic production.

8. The Hidden Problem: Post-harvest Loss

Vegetables are highly perishable. The Horticulture Department explicitly identifies post-harvest and consumption losses. Reducing post-harvest losses can increase effective production without cultivating additional land. Hence, investment in: Collection centres, pack houses, Grading, Sorting, Packaging, Cold rooms, Storage, Efficient transportation

9. Processing and Value Addition

Fresh vegetables have limited shelf life. Processing can transform a temporary surplus into a longer-lasting product. Examples include: Pickles, Chutneys, Sauces, dried vegetables, Fermented products, Purees, and Ready-to-Cook products. Surplus produce should become processed value rather than wasted biomass. This creates additional employment for Women entrepreneurs, Self-help groups, Farmer organisations, Rural youth, and small food-processing enterprises.

10. Farmer Organisations

A major challenge for small farmers is fragmented production. One farmer may have little bargaining power. But a group of farmers producing a standardised crop can collectively negotiate: (Inputs, Transportation, Packaging, Wholesale prices, Institutional buyers, Processing contracts). Nagaland's MIDH framework explicitly promotes aggregation through farmer interest groups, FPOs and FPCs to achieve economies of scale.

11. Water: The Paradox of a Rain-rich State

Rainfall does not automatically mean reliable irrigation. Nagaland's rugged terrain and irregular rainfall patterns can produce periods of water shortage despite substantial rainfall. The Department of Horticulture identifies water-resource creation as an important intervention and reports the use of community tanks, farm ponds and reservoirs. Drip irrigation, mulching and water harvesting can increase the productivity of each unit of water.

12. Regional Market Expansion

The future market for Nagaland vegetables should not be restricted to individual villages or local markets. There is scope to develop stronger linkages with regional markets across Northeast India. But regional trade requires this is why a cluster of organised farmers can be more economically powerful than many isolated producers.

13. Employment Generation

Vegetable cultivation is labour-intensive across its entire value chain. Employment can arise. This means vegetable development can create employment not only for farmers but also for: Rural youth, Women, Entrepreneurs, transport operators, Food processors, Retailers, Agricultural service providers

Conclusion

The scope of vegetable cultivation in Nagaland is substantial and strategically important. The state already has a large vegetable production base, while its government recognises that its diverse agro-climatic conditions provide an underexploited comparative advantage. The greatest scope for vegetable cultivation in Nagaland is not an expansion of acreage; it is an expansion of value. If Nagaland can convert its ecological diversity into production advantage, production into marketable surplus, surplus into value-added products, and value into farmer income, vegetable cultivation can become much more than a farming activity.

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Just Agriculture Multidisciplinary *e- newsletter*

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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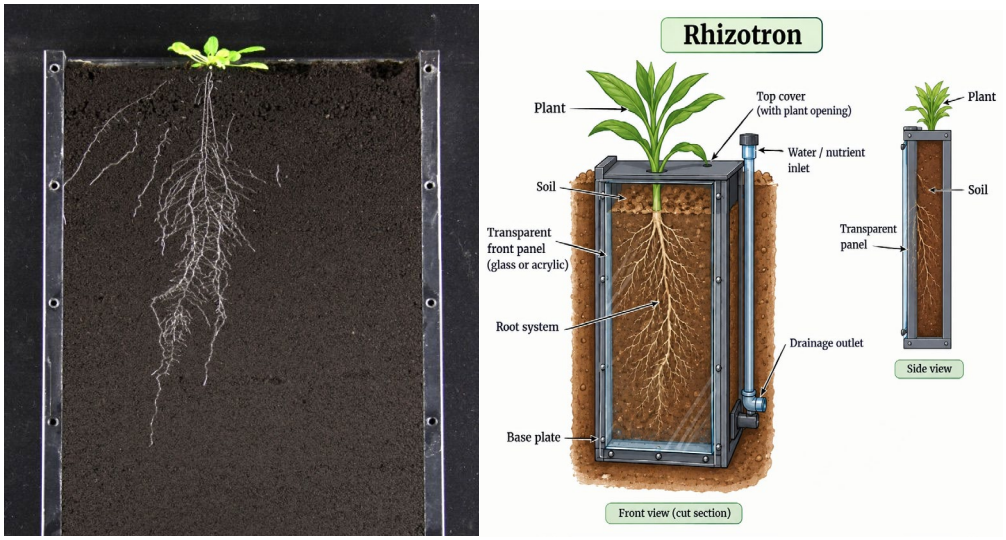
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ARTICLE ID: 24

Rhizotron: A Window into the Hidden Half of Plants

Introduction:

When we admire a field of healthy green crops, we are looking at only half the story. The other half, the roots, grows quietly underground, drawing water and nutrients and holding the plant firmly in place. Because roots are hidden in soil, they have long been the most neglected part of the plant. Digging them out is the usual way to study them, but this destroys the very system we want to understand. Scientists needed a better way, and the answer was a window into the soil. That window is called a rhizotron.



Rhizotron(https://share.google/FaVbI5vnnnSHqSvlz)

What is a Rhizotron?

The word comes from the Greek rhizos, meaning root, and tron, meaning instrument (Klepper and Kasper, 1994). A rhizotron is a facility or building with transparent viewing surfaces through which underground plant parts can be seen and measured. It lets researchers study roots and shoots together in a field-like environment, and observe the same plants repeatedly over seasons, without disturbing them.

Rhizotrons are usually well instrumented and allow control of drainage. They are excellent for collecting descriptive and semi-quantitative data on how root and shoot systems of different cultivars or species change over time, or in response to treatments such as drought or nutrient stress.

Meet the Rhizotron Family

1. Minirhizotron: the root detective

The idea began with Bates (1937), who pushed pieces of lamp glass into the ground to watch roots growing against them. Bohm (1974) was the first to use the term "minirhizotron" and added a battery-powered light source.

Waddington (1971) later improved the method with fibre optics. Today, even small, low-cost CD-based minirhizotrons are used for young plants and small herbaceous species. They are cheap, reusable and thin enough that they hardly hide the roots growing in the middle of the soil, making them ideal for long-term tracking of root form (Cassidy et al., 2020).

2. Above-ground rhizotron: no digging required

Underground installations are expensive and demand heavy labour, so researchers developed above-ground versions that are far easier to use. The first was built by Wright and Wright (2004): a star-shaped unit with eight glass panels, suitable for both greenhouse and field. A larger version designed by Silva and Beeson (2011) helped study how roots of woody plants grow naturally, and how low soil moisture affects them, thanks to its drainage facility.

3. Rhizobox: a soil sandwich

Used by Wenzel et al. (2001) in controlled environments, a rhizobox is a slim chamber of soil with a transparent acrylic pane. It imitates natural conditions, and a digital camera pointed at the pane records how roots spread and branch.

4. Rhizoponics: roots in water

This hydroponic version offers easy access to roots while giving full control over the root environment. It is portable and inexpensive, and fits inside growth cabinets. Mathieu et al. (2015) used it to study the root system architecture of adult Arabidopsis plants.

5. Wetland rhizotron: roots in flooded soils

Even waterlogged habitats can be studied. Busch et al. (2006) compared two wetland sedges, Eleocharis cellulosa and Rhynchospora tracyi, under different water levels and phosphate supply. As water rose, E. cellulosa showed bigger gains in root density, root biomass, shoot length and shoot biomass than R. tracyi, revealing how differently species cope with flooding.

How Do You Measure a Root Through Glass?

Early researchers simply marked root positions on the outside of the viewing panel. Later, rectangular grids and wire grids embedded in the panel (Huck and Taylor, 1982) made measuring root length more systematic. For finer details such as diameter and surface area, a microscope gives much greater accuracy.

Software That Reads Roots

Modern rhizotron work relies on image analysis. Some popular tools are:

- **RhizoVision Explorer**: a free, open-source program that measures root length, diameter and volume from scanned or digital images.
- **SmartRoot**: an ImageJ plug-in for tracing and analysing complex root system architecture.
- **GiA Roots**: software built for high-throughput analysis of root architecture traits.
- **WinRhizo**: a commercial system, widely used with specialised scanners to study root morphology.
- **IJ_Rhizo / ImageJ**: open-source image processing with custom macros for scanned root samples.

The Road Ahead

Rhizotrons bridge the gap between artificial laboratory settings and destructive field sampling. By allowing real-time, non-destructive observation of the rhizosphere, they give vital insights into root architecture, nutrient uptake and partnerships with soil organisms. The data they provide help in developing climate-resilient crops and sustainable farming practices, which is crucial in meeting the global challenge of food security. The next time you see a green field, remember that a remarkable story is unfolding below, and the rhizotron lets us read it.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 25

Artificial Intelligence and Agricultural Robotics for Precision Weed Management in India: Opportunities, Challenges and Future Prospects

Abstract

Artificial intelligence (AI), machine learning (ML), computer vision, drones and agricultural robotics are emerging as promising technologies for improving the efficiency and sustainability of Indian agriculture. Weed management is a particularly important application because weeds compete with crops for essential resources, increase cultivation costs and may contribute to herbicide resistance when control practices are inappropriate or repeatedly relied upon. Conventional weed management through manual labour, mechanical operations and blanket herbicide application faces challenges related to labour availability, operational costs and the need for timely intervention. AI-enabled systems can identify weeds, map their distribution and guide selective mechanical or chemical control. Robotic weeders integrate observation, action, guidance and mapping to enable precise, automated field operations, while drones support remote sensing and weed-infested area identification. This article reviews the potential of AI and robotics for weed management in India, with particular relevance to groundnut, cotton and other crops cultivated in Gujarat. It also discusses the technological, economic and institutional constraints affecting adoption and highlights the importance of locally validated AI models, custom-hiring services and integration with integrated weed management. Successful adoption will depend on affordability, field-level performance, crop safety and demonstrable economic and environmental benefits.

Keywords: Artificial intelligence, agricultural robotics, weed management, machine vision, precision agriculture, drones, smart sprayers.

1. Introduction

Indian agriculture is increasingly exploring digital technologies to improve productivity, resource-use efficiency and environmental sustainability. Artificial intelligence (AI) enables computer systems to analyse images, recognise patterns and support decisions using agricultural data. When integrated with machine vision, sensors, geographic information systems (GIS), unmanned aerial vehicles (UAVs) and automated machinery, AI can facilitate precise crop management.

Weed management is a suitable area for these applications because weed species, density and distribution vary across fields. Manual weeding requires considerable labour, while conventional herbicide application may treat areas where weed infestation is limited. Delayed control can allow weeds to compete with crops during critical growth stages.

AI-enabled weed management follows a targeted approach: **detect the weed, identify its location, select an appropriate control method and apply the intervention precisely.** This approach can improve the efficiency of mechanical weeding and herbicide application while generating useful information for future field management. However, AI should complement established agronomic practices rather than replace integrated weed management.

2. Artificial Intelligence in Weed Management

AI-based weed management combines image processing, machine learning, deep learning, remote sensing and automated decision-making. Cameras capture field images, while algorithms analyse plant colour, shape, texture, leaf structure and spatial relationships to distinguish weeds from crops.



Machine-learning and deep-learning methods, including convolutional neural networks and object-detection models such as YOLO, can identify individual plants or weed-infested areas. Image-segmentation methods can further identify the precise boundaries of weeds, supporting targeted treatment.

The effectiveness of these models depends on the quality and diversity of their training data. Differences in crop varieties, weed species, soil backgrounds, lighting, plant growth stages and field conditions can affect detection accuracy. Therefore, models developed in other countries must be validated under Indian agricultural conditions before practical recommendations are made.

An AI-enabled weed management system generally involves six stages: data acquisition, image processing, weed detection, spatial localisation, control action and post-treatment verification. Accurate detection alone is insufficient; the complete system must position and operate its equipment correctly to achieve effective weed control without damaging crops.

3. Robotic Weed Management

Agricultural robots integrate AI, machine vision, navigation systems and specialised tools to identify and remove weeds with limited human intervention. They may be self-propelled or attached to conventional farm machinery. Depending on their design, they can operate between crop rows or perform selective weed control within crop rows.

Four major functions underpin robotic weed management:



1. Observation: Cameras and sensors capture field images and identify weeds using AI-based recognition systems.

2. Action: Specialised end-effectors perform weed control through mechanical removal, targeted herbicide application, thermal treatment or electrical methods.

3. Guidance: GPS/GNSS, cameras, wheel encoders and other navigation technologies guide the robot through crop rows and help position the control equipment accurately.

4. Mapping: Weed locations and infestation patches are recorded spatially to support targeted treatment, subsequent scouting and future management decisions.

Mechanical robotic weeders use blades, hoes or rotating tools to remove weeds. Smart sprayers apply herbicides selectively to identified targets, potentially reducing unnecessary chemical application. Thermal and electrical systems provide alternative approaches where their energy requirements, crop safety and economics are suitable.

Research by Upadhyay *et al*. (2024) reviewed ground robotic technologies for site-specific weed management, while Balabantaray *et al*. (2024) investigated robotic weed targeting using the YOLOv7 deep-learning model. These studies demonstrate technological progress, although their results should not be interpreted as direct proof of effectiveness under all Indian farming conditions.

4. Drone Technology and Precision Weed Mapping

Unmanned aerial vehicles provide a rapid means of collecting field images for crop monitoring and weed mapping. Equipped with RGB or multispectral cameras and positioning



systems, drones can capture georeferenced imagery that is analysed using AI, image processing and GIS.

A typical workflow involves surveying the field, processing the imagery, identifying possible weed patches, generating a spatial weed map and verifying the findings through ground scouting. The map can then guide targeted spraying or mechanical weed control.

Multispectral imagery can help distinguish vegetation from soil and identify differences in plant condition. However, vegetation indices alone cannot reliably identify every weed species because crops and weeds may exhibit similar spectral characteristics. High-resolution imagery, crop-row information and locally validated classification models may be necessary.

It is important to distinguish between weed mapping and weed treatment. A drone may only collect images, while ground machinery performs the actual control operation. Drone-based spraying is a separate application subject to applicable pesticide-use requirements and aviation regulations.

Smart sprayers complement this approach by connecting weed detection with electronically controlled nozzles. Edge computing allows image processing to occur directly on the equipment, reducing dependence on continuous internet connectivity. Actual herbicide savings depend on weed distribution, detection performance, equipment calibration and the effectiveness of the conventional method used for comparison.



5. Opportunities for AI Adoption in Indian Agriculture

AI and robotics offer several potential benefits, including more accurate weed detection, improved timeliness, reduced unnecessary spraying, lower repetitive labour requirements and better field records. However, these benefits must be demonstrated under actual operating conditions.

India's digital agriculture initiatives provide an enabling environment for technology adoption. The Digital Agriculture Mission supports digital agricultural infrastructure, while Bharat-VISTAAR aims to improve access to agricultural information and advisory services through AI-enabled, multilingual systems. The Namo Drone Didi programme promotes drone services through women's self-help groups, providing a potential mechanism for shared access to precision-agriculture operations. These initiatives support the broader digital agriculture ecosystem but should not be interpreted as evidence of widespread adoption of autonomous robotic weeders.

Agricultural universities, ICAR institutes, Krishi Vigyan Kendras and extension organisations have an important role in developing local weed datasets, validating AI models, testing equipment and training farmers and operators.

In Gujarat, groundnut, cotton, pearl millet, sesame and other crops provide opportunities for region-specific research. In groundnut and cotton, camera-guided inter-row cultivation and targeted spraying may be promising where crop establishment and row spacing permit machinery operation. However, weed identification becomes more difficult when crop foliage overlaps or weeds grow close to crop stems. Research at Junagadh Agricultural University and similar institutions could evaluate these technologies under Saurashtra's soil, rainfall and cropping conditions.

6. Challenges and Strategies for Adoption

Despite rapid technological development, several constraints limit large-scale adoption.

- **High investment costs:** Advanced robots require cameras, sensors, computing systems, navigation equipment and specialised actuators. Shared machinery services and custom-hiring centres may make these technologies more accessible to smallholder farmers.

- **Limited local datasets:** AI models trained on limited or non-representative images may perform poorly in new environments. Region-specific datasets covering important weeds, crop growth stages and field conditions are therefore essential.
- **Crop–weed confusion:** Similar-looking seedlings, shadows, dust and overlapping leaves can reduce detection accuracy. Systems should incorporate crop-row information, suitable sensors and manual override options where necessary.
- **Field variability and operational limitations:** Uneven terrain, soil conditions, residue, navigation errors and actuator delays may affect performance. Testing should assess the complete system under realistic field conditions.
- **Maintenance and digital skills:** Farmers and operators require training in equipment operation, calibration, maintenance and troubleshooting. Offline functionality and simple local-language interfaces can improve usability.
- **Economic feasibility:** Adoption decisions should consider capital costs, depreciation, labour, fuel or electricity, maintenance, software and service charges. Custom-hiring arrangements may be more practical than individual ownership, depending on field size and annual equipment use.

AI-enabled weed management must also be integrated with sound herbicide stewardship. Targeted spraying does not eliminate the need for appropriate herbicide selection, mode-of-action rotation, crop rotation, mechanical control and monitoring for herbicide resistance.

7. Future Prospects and Conclusion

Future research should focus on affordable robotic weeders, lightweight deep-learning models, locally representative datasets, real-time detection, reliable navigation and modular equipment suited to Indian crops. Integration with integrated weed management can combine preventive, cultural, mechanical and chemical methods according to the crop and weed situation.

Agricultural research institutions should compare AI-enabled weed management with recommended conventional practices using weed density, control efficacy, crop injury, labour requirements, operational capacity, herbicide use, crop yield and economic returns. Such evaluations are necessary to determine whether a technology provides a meaningful advantage over existing alternatives.

AI, robotics and drone-based sensing offer significant opportunities to modernise weed management in Indian agriculture. Nevertheless, their effectiveness depends on local validation, affordability, reliable operation and farmer acceptance. For Gujarat and the Saurashtra region, crop-specific research in groundnut, cotton and other important crops can help identify practical applications and suitable adoption models.

The future of weed management in India lies in combining agronomic expertise with intelligent, affordable and locally validated technologies. AI and robotics can contribute to more precise and sustainable agriculture when they strengthen integrated weed management and deliver measurable benefits under real farming conditions.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 26

Integrated Management of Plant Viral Diseases in Agricultural Crops

Abstract

Plant viral diseases pose a significant threat to agricultural productivity, causing symptoms such as leaf curling, mosaic, yellowing, and stunted growth, resulting in considerable yield and quality losses. Since effective curative treatments are generally unavailable after infection, preventive and integrated management strategies are essential. These strategies include cultural practices, sanitation, physical barriers, vector management, host resistance, and biotechnological tools for early and accurate virus detection. In Northeast India, diverse agroclimatic conditions and the cultivation of important crops such as tomato, chilli, and king chilli (*Capsicum chinense*), locally known as U-Morok in Manipur, highlight the need for effective management of viral diseases. Whiteflies, aphids, thrips, and other insect vectors contribute to the transmission of several plant viruses, making regular field monitoring, the use of healthy planting materials, removal of infected plants, and appropriate vector management particularly important. Host resistance breeding, diagnostic techniques such as ELISA and PCR, and emerging technologies such as RNA interference and CRISPR/Cas offer additional opportunities for disease prevention and management. An integrated, region-specific approach supported by farmer awareness and extension services is essential to reduce crop losses, strengthen sustainable crop production, and improve agricultural resilience in Northeast India.

Introduction

Plant viral diseases represent a major constraint to agricultural productivity worldwide. Unlike fungal or bacterial pathogens, viruses cannot be observed directly with the naked eye; however, their effects on crops are severe. Viral infections commonly produce symptoms such as leaf yellowing, mosaic patterns, leaf curling, and stunted growth. These symptoms significantly reduce both crop yield and quality, resulting in considerable economic losses for farmers.

Unlike many other plant pathogens, there are no curative measures available once a plant becomes infected with a virus. Therefore, the management of plant viral diseases requires a comprehensive and preventive approach. Integrated management of viral diseases involves the use of multiple strategies such as cultural practices, host resistance, vector control, sanitation, and modern biotechnological tools to reduce virus spread and minimize crop losses.

What are Viral Diseases?

Plant viruses are microscopic infectious agents that depend entirely on living host plants for survival and multiplication. They are primarily transmitted through several routes, including:

- Insect vectors such as aphids, whiteflies, and leafhoppers
- Infected seeds and vegetative planting materials
- Mechanical transmission through contaminated tools or human handling

Some common viral diseases include leaf curl disease of chilli and tomato, yellow vein mosaic of okra, banana bunchy top disease, and papaya leaf curl disease. These diseases are widely prevalent and pose serious threats to crop productivity.

Challenges in Managing Viral Diseases

Management of viral diseases is particularly difficult due to several factors:

- No effective chemical cure is available once infection occurs.
- Viruses spread rapidly, especially through insect vectors.
- Symptoms often appear after the infection has already established within the plant.

These characteristics make early prevention and integrated management essential for effective disease control.

Key Components of Integrated Management of Viral Diseases

1. Cultural and Agronomic Practices

Cultural and agronomic practices play an important role in reducing the incidence of viral diseases in crops. These practices include the removal and destruction of infected plants to prevent further spread of infection, maintaining proper plant spacing to avoid overcrowding and reduce vector movement, practicing crop rotation to break disease cycles, and avoiding continuous cultivation of the same crop in the same field. The adoption of these cultural measures helps minimize the chances of disease transmission and contributes to improving overall crop health and productivity.

2. Physical Methods

Physical methods play an important role in reducing vector entry and preventing virus transmission in crops. The use of physical barriers such as insect-proof nets in nurseries effectively protects young seedlings from infestation by insect vectors that transmit viral diseases. In addition, mulching practices help repel insect vectors and limit their movement within crop fields. These physical measures contribute significantly to lowering the chances of viral infection and improving overall plant protection.

Eg. Yellow polythene mulch and reflective mulches may help manage whitefly populations in tomato and cucurbit crops. These mulches can interfere with the attraction and landing behaviour of insect vectors, thereby reducing whitefly colonization and potentially limiting the spread of whitefly-transmitted viral diseases. Sawdust mulch may help conserve soil moisture and suppress weeds, but its effectiveness in reducing whitefly populations and viral infections is less established. Therefore, mulching should be combined with yellow sticky traps, removal of virus-infected plants, and other integrated pest management (IPM) practices.

3. Sanitation and Exclusion

Sanitation and exclusion measures are essential for preventing the introduction and spread of viral diseases in crops. The use of certified virus-free seeds and planting materials is strongly recommended to minimize the risk of primary infection. Regular inspection of nursery stock is necessary for the early detection of infected plants. Additionally, the removal and destruction of infected plants, crop debris, and weeds help eliminate potential sources of viral inoculum. The elimination of volunteer plants that may serve as virus reservoirs further reduces the chances of disease persistence in the field. Collectively, these sanitation measures significantly reduce primary sources of infection and contribute to effective disease management

4. Vector Management

Vector management is a critical component in the control of plant viral diseases, as many viruses are transmitted by insect vectors such as aphids, whiteflies, thrips, and leafhoppers. Effective control of these vector populations helps reduce the spread of viral pathogens. The use of yellow sticky traps is an important method for monitoring insect populations and detecting the early presence of vectors in the field. The adoption of biological control agents, including natural predators and parasitoids, supports the regulation of vector populations in an environmentally

friendly manner. In addition, the timely and judicious application of recommended insecticides helps control vector populations and prevents excessive spread of viruses. Overall, effective vector management significantly reduces virus transmission and lowers the incidence of viral diseases in crops.

Eg. In Northeast India, chilli leaf curl disease can become a serious problem when whitefly populations increase under favourable environmental conditions. Yellow sticky traps are installed at approximately 4–5 traps per acre to monitor and capture adult whiteflies (*Bemisia tabaci*), which transmit chilli leaf curl-associated viruses. Regular monitoring of whitefly populations, combined with the removal of virus-infected plants and other integrated pest management practices, can help reduce the spread of the disease.

5. Host Resistance Breeding

Host resistance breeding is considered one of the most effective and economical strategies for managing plant viral diseases. The use of resistant or tolerant crop varieties helps reduce disease incidence and minimizes yield losses. Resistant varieties can be developed through conventional breeding methods by selecting and crossing plants with desirable resistance traits. In addition, modern techniques such as marker-assisted selection enable breeders to identify and incorporate resistance genes more efficiently and accurately. In certain cases, cross-protection techniques involving the use of mild virus strains may also be adopted, where appropriate, to protect plants from more severe virus strains. Overall, the use of resistant varieties provides a long-term, cost-effective, and sustainable approach to viral disease management in crops.

6. Biotechnological and Omics Tools

Biotechnological and omics tools provide advanced and innovative solutions for the management of plant viral diseases. Modern biotechnology enables the development of virus-resistant transgenic or genome-edited plants, which enhances the plant's ability to withstand viral infections. Techniques such as RNA interference (RNAi) and artificial microRNAs are widely used to suppress viral gene expression and limit virus multiplication within host plants. In addition, CRISPR/Cas technology has emerged as a powerful tool for the targeted disruption of viral genes, thereby improving resistance against viral pathogens. Early detection of viruses is also possible through advanced diagnostic techniques such as enzyme-linked immunosorbent assay (ELISA), polymerase chain reaction (PCR), and next-generation sequencing, which allow accurate identification of both known and emerging viruses. Overall, these technologies facilitate early detection, improve resistance, and support the effective management of viral diseases in modern agriculture.

7. Awareness and Monitoring

Awareness and monitoring are essential components of effective management of plant viral diseases. Regular monitoring of crop fields is necessary for the early detection of disease symptoms and timely intervention. Frequent field inspections help in identifying early symptoms of viral infection, which allows for prompt action before the disease spreads extensively. Immediate removal and destruction of infected plants reduce the chances of further transmission to healthy plants. In addition, increasing awareness among farmers and extension workers regarding symptom identification and preventive measures supports rapid response and effective disease containment, thereby minimizing crop losses.

Eg. Tomato and king chilli (*Capsicum chinense* Jacq.), locally known as U-Morok in Manipur, are susceptible to several viral diseases that can adversely affect plant growth and productivity. Tomato leaf curl disease is commonly associated with begomoviruses, which are transmitted by the whitefly *Bemisia tabaci*. Similarly, king chilli is affected by chilli leaf curl virus, transmitted by whiteflies, while other viral diseases, such as cucumber mosaic and potato virus Y, can be transmitted by aphid species. These insect vectors contribute to the spread of viral diseases and pose a significant challenge to tomato and king chilli cultivation in Northeast India.

Conclusion

Plant viral diseases pose a serious threat to agricultural productivity and crop quality worldwide. Since effective curative measures are not available once plants become infected, prevention and timely management remain the most reliable strategies for

controlling viral diseases. Integrated management approaches, including cultural practices, physical methods, sanitation, vector control, host resistance breeding, and the application of modern biotechnological tools, provide a comprehensive framework for minimizing disease spread and reducing crop losses.

Regular monitoring, early detection, and increased awareness among farmers further enhance the effectiveness of these strategies. The adoption of integrated management practices not only improves crop health and yield but also promotes sustainable and environmentally friendly agricultural production. Therefore, the consistent implementation of integrated viral disease management strategies is essential for ensuring long-term crop protection, productivity, and food security.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 27

Safe Food for All: The Case for Residue-Free Farming

Every meal begins in a field and what happens there decides what ends up on the plate. As farms have become more dependent on synthetic fertilizers and pesticides, a quiet question has followed: how clean is the food we eat and what is this style of farming doing to the soil, the water and the people who work the land? This article looks at why residue-free farming deserves attention, what the numbers say and how a student-led outreach effort tried to carry the idea to farming families.

The Hidden Cost of Chemical-Heavy Farming

The World Health Organization notes that pesticides can be toxic to people, with effects ranging from acute poisoning to long-term problems, including cancer and reproductive harm, depending on how much exposure occurs and in what way. Those at greatest risk are people who handle these chemicals at work or at home. For the public, exposure through food and water is considerably lower, which is why international bodies set maximum residue limits and call for regular monitoring of food (WHO, n.d.).

The land pays a price too. A global FAO assessment found that roughly one-third of the world's soils are moderately to highly degraded through erosion, salt build-up, compaction, acidification and chemical pollution (FAO & ITPS, 2015). Closer to home, a large ICAR-led analysis of about 254,000 soil samples from 620 districts across 29 states linked falling soil organic carbon to unbalanced fertilizer use, skewed towards urea and phosphorus, along with rising temperatures (The Hindu, 2025). Soil carbon matters because it governs soil structure, water-holding capacity and the microbial life that feeds crops.

Official figures show that Indian farmers used about 58,700 tonnes of chemical pesticides (technical grade) in 2021–22, alongside roughly 8,900 tonnes of biopesticides, which made up about 13% of the total (Lok Sabha, 2023).

A Growing Appetite for Cleaner Food

Consumers and producers are already moving in this direction. By the end of 2022, about 96.4 million hectares of farmland worldwide were managed organically by some 4.5 million producers, while global organic sales approached €135 billion (Willer et al., 2024; FiBL, 2024). India sits near the top of this story. It ranks second in the world by organic area and first by number of organic producers, as the table below shows.

Table 1. Countries with the largest organic farming area, 2022

Rank	Country	Organic area, 2022 (million ha)
1	Australia	53.0
2	India	4.7
3	Argentina	4.1

India also leads in producer numbers, with about 2.5 million (Willer et al., 2024). Government certification records under the National Programme for Organic Production list about 5.4 million hectares of certified cultivable land in 2022–23, plus several million more under wild-harvest collection, although such totals differ according to how each source defines organic land (APEDA, 2023). Either way, organic farming still covers only a small share of India's cropland, which signals a wide gap between potential and practice.

That gap is partly a story of scale. Around 86% of Indian operational holdings are small or marginal, at under two hectares (Department of Agriculture & Farmers Welfare, n.d.). These farmers face the steepest hurdles in making the switch: limited technical knowledge, uncertain yields, costly certification and weak links to buyers.

Taking the Message to the Farm Gate

To test how scientific knowledge could travel beyond the campus, a group of agriculture students ran a community outreach in nearby rural areas, with a special focus on women, adolescent girls, young people and small farmers. Their approach combined several strands:

- **Awareness:** Door-to-door visits, posters and street plays explained how the overuse of pesticides and fertilizers affects health, soil and long-term farm income and why the idea of 'farm to family' safe food is practical as well as ethical.
- **Demonstrations:** Farmers saw how to prepare low-cost natural inputs such as Jeevamrit, Beej Amrit, Ghanjeevamrit, vermicompost, botanical extracts and neem-based preparations.
- **Soil and crop care:** The team helped with soil sampling and encouraged crop rotation, mixed cropping and balanced nutrient management.
- **Nutrition and markets:** Households were encouraged to start kitchen gardens and farmers were introduced to direct selling and closer farmer–consumer links.
- **Feedback:** Participants were asked what worked and what could be scaled up.

What Farmers Can Expect and What Stands in the Way

The hoped-for gains are easy to see. Farmers who replace some purchased inputs with farm-made ones can lower their cash costs, healthier soils tend to hold moisture better and growers who sell directly to local consumers may earn better prices. Households with kitchen gardens gain fresher, more varied food. These are expected benefits rather than guarantees and they will vary by crop, soil and season.

The obstacles are real. Yields can dip during the first seasons of conversion, which discourages many growers. Natural and organic systems demand more labour and closer monitoring. Extension support is thin in many places, certification can be complicated and expensive and fair prices depend on reliable market links.

Still, the direction of travel is encouraging. Demand for chemical-free food keeps rising. Public programmes such as the Paramparagat Krishi Vikas Yojana and the Participatory Guarantee System are making support and certification more accessible to smallholders, while farmer producer organisations and direct-marketing channels are widening market access. Continued research on bio-inputs should help make these methods more productive and more affordable.

Why It Matters Beyond the Farm?

Residue-free farming is more than a technique. It ties together public health, soil conservation, rural livelihoods and the participation of women and youth. When knowledge built in classrooms and laboratories is carried to the people who grow our food, in terms they can use and afford, safe food stops being a slogan and becomes a shared outcome.

Key Takeaways

- Pesticide risk is highest for those who handle the chemicals and monitoring of residues in food remains essential.
- Unbalanced fertilizer use is draining organic carbon from Indian soils.

- India is a global leader in organic producers and area, yet organic farming remains a small share of its cropland.
- Low-cost, locally made inputs, kitchen gardens and direct marketing give small farmers practical entry points.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 28

Fungal pangenomics: a new perspective on genome diversity, evolution, and pathogenicity

Abstract

Fungal genome diversity is increasingly recognised as a key factor shaping pathogenicity, host adaptation, and ecological interactions. However, a single reference genome often insufficient to capture the full genetic content of a fungal species. Fungal pangenomics addresses this limitation by analysing multiple isolates to distinguish conserved core genes from variable accessory and isolate-specific genes. This article discusses the concepts and methodological considerations of fungal pangenome construction, the limitations of reference-genome analysis, and the roles of accessory genes and genome plasticity in fungal evolution. It also explores potential applications in pathogen surveillance, crop resistance breeding, and sustainable disease management, while emphasising the importance of experimental validation.

Introduction

Fungi are among the most versatile organisms on Earth. They decompose organic matter, recycle nutrients, establish beneficial associations with plants, and contribute to the production of enzymes and biologically active compounds. At the same time, many fungi cause destructive diseases in agricultural crops, threatening productivity, grain quality, and food security (Dean et al., 2012).

A genome is the complete set of genetic information carried by an organism. Fungal genomes can vary in gene content and architecture, including the distribution of repetitive DNA and accessory regions (Möller & Stukenbrock, 2017; Bertazzoni et al., 2018). Modern DNA sequencing has enabled scientists to explore fungal genomes in remarkable detail. Isolates within a fungal species can differ in host range, aggressiveness, environmental adaptation, and metabolite production. Therefore, a single genome may not capture the species' full genetic potential. To understand this broader genetic diversity, scientists are increasingly turning to an approach known as pangenomics. The fungal pangenome offers a wider window into the genetic world of fungi, revealing not only genes shared by different isolates but also those present in some isolates and absent in others. These differences can provide clues about fungal evolution, adaptation, interactions with plants, and potential applications in agriculture.

Pan genome and methodological considerations for fungal pangenome construction

Pan-genome analysis, which consist of the total gene repertoire across multiple isolates, allows classification of genes into core genes (present in all isolates), dispensable genes (present in some but not all isolates), and unique genes (specific to a single isolate) (Medini et al., 2005). While core genes typically encode essential cellular processes, dispensable and unique genes often contribute to environmental adaptation, virulence, and host interaction (Fig. 1).

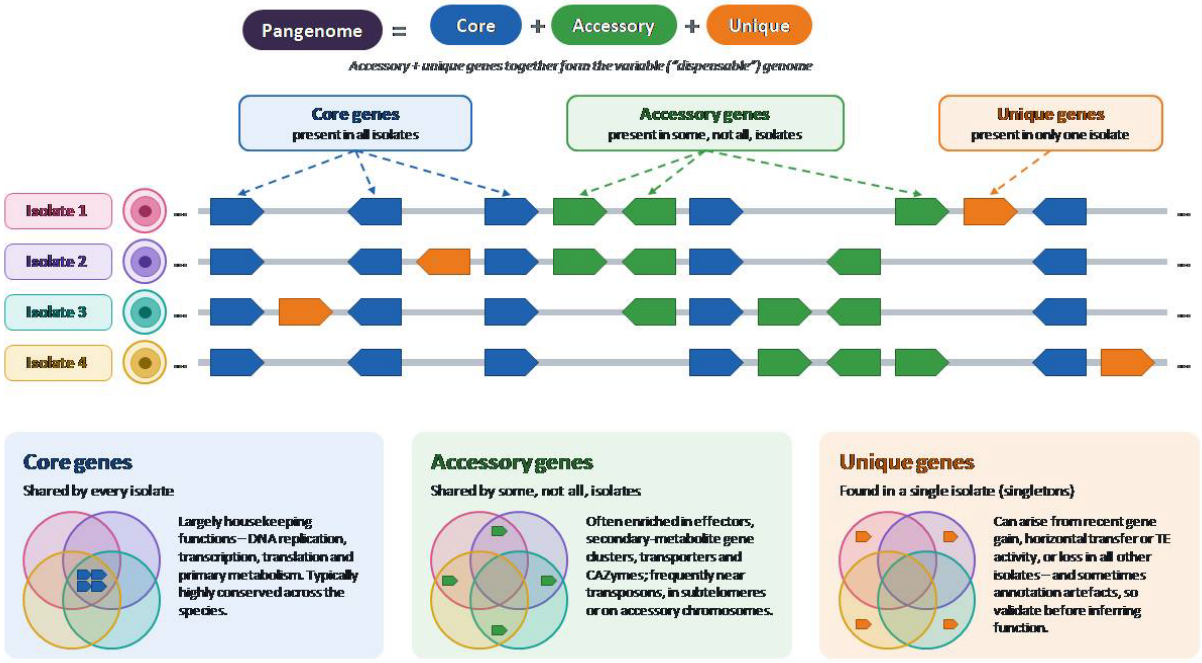


Fig 1. Conceptual representation of the fungal pangenome

The construction of a fungal pangenome requires representative isolate sampling, high-quality genome assemblies, consistent gene annotation, and robust comparative genomic analyses. The selection of isolates should reflect the genetic and ecological diversity of the target species. For plant-pathogenic fungi, relevant sampling criteria may include geographical origin, host genotype, disease severity, and differences in pathogenicity. For beneficial plant-associated fungi, sampling may encompass isolates differing in plant growth promotion, biocontrol efficacy, and environmental adaptation.

Following genome sequencing, quality assessment, assembly, and gene prediction, orthologous gene clustering is performed to establish the shared and variable components of the genome. Subsequent analyses of gene presence–absence variation, gene-family expansion and contraction, and functional annotation can provide insights into genome evolution and identify candidate genes associated with specific biological characteristics.

The accuracy of pangenome reconstruction is strongly influenced by genome completeness, assembly continuity, annotation consistency, and the taxonomic and genetic diversity of the sampled isolates. Incomplete assemblies or inconsistent gene predictions can produce false gene-absence calls, thereby affecting estimates of core and accessory genome composition. Similarly, inadequate or biased sampling may underestimate species-level genomic diversity and influence inferences regarding pangenome openness or closure. These limitations highlight the importance of stringent quality control, standardised analytical workflows, and appropriate sampling strategies.

Limitations of reference-genome analysis and the evolution of fungal genomes

Genome sequencing has transformed fungal biology by enabling gene identification, functional prediction, evolutionary analysis, and investigation of disease-associated mechanisms. However, a reference genome typically represents a single isolate or genome assembly and may not capture the full genetic diversity within a species. Plant-pathogenic fungi can vary in genome size, composition, and architecture, even among closely related isolates (Möller & Stukenbrock, 2017). Similarly, isolates of beneficial fungi may differ in colonisation ability, stress tolerance, and metabolite production.

Table: Genomic insights from plant-pathogenic fungi

Fungal–plant association	Key genomic finding	Significance	Reference
Zymoseptoria tritici–wheat	Pangenome studies reveal extensive gene presence–absence variation and a substantial accessory genome. genome analysis of 5 isolates showed 15,749 non-redundant proteins, including 9,149 core (58.1%) and 6,600 accessory (41.9%) proteins.	Highlights genomic diversity that may contribute to host interaction, adaptation, and pathogenicity.	Plissonneau et al. (2018); Badet et al. (2020)
Fusarium graminearum–wheat/barley	A population-genomic analysis of 60 isolates identified approximately 1,681 accessory genes.	Shows that a single reference genome may not capture the full genetic diversity of a cereal pathogen.	Kelly & Ward (2018)
Magnaporthe oryzae–rice	Bao et al. (2022) analysed 156 strains and identified 24,100 genes, including 16,911 core genes (population frequency ≥95%), 1,378 strain-specific genes (≤5%), and 12,005 genes absent from reference strain 70-15. Zhang et al. (2018) compared 13 Magnaporthales/Sordariomycetes fungi and identified clade-specific evolutionary patterns and positive selection in genes associated with pathogenic lifestyles.	Population-level pangenomics reveals secreted-protein variation within *M. oryzae*, while broader comparative genomics provides evolutionary context for the emergence of pathogenic lifestyles.	Bao et al. (2022); Zhang et al. (2018)
Fusarium oxysporum species complex–multiple hosts	Some members contain lineage-associated genes and accessory chromosomes; accessory genomic regions can contribute to host adaptation and pathogenicity.	Provides a framework for studying host specificity and the evolution of pathogenic traits.	Ma et al. (2010); van Westerhoven et al. (2024)
Ustilaginoidea virens–rice	Pan genome analysis of 8 diverese isolates from India revealed 7,672 gene clusters, comprising 7,025 core (91.6%), 474 dispensable (6.17%), and 173 singleton (2.25%) clusters; 2,429 genes were reported absent from the reference genome.	It may help prioritise candidate genes associated with genomic diversity and adaptation; functional roles require validation.	Unpublished

Consequently, single-genome analysis provides detailed information about an individual isolate, whereas pangenomics enables broader comparisons of conserved and variable genetic content across a defined collection of isolates.

Fungal genome diversity arises through several evolutionary processes, including mutation, recombination, gene duplication and loss, horizontal gene transfer, and structural variation. Comparative pangenome analysis therefore provides a framework for investigating the relationship between genome evolution and phenotypic diversity in plant-pathogenic and beneficial fungi.

However, associations between variable genomic regions and particular traits require further validation through functional and experimental studies.

Beyond the core genome: the significance of accessory genes

Although core genes provide the conserved genetic foundation of a fungal species, accessory and singleton genes contribute to genomic variation among isolates. For example, in the *Fusarium oxysporum* species complex, accessory chromosomes can carry genes associated with host specificity and pathogenicity. The tomato-pathogenic strain F.

oxysporum f. sp. *lycopersici* contains five accessory chromosomes, and chromosome 14 has been linked to pathogenicity towards tomato (Ma et al., 2010).

Similarly, comparative genomic analysis of 69 banana-pathogenic *F. oxysporum* strains revealed substantial diversity in accessory regions, with segmental duplications contributing to their evolution (van Westerhoven et al., 2024). Furthermore, In *Zymoseptoria tritici*, analysis of five reference-quality genomes identified 15,749 non-redundant proteins, including 9,149 core proteins (58.1%) and 6,600 accessory proteins (41.9%), with the variable genome enriched in candidate effectors and other potentially adaptive functions (Plissonneau et al., 2018). In *Magnaporthe oryzae*, comparative analysis of 31 isolates representing five pathotypes revealed substantial variation in candidate effector and avirulence gene repertoires, consistent with differences in host adaptation (Zhang et al., 2018).

These examples demonstrate how variable genomic regions can provide insights into fungal evolution and host adaptation (Table 1). However, the presence of an accessory gene alone does not establish its function; experimental validation is necessary to confirm its contribution to pathogenicity or other biological traits.

Furthermore, fungal diversity is not explained by gene presence or absence alone. Gene duplication, copy-number variation, recombination, and chromosomal rearrangements can also shape genome architecture and contribute to differences among isolates (McCarthy & Fitzpatrick, 2019; Mondo & Grigoriev, 2025). Consequently, pangenome analysis should be interpreted alongside phenotypic and functional evidence rather than treating variable genes as direct indicators of pathogenicity or adaptation.

Agricultural applications of fungal pangenomics

Fungal pangenomics offers opportunities to translate genomic insights into practical applications in crop protection and sustainable agriculture. Comparative analysis of fungal isolates collected across geographical regions can improve pathogen surveillance by revealing population structure, genetic lineages, and genomic variation associated with disease outbreaks. Characterising pathogen diversity can also inform resistance breeding by supporting the selection of representative isolates for screening crop varieties and assessing the robustness of host resistance against genetically diverse pathogen populations.

Integrating pangenome data with pathogenicity assessments, host-interaction studies, and gene-expression analyses can help identify candidate genes associated with virulence, host adaptation, and disease development. In beneficial plant-associated fungi, comparative genomic analyses

can help investigate genes potentially involved in plant colonisation, nutrient acquisition, environmental stress tolerance, enzyme production, and secondary metabolism. These insights may support the selection of microbial resources for plant growth promotion and biological disease control.

Beyond these applications, comparisons of conserved and variable genomic components can provide insights into fungal evolution, genetic relationships, and adaptation to different hosts and environments. Realising these benefits requires representative isolate sampling, high-quality genome assemblies, consistent bioinformatic analyses, and integration of genomic data with phenotypic evidence. Experimental validation remains essential to establish the biological functions of candidate genes and determine their practical value in agriculture.

Conclusions and future perspectives

Fungal pangenomics provides a comprehensive framework for understanding genomic diversity within fungal species by distinguishing conserved core genes from variable accessory and isolate-specific genes. In plant-associated fungi, this approach offers opportunities to investigate pathogenicity, host adaptation, ecological interactions, and beneficial traits relevant to sustainable agriculture. Integrating pangenomic analyses with phenotypic and functional data can help identify candidate genomic features associated with disease development, environmental adaptation, and beneficial plant–fungus interactions.

Future research should focus on representative isolate sampling, the development of high-quality genome assemblies, and the integration of pangenomic data

with phenotypic, transcriptomic, and metabolomic analyses. The functional relevance of candidate genes should be further established through experimental validation, thereby enabling the translation of genomic insights into practical applications for crop protection and sustainable agriculture.

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Just Agriculture
Multidisciplinary
e- newsletter

e-ISSN: 2582-8223

Volume - 7
Issue - 3
November, 2026

www.justagriculture.in

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ARTICLE ID: 29

From Drudgery To Productivity: Gender-Responsive Technologies For Empowering Farm Women In India

Abstract

Women play a vital role in Indian agriculture and contribute substantially to activities ranging from sowing and weeding to harvesting, livestock care, post-harvest processing and value addition. However, many operations continue to depend on manual labour involving excessive force, repetitive movements and awkward postures. Agricultural drudgery is therefore an occupational health, productivity and gender-equity concern. Gender-responsive technologies designed around the physiological and ergonomic needs of women can reduce physical workload while improving efficiency and productivity. This article highlights major sources of drudgery among farm women, the importance of ergonomic design, selected women-friendly technologies, and pathways for wider adoption through training, custom hiring, self-help groups and entrepreneurship. Recent evidence from Telangana on millet post-harvest operations demonstrates the practical value of improved machinery. Integrating women-centred technology with extension support and enterprise development can help transform agricultural work into safer, more productive and economically empowering employment.

Keywords: Farm women, agricultural drudgery, ergonomics, women-friendly technologies, mechanization, occupational health, empowerment

Introduction

Women are indispensable contributors to Indian agriculture. Their participation extends across seed treatment, sowing, transplanting, weeding, harvesting, threshing, cleaning, grading, storage, livestock management and food processing. Yet many of these activities remain labour-intensive and are performed with traditional tools that may not suit women's body dimensions, strength and working postures.

Agricultural drudgery refers to the physical and mental strain associated with demanding work, particularly where activities involve excessive force, repetitive movements, prolonged static postures or unsuitable tools. ICAR's recent gender strategy identifies high physical drudgery and occupational health risks among women engaged in activities such as transplanting, weeding, harvesting, carrying loads and livestock care, while emphasizing improved access to women-friendly technologies.

Ergonomics provides a practical framework for adapting tools, equipment and work methods to human capabilities and limitations. The aim is not simply to replace human labour with machines, but to reduce unnecessary physical hardship while improving safety, efficiency and dignity at work.

1. Major Sources of Drudgery

Common drudgery-prone activities include manual weeding, harvesting with traditional sickles, transplanting, carrying agricultural produce, threshing, winnowing, dehusking, shelling and repetitive post-harvest processing.

Bending, squatting, lifting, repetitive hand movements and prolonged work duration can increase fatigue and musculoskeletal discomfort.

The burden is especially important in smallholder systems where mechanization may be limited by cost, farm size, accessibility and lack of training. Thus, appropriate-scale technologies and shared access models are essential.

2. Ergonomics and Women-Friendly Technology

Ergonomic assessment should consider body height and reach, grip strength, operating force, posture, duration of work, repetitive movements and physiological workload. A technically efficient machine may still be inappropriate if it is too heavy, difficult to operate or causes uncomfortable postures.

ICAR's All India Coordinated Research Project on Ergonomics and Safety in Agriculture and Allied Sector continues to emphasize women-friendly tools that reduce occupational hazards and drudgery while improving comfort, productivity and empowerment.

Agricultural task	Suitable intervention	Expected benefit
Weeding	Handy hoe, improved weeder	Less bending; lower physical workload
Harvesting	Ergonomic sickle, harvesting aids	Improved grip and work efficiency
Shelling/dehusking	Small-scale shellers	Reduced repetitive manual effort
Threshing/winnowing	Improved threshers and winnowers	Reduced time and drudgery
Millet processing	Small-scale processing equipment	Higher efficiency and value-addition potential

3. Evidence from Millet Post-Harvest Operations in Telangana

A recent 2026 study by ICAR–Indian Institute of Millets Research, Hyderabad, assessed traditional and improved millet post-harvest practices among 32 farm women in Chalki and Gangapur villages of Telangana. Threshing and winnowing were identified as particularly physically demanding and time-consuming under traditional practices. Adoption of improved technologies reduced working time, minimized health-related problems, improved work efficiency and productivity, and contributed to income and livelihood security.

This Telangana evidence is particularly relevant because millet processing is increasingly linked with household nutrition, value addition and rural enterprise. Technologies that reduce post-harvest drudgery can therefore support both occupational health and women's participation in millet value chains.

4. Technology Access: From Individual Ownership to Shared Services

High equipment cost can prevent small and marginal farmers from adopting machinery. Custom Hiring Centres and women-led machine banks can provide access without requiring individual ownership. ICAR's 2025 Gender Strategy recommends women-led machine banks and resource centres at local levels to strengthen access to tools, machines and information.

Women-friendly technologies already commercialised or promoted through ICAR-CIWA include a women-friendly handy hoe, five-tine weeder, hand-operated maize dehusker-cum-sheller, coconut dehusker and several drudgery-reducing devices. Such technologies demonstrate the importance of developing equipment specifically around users' needs.

5. Women, SHGs and Rural Entrepreneurship

Self-Help Groups (SHGs), Farmer Producer Organisations and women collectives can become important pathways for technology adoption. Groups can collectively access machinery and provide custom services to neighbouring farmers. They can also use processing equipment for millet cleaning, grading,

flour preparation, food processing, packaging and value addition.

Thus, drudgery reduction can move beyond labour saving towards entrepreneurship. When women have access to technology, training, finance and markets, agricultural mechanization can contribute to income generation and greater participation in farm and value-chain decisions.

6. Extension and Training Priorities

Technology adoption depends on awareness, skill and continued support. KVKs, State Agricultural Universities, ICAR institutes and extension agencies should provide demonstrations in local languages covering operation, maintenance, safety, ergonomic practices, economics and available access mechanisms. Women should also participate in technology evaluation so that weight, handle size, portability, operating force, safety and maintenance requirements reflect real user preferences.

A useful adoption pathway is: needs assessment → participatory technology selection → demonstration → hands-on training → access through custom hiring or collectives → follow-up support → impact assessment. This approach can improve sustained use rather than one-time distribution.

7. Future Directions

Future agricultural mechanization should follow a human-centred, gender-responsive approach. Technologies should be affordable, easy to operate, adjustable where possible, locally repairable, suitable for small farms and accessible through community facilities. Digital tools can complement physical technologies through local-language training videos, machinery booking, advisory services and technology directories.

The broader goal should be to remove unnecessary physical hardship while retaining and strengthening women's productive role in agriculture. This aligns with current national emphasis on gender-responsive agricultural systems, women-friendly technologies, entrepreneurship and inclusive extension.

Conclusion

Farm women are central to Indian agriculture, but their contribution is often accompanied by substantial physical drudgery. Ergonomically designed tools, improved weeders, harvesting aids, shellers, threshers, winnowers and millet-processing technologies can reduce workload and improve work efficiency. Evidence from Telangana demonstrates the practical benefits of improved millet post-harvest technologies. However, technology alone is not enough. Affordable access, hands-on training, custom hiring, women-led collectives, entrepreneurship support and participatory technology design are equally important. The future of agricultural mechanization should therefore be guided by the principle of technology developed 'for women, with women and by women'. Integrating ergonomics with agricultural engineering, Home Science, extension education and rural entrepreneurship can help create safer, more productive and empowering agricultural systems.

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