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Can We Breed Crops to Store More Carbon?

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Abstract

Crop breeding has traditionally prioritised yield, quality, stress tolerance and resistance to biotic and abiotic stresses. Increasing evidence suggests that genetic improvement could also contribute to climate mitigation by modifying traits that regulate plant carbon acquisition, allocation and transfer to soil. This article examines whether crops can be bred to enhance carbon inputs to agricultural soils while maintaining productivity and resilience. Particular attention is given to root biomass, root architecture, rooting depth, rhizodeposition, carbon allocation and plant–microbe interactions as potential breeding targets. Recent evidence indicates substantial genetic variation in root traits and suggests that genotype selection can increase root-derived carbon inputs without necessarily reducing yield. Advances in quantitative genetics, genome-wide association studies, genomic selection and high-throughput root phenotyping provide opportunities to integrate these traits into crop improvement programmes. However, greater biomass or root carbon input does not automatically result in persistent soil organic carbon (SOC) sequestration because the fate of plant-derived carbon is regulated by decomposition, microbial transformation, soil properties, aggregation and environmental conditions. Therefore, carbon-oriented breeding requires multi-environment field evaluation that links genotype, root traits, carbon inputs and changes in soil carbon stocks over time. The emerging concept of "high-carbon crops" provides a framework for integrating productivity, climate resilience, resource-use efficiency and carbon-related traits within breeding objectives. Carbon-smart crops could complement agronomic practices such as residue retention, diversified rotations and cover cropping, but their climate benefits must be demonstrated through appropriate measurement, reporting and verification. Breeding crops for greater and more persistent soil-carbon inputs is therefore a promising research direction, but remains an emerging frontier rather than an established pathway for agricultural carbon sequestration.

Introduction

Crop improvement has traditionally focused on increasing yield, improving grain quality, enhancing resistance to pests and diseases, and developing varieties capable of performing under drought, heat, salinity and other environmental stresses. However, climate change is creating a

new challenge for plant breeders: can crops be developed not only to produce more food but also to contribute to atmospheric carbon dioxide (CO_2) removal and soil carbon storage?

Plants naturally capture atmospheric CO_2 through photosynthesis and convert it into organic carbon. Overtime this carbon is distributed in plant parts such as leaves, stem, grains and roots. A portion of the carbon returned to agricultural soils through roots, root exudates and crop residues may contribute to soil organic carbon (SOC). However, not all carbon captured by a crop becomes long-term soil carbon. Some is rapidly decomposed and returned to the atmosphere.

This distinction has opened an emerging research area at the intersection of genetics, plant breeding and soil science. If genetic variation among crop varieties affects biomass production, root growth, carbon allocation and rhizosphere interactions, then it may be possible for breeders to select genotypes with traits that enhance carbon inputs to soil without compromising crop productivity.

Recent studies indicate that genetic improvement has already affected carbon inputs for some major crops and that root traits are an important but underexploited avenue for future breeding (Poffenbarger et al., 2023). The question, therefore, is not simply whether crops can capture more carbon, but whether breeders can develop **carbon-smart crops that combine productivity with greater and more persistent carbon inputs to soil**.

From Carbon Fixation to Carbon Sequestration

The basic pathway through which crops interact with the carbon cycle can be represented as in the **Fig.1**

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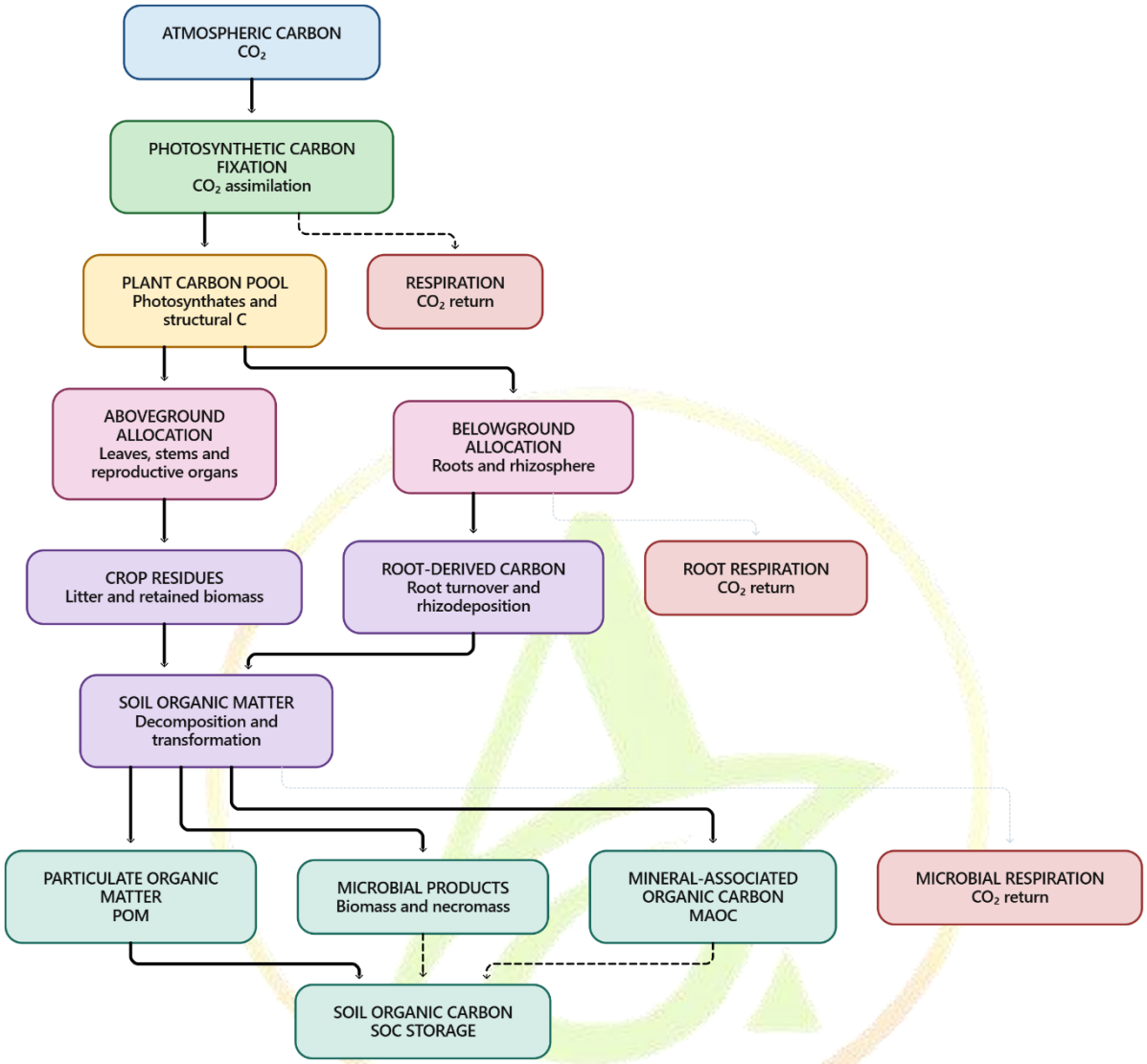


Figure 1. Conceptual pathway of plant-derived carbon from atmospheric CO_2 fixation to soil organic carbon storage

Photosynthesis is the primary process through which atmospheric CO_2 enters plant biomass. During crop growth, carbon is allocated to different plant organs according to genotype, developmental stage and environmental conditions. At harvest, a substantial proportion of aboveground carbon may leave the field as grain, whereas roots, root-derived compounds and retained residues remain important pathways for carbon return to soil.

It is important to distinguish carbon fixation, carbon storage and carbon sequestration. Carbon fixation refers to the incorporation of atmospheric CO_2 into organic compounds through photosynthesis. Carbon storage refers to carbon retained within a biological or soil pool at a particular point in time. Carbon sequestration is any net increase of carbon inside reservoir over time. As a result, a higher biomass crop does not necessarily mean higher long-term carbon

sequestration. The persistence of plant-derived carbon depends on decomposition, microbial transformation, soil aggregation, mineral interactions and environmental conditions. For plant breeders, this means that increasing biomass alone may be an insufficient objective. The more relevant question is how a genotype captures, allocates and transfers carbon into soil pools.

Where Genetics Enters the Carbon Equation

Genetic variation occurs in many traits that influence crop carbon acquisition and allocation. Crop genotypes can differ in photosynthetic characteristics, biomass production, phenology, root-to-shoot ratio, root architecture, nutrient-use efficiency and water-use efficiency. Root traits are particularly interesting because they have traditionally received less attention in breeding than aboveground traits. Root systems are important for water and nutrient uptake, soil exploration, plant anchorage and interactions with soil microbes. Thus, genetic variability in root provides an opportunity to incorporate belowground traits in crop improvement programmes (Mathew and Shimelis, 2022).

A particularly relevant review by Heinemann et al. (2023) brought together data from 13 international field studies involving winter wheat, spring wheat, silage maize, winter rapeseed and sunflower. Across the studies, systematic genotype selection increased mean root biomass by 22%. The authors estimated that median root-carbon inputs could potentially be increased by 6.7% in spring wheat, 6.8% in winter rapeseed, 12.2% in silage maize, 21.6% in winter wheat and 26.4% in sunflower without reducing yield. These findings do not demonstrate that all high-root-biomass varieties will increase long-term SOC. However, they provide an important breeding message: there is exploitable genetic variation in root biomass, and root traits can potentially be selected alongside yield (Heinemann et al., 2023).

Why Roots Could Be the Hidden Carbon Opportunity

The most interesting opportunity for carbon-oriented breeding may lie belowground. Roots transfer carbon into soil through several pathways, including root biomass, root turnover and rhizodeposition. Root-derived compounds can subsequently be transformed by microorganisms and incorporated into different soil organic matter pools. Root depth may also be important. Carbon deposited deeper in the soil profile can encounter different physical, chemical and biological environments from those near the surface. Consequently, breeding for deeper or differently distributed root systems has been proposed as one possible pathway for increasing the efficiency of soil carbon storage.

A 2024 study by Cotrufo et al. investigated whether encouraging deeper rooting in maize could sequester additional soil carbon. They conducted a two-year field experiment with isotopically labelled maize roots and exudates, they tracked the formation of new SOC to a depth of 90 cm. The result showed that root decomposition and root exudates contributed differently to soil organic matter formation. Through modelling, they estimated that shifting root inputs deeper or increasing root allocation could yield SOC gains on the order of 0.05-0.15 Mg C ha^{-1} yr^{-1} under the scenarios considered. Importantly, they concluded that the per-hectare impact for maize is relatively modest compared with some management-based strategies, although the extensive global maize area means modest effects could become meaningful at scale (Cotrufo et al., 2024).

This represents an important scientific lesson. **Deep roots may contribute to carbon sequestration, but the magnitude of the effect must be quantified rather than assumed.**

Can Modern Breeding Technologies Find Carbon-Smart Genotypes?

Traditional breeding depends on phenotypic selection within genetically varied populations. Modern plant breeding adds tools for detecting and choosing complex characteristics.

Quantitative trait locus (QTL) analysis and genome-wide association studies (GWAS) can identify genomic regions associated with root architecture and other physiological traits. Marker-assisted selection can assist the transfer of favourable alleles, while genomic selection can potentially predict breeding values using genome-wide molecular information.

However, genomic technologies are only useful when the phenotype is measurable. Root traits remain difficult to quantify at the scale required for breeding programmes. Root excavation, soil coring, imaging, hydroponic systems, rhizotrons, digital phenotyping and other approaches are therefore increasingly important.

Mathew and Shimelis (2022) emphasized that combining root phenotyping with genomic tools is essential for developing crop varieties with desirable root systems. They also emphasized that root traits have historically been underused because of difficulties in measurement and incomplete understanding of their genetic control.

For carbon-oriented breeding, this suggests a future pipeline in the **Fig. 2.**

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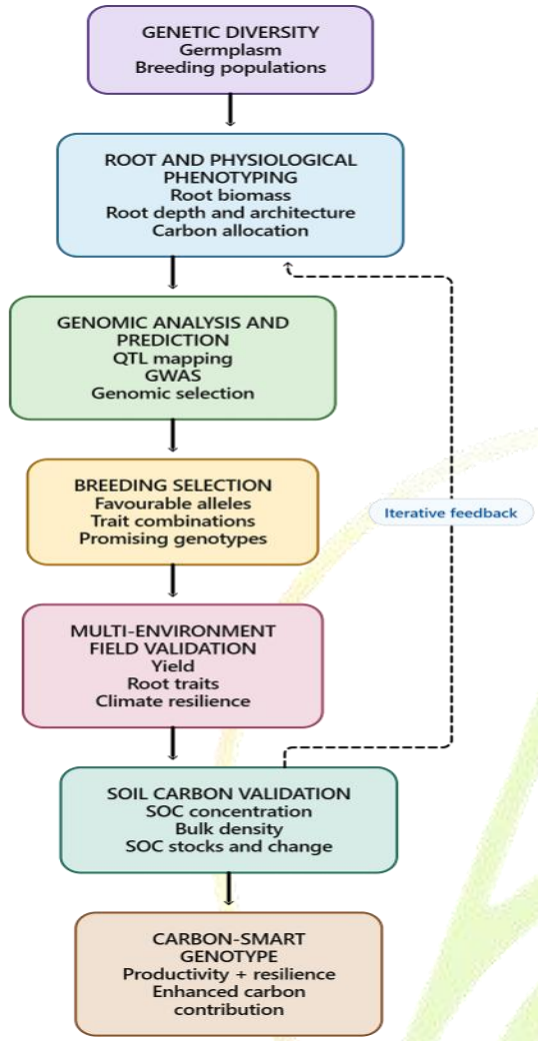


Figure 2. Conceptual framework for integrating genetic improvement with carbon-related crop traits and soil carbon assessment

Such an approach would allow carbon-related traits to be evaluated together with yield, disease resistance and climate resilience rather than as isolated breeding objectives.

The Plant-Microbe Connection

Carbon entering soil does not remain biologically unchanged. Roots interact continuously with bacteria, fungi and other soil organisms. Microbial activity influences the stabilization and transformation of plant derived organic matter, with root exudates serving as carbon substrates for microorganisms. Therefore, genotype can affect soil carbon indirectly through changes in root traits and plant-microbe interactions. This constitutes an important research frontier:

Genotype × Root traits × Microbiome × Soil × Environment

Plant breeders have traditionally selected plants based mainly on plant performance. but, future breeding may increasingly take into account how plant traits affect the rhizosphere and soil

biological processes. The scientific challenge is that plant-microbe interactions are strongly influenced by soil type, climate, management and microbial community composition. Therefore, selecting a genotype for a particular microbial association does not necessarily guarantee the same outcome across different environments. The microbiome should consequently be viewed as an important component of the carbon system, but not yet as a simple breeding target with predictable outcomes.

More Biomass Does Not Necessarily Mean More Carbon Sequestration

One of the biggest misconceptions in carbon-oriented agriculture is that increasing plant biomass automatically increases long-term carbon sequestration. The relationship is considerably more complex. A genotype with greater shoot biomass may return more residue to soil, but that residue may decompose rapidly. Similarly, greater root biomass may increase carbon inputs but does not guarantee that the carbon will remain in soil for long periods.

There may also be trade-offs between root growth and reproductive allocation. Carbon invested in roots is carbon that is not simultaneously available for other plant functions. Breeding must therefore seek an appropriate balance between grain production, root development, stress adaptation and carbon allocation. Poffenbarger et al. (2023) found that historical breeding has already changed aboveground residue carbon inputs in crops like maize and soybean, while the effects on root-to-shoot ratios have tended to be smaller or less consistent. They identified root depth, suberin content, rhizodeposition and mycorrhizal association as potential targets for improving the stabilization of crop-derived carbon. This leads to a crucial principle: The goal should not be to breed the crop with the largest biomass, but to breed the crop with the most favourable combination of productivity, resilience, carbon allocation and carbon retention.

How Would We Know Whether a Crop Stores More Carbon?

A carbon-smart genotype cannot be evaluated only by measuring plant height, biomass or root mass. Field experiments need to assess both plant traits and changes in soil carbon. Relevant measurements may include aboveground biomass, root biomass, root distribution, crop residues, soil organic carbon concentration, soil bulk density and soil carbon stocks. The depth of soil sampling is also important. Carbon changes occurring in surface soil may differ from those occurring at depth. Repeated measurements are therefore necessary to determine whether an apparent increase represents persistent accumulation or simply a temporary change in carbon pools. This creates an important distinction between carbon-input traits and actual soil-carbon outcomes.

A genotype may have more roots and produce greater carbon inputs, but the ultimate effect on SOC depends on what happens to those inputs after they enter the soil. Consequently, long-term and multi-environment field trials will be essential before carbon-related traits can become reliable breeding objectives.

From Carbon-Smart Crops to Carbon Credits

Another distinction is necessary between carbon-sequestration potential and carbon credits. A crop variety with deeper roots or greater root biomass does not automatically generate a carbon credit. Carbon-credit systems require quantification of additional carbon removal or avoided emissions under a defined methodology, including appropriate baseline determination, measurement, reporting, verification and treatment of uncertainty. Plant breeding can potentially create biological capacity for greater carbon storage, but this capacity must be demonstrated under actual management conditions before it can be considered a measurable climate benefit. This distinction will become increasingly important as agricultural carbon markets expand. A scientifically credible carbon strategy must therefore connect genetics with field measurements and robust measurement, reporting and verification (MRV).

Towards "High-Carbon" Crops

The idea of breeding specifically for carbon-related characteristics is now moving from a conceptual possibility towards a defined research agenda. A recent perspective proposed the concept of "high-carbon crops": cultivars designed to combine high productivity with enhanced soil-carbon inputs and stabilization. The proposed framework includes aboveground characteristics such as photosynthetic efficiency and carbon partitioning together with belowground traits such as root size, root architecture, exudation and biochemical composition. The concept is important because it does not propose replacing yield breeding with carbon breeding. Instead, it proposes integrating the two objectives. Future breeding programmes could therefore consider a broader selection index:

Yield + Climate resilience + Resource-use efficiency + Root traits + Carbon contribution

Such an approach would also allow carbon-oriented varieties to be combined with improved agronomic management, including residue retention, cover crops, diversified rotations and appropriate nutrient management. The strongest carbon benefit is therefore unlikely to come from genetics alone. It is more likely to emerge from the interaction of genotype, soil, climate and management.

Conclusion

Can we breed crops to store more carbon?

The evidence suggests that we can potentially breed crops with traits that increase carbon inputs to soil, but breeding for durable soil-carbon sequestration remains an emerging scientific frontier. Genetic variation in root biomass, root architecture, carbon allocation and other physiological traits provides opportunities for developing crops with greater belowground carbon inputs. Modern genomic tools and high-throughput phenotyping may further improve the ability of breeders to identify and select these characteristics.

However, greater root biomass or plant biomass should not automatically be interpreted as greater long-term carbon sequestration. The fate of plant-derived carbon depends on decomposition, microbial transformation, soil properties, environmental conditions and agricultural management.

The future objective should therefore be the development of carbon-smart crops: crops capable of maintaining high productivity while efficiently capturing atmospheric carbon, allocating an appropriate proportion belowground and contributing to persistent soil-carbon pools. The next generation of crop improvement may consequently be evaluated by a broader question than "How much grain can this genotype produce?"

It may also need to ask:

"How efficiently can this crop produce food while contributing to a healthier and more carbon-rich soil?"

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"The Pond Economy: How Chhattisgarh Built a Fisheries Powerhouse in 20 Years"

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Abstract

Chhattisgarh's fisheries sector has grown from a fledgling industry at the state's formation in 2000 into a national leader in inland aquaculture. Production rose steadily from 1.39 lakh tonnes in 2007-08 to 6.52 lakh tonnes in 2022-23, then accelerated sharply to 8.73 lakh tonnes by 2024-25, boosted by PMMSY investments worth over ₹950 crore. This represents a 10.9% CAGR since 2007-08, nearly double India's national growth rate of 6.2%. The state's dense network of more than 1.29 lakh ponds spread over 2.03 lakh hectares—92% of which are actively employed for farming—is the key to its success. As the nation's top inland fisheries state, Chhattisgarh today supports over 2 lakh farmers and is ranked sixth in fish output and fifth in seed production. Although there are some estimations and data gaps for previous and some current years, the general growth pattern is evident and consistent.

Introduction

When Chhattisgarh was first established in 2000, it had a tiny, undeveloped fishing industry that relied on imported fish seed. Production increased from less than 1 lakh tons to 8.73 lakh tons by 2024–2025 because to improvements in pond infrastructure, increasing seed self-sufficiency, and government initiatives like the Blue Revolution and PMMSY. This paper compares Chhattisgarh's performance to the expansion of India's national fisheries and tracks that growth over four stages, from the early years to a current policy-driven surge. It demonstrates how the state created a long-lasting competitive advantage out of its abundant water resources.

Phase One: The Early Years (2000-01 to 2006-07)

When Chhattisgarh split from Madhya Pradesh in November 2000, its fisheries sector was still developing: productivity stood at just 1,850 MT per hectare and relying on imported fish seed since local seed production was low, with farming spread across about 1.335 lakh of the 1.538 lakh hectares of available water area [1]. By 2001-02, seed self-sufficiency was improving, with around 25 crore fishlings produced that year, rising to 135 crore by 2015-16, though total output figures for 2001-02 itself aren't available - the earliest tonnage data found is 120,070 tonnes in 2004-05

[2][3]. Growth accelerated markedly in later years: an ICAR-published study found community pond productivity had reached 3,055 kg/ha/year (against a national average of 2,200 kg/ha/year) and reservoir productivity 202 kg/ha/year (against a national average of 48 kg/ha/year) [4].

Phase Two: Steady and Proven Growth (2007-08 to 2017-18)

Starting in 2007-08, Chhattisgarh's fish production data becomes reliable, showing a clear pattern of growth. Production began at 1.39 lakh tonnes and expanded in three distinct phases [5]:

- 2007-08 to 2009-10: Production grew from 1.39 to 1.74 lakh tonnes, a CAGR of approximately 11.7 per cent [5]
- 2010-11 to 2013-14: Production grew from 2.28 to 2.85 lakh tonnes, a CAGR of approximately 7.7 per cent [5]
- 2014-15 to 2017-18: Production grew from 3.14 to 4.57 lakh tonnes, a CAGR of approximately 13.3 per cent [5]

Across the full 2007-08 to 2017-18 period, output grew at an overall CAGR of roughly 12.6 per cent per year, taking production from 1.39 to 4.57 lakh tonnes — more than tripling over the decade [5]. This phase overlapped with the Indian government's Blue Revolution scheme (2015-16 to 2019-20), which had a central outlay of Rs 3,000 crore, under which fisheries projects worth around Rs 5,000 crore were approved nationally, including for inland aquaculture states like Chhattisgarh [6][7].

Phase Three: Continued Expansion with Some Data Gaps (2018-19 to 2022-23)

Production rose steadily through this period: 4.89 lakh tonnes in 2018-19, 5.72 lakh tonnes in 2019-20, 5.77 lakh tonnes in 2020-21, 5.91 lakh tonnes in 2021-22, and 6.52 lakh tonnes in 2022-23 [8][9]. Compared to Chhattisgarh's fish production of just about 1 lakh tonnes in 2007–08 [10], this marks a substantial and sustained increase. There were no notable declines or plateaus in the increasing trend during the course of the five years.

Phase Four: Rapid Acceleration (2023-24 to 2024-25)

The most dramatic growth happens at the dataset's end, with production jumping to 7.30 lakh tonnes in 2023-24 and soaring to 8.73 lakh tonnes in 2024-25 [11][10] — a remarkable 19.6 per cent increase in a single year. This surge aligns with a concrete government initiative: under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), the central government approved Rs 956.86 crore for fisheries and aquaculture projects in Chhattisgarh over six years, releasing Rs 274 crore

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between 2020-21 and 2025-26 [12]. These investments boosted farmers' incomes, encouraged entrepreneurship, created rural jobs, and reduced post-harvest losses, directly contributing to this rapid production increase [12].




The Bigger Picture: Water Resources and National Ranking

Chhattisgarh's fisheries success is rooted in its strong water resource base. The state has over 1.29 lakh ponds spanning about 2.03 lakh hectares, with nearly 92% of this area actively used for fish farming [13]. This dense network of pond-based water bodies gives Chhattisgarh a significant advantage in freshwater aquaculture compared to other landlocked states. Today, it ranks 6th nationally in fish production and 5th in fish seed production, having become self-sufficient in seed supply and now exporting surplus to other states [14][15]. More than 2 lakh fish farmers are engaged in the sector [16][17], supported by over 2 lakh hectares of water area under cultivation [14]. The state has also been recognized as the best inland state in fisheries at the national level [16][17].

This local story mirrors a larger national trend. India's total fish production nearly doubled from 95 lakh tonnes in 2013-14 to a record 197.75 lakh tonnes in 2024-25, making India the world's second-largest fish producer after China, contributing about 8% of global output [18][19].

	2007-08	**2022-23**	**Growth Multiple**	**CAGR**
Chhattisgarh	1.39 lakh tonnes	6.52 lakh tonnes	~4.7x	~10.9%/year
All India	71.27 lakh tonnes	175.45 lakh tonnes	~2.5x	~6.2%/year

Chhattisgarh's roughly 4.7-fold growth in fish production since 2007-08 — a CAGR of about 10.9 per cent — has significantly outpaced India's national growth rate of around 6.2 per cent CAGR over the same period [20][21]. While the country's total fish production grew 2.5 times (from 71.27 to 175.45 lakh tonnes), Chhattisgarh's output grew nearly twice as fast in relative terms, reflecting the state's disproportionate contribution to India's inland fisheries expansion.

Understanding the Data Gaps

It's important to note some limitations in this dataset. No verified figures exist for seven years from 2000-01 to 2006-07, and three recent years (2019-20, 2021-22, 2022-23) also lack total production data. Additionally, figures for 2008-09 and 2018-19[3] are tentative estimates rather than fully confirmed numbers. While these gaps mean caution is needed when interpreting specific years, the overall trend of strong and sustained growth in fish production is clear and undeniable.

Conclusion

Over two decades, Chhattisgarh has grown from a newly formed state with minimal fisheries infrastructure into a national powerhouse, with production rising nearly seven-fold to 8.73 lakh tonnes by 2024-25. This growth was driven by sustained policy support - from the early Blue Revolution scheme to PMMSY investments exceeding ₹950 crore - combined with the state's natural advantage of over 1.29 lakh ponds across 2.03 lakh hectares. Chhattisgarh's CAGR of roughly 10.9per cent since 2007-08 has consistently outpaced India's national average of 6.2 per cent, making it a disproportionate contributor to the country's fisheries expansion. Today, ranking 6th nationally in production and 5th in seed production, with over 2 lakh farmers engaged in the sector, the state reflects what focused investment and resource utilization can achieve. As India becomes the world's second-largest fish producer, Chhattisgarh's pond-based model offers a replicable case for inland aquaculture development nationwide.

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Black Thrips (*Thrips parvispinus*): A Growing Challenge to Chilli and Vegetable Production

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Introduction

Chilli (*Capsicum annuum* L.) is one of the major spice and vegetable crops of India, with substantial economic, nutritional and export importance. India is among the world's leading producers of chilli and fruits are rich in vitamin A, C and E, carotenoids and other antioxidant compounds, while the crop provides an important source of income for small and commercial farmers. However, chilli production is constrained by a complex of insect pests and diseases, among which thrips are particularly important because of their ability to cause direct feeding damage to tender foliage, flowers and developing fruits. In recent years, the invasive black chilli thrips, *Thrips parvispinus* Karny (Thysanoptera: Thripidae), has emerged as an important threat to chilli production in India.

T. parvispinus is regarded as a Southeast Asian species and has subsequently spread to several regions outside its presumed native range (Mound & Collins, 2000) and is a highly polyphagous species capable of infesting a wide range of agricultural, horticultural and ornamental plants. It has been reported as an important pest of pepper and other crops, particularly under warm tropical and subtropical conditions. The species was first recorded in India in 2015 from papaya in Karnataka (Tyagi *et al*., 2015). Following its establishment expanded rapidly to several regions of the country and was subsequently reported from a growing number of cultivated and non-cultivated hosts. Its ability to exploit diverse host plants, reproduce rapidly and persist across cropping systems has facilitated its establishment and spread, increasing the risk of infestation in newly planted crops.

The emergence of *T. parvispinus* is particularly significant because chilli is highly susceptible to thrips injury, and the pest can exploit tender leaves, growing points, flower buds and flowers. Both adults and immature stages feed by damaging plant tissues, resulting in characteristic silvering, bronzing, leaf distortion, curling, necrosis and drying of growing points. Feeding in flowers can interfere with flowering and fruit set, ultimately reducing yield and fruit quality. Moreover, its concealed feeding behaviour within flowers and young foliage can make early

detection and effective control difficult. These characteristics, combined with a short generation time, high reproductive potential and broad host range, favour rapid population build-up under suitable environmental conditions.

Severe infestations of *T. parvispinus* in southern India have highlighted its potential as a major constraint to chilli production. The species has become predominant in several chilli-growing areas and has been associated with severe crop damage and substantial yield losses (Sridhar *et al*., 2021). Its rapid spread, expanding host range and dominance over other thrips species emphasize its adaptability and potential for movement among cultivated crops, weeds and alternate hosts.

The increasing importance of *T. parvispinus* highlights the need for systematic surveillance, early identification and region-specific integrated pest management. Understanding its distribution, biology, damage potential and management options is essential for minimizing crop losses and limiting further spread in India.

Distribution and Current Status in India

T. parvispinus has progressively expanded its geographical distribution in India. It has been reported from Andhra Pradesh, Chhattisgarh, Haryana, Karnataka, Kerala, Madhya Pradesh, Tamil Nadu, Telangana, Uttar Pradesh and West Bengal, among other regions (Tyagi *et al.*, 2015; Rachana *et al.*, 2022).

The rapid expansion of this invasive thrips is of particular concern because of its ability to establish populations on diverse host plants and persist across cropping systems. Its occurrence in different geographical regions also increases the likelihood of movement between cultivated crops and alternate hosts.

Host Range

Beyond chilli, *T. parvispinus* has a broad host range encompassing agricultural, horticultural and ornamental crops. Reported hosts include capsicum, black gram, red gram, cotton, beans, mango, coriander, watermelon, bitter gourd, ivy gourd and jasmine, among others. The availability of alternate hosts facilitates its persistence between cropping seasons and movement among crops, thereby promoting population build-up and geographical spread. Consequently, *T. parvispinus* has become increasingly dominant over other thrips species in some chilli-growing areas, particularly in southern India (Sridhar *et al*., 2021). The broad host range of this pest also has important implications for its management because weed hosts, neighbouring

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crops and ornamental plants may serve as reservoirs for population maintenance and subsequent infestation of chilli.

Identification Characteristics of *T. parvispinus*

Adults are small and slender, generally measuring about 1.0-1.5 mm in length. The adult body is predominantly dark brown to black, whereas immature stages are comparatively lighter. Adults possess two narrow wings fringed with long hairs along their margins. Females are generally larger than males. Both adults and immature stages occur on young leaves, flower buds and flowers. Infested plant parts commonly exhibit a silvery or bronzed appearance accompanied by characteristic black fecal spots (Tyagi *et al*., 2015).

Biology and Life Cycle

The female lays eggs within plant tissues, particularly tender leaves, flower buds and flowers. Under favourable conditions, *T. parvispinus* develops rapidly and can complete its life cycle within approximately two weeks. Studies on chilli have reported development from egg to adult in about 13-14 days under favourable conditions (Rachana *et al*., 2022). The larval stages are primarily associated with actively growing plant tissues, whereas prepupal and pupal stages are generally less active. Adults frequently occur in flowers and on tender foliage. The short generation time, rapid development and high reproductive potential enable populations to increase rapidly when temperature, host availability and other environmental conditions are favourable.

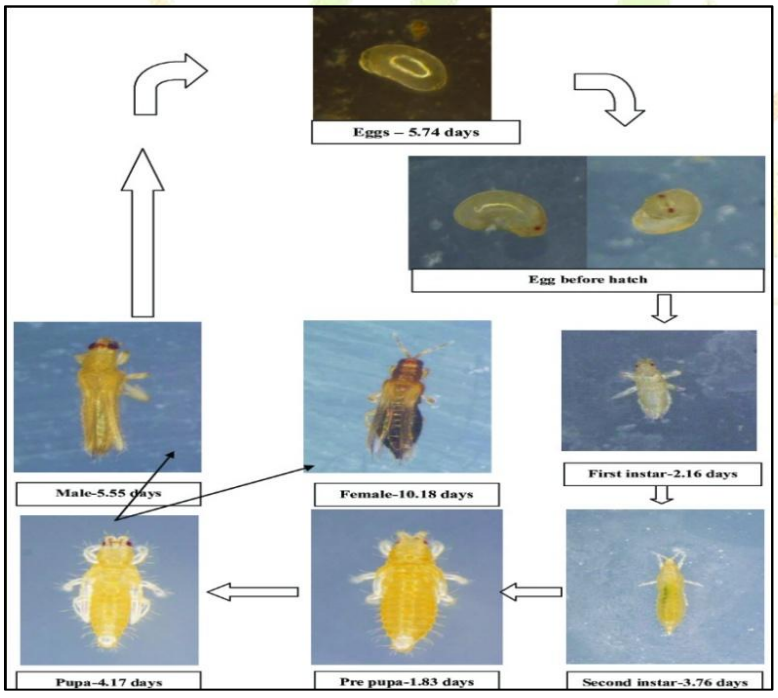


Figure 1. Life cycle of *Thrips parvispinus* (Karny) (Priyanka *et al.*, 2024)

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Damage Symptoms

Both immature and adult stages of *T. parvispinus* cause damage through feeding on plant tissues. The pest preferentially attacks young leaves, growing points, flower buds, flowers and developing fruits.

- Silvery or bronzed patches on tender leaves.
- Upward curling of leaves, often producing a cup-like appearance.
- Leaf distortion, shrivelling and drying of growing tips.
- Suppression of plant growth.
- Flower damage and premature flower shedding.
- Reduced fruit setting.
- Rough, brown or cork-like lesions on developing fruits.
- Stunting and weakening of severely infested plants.

During severe outbreaks, substantial yield losses may occur. Severe outbreaks have been associated with yield losses of up to 80-100% in some affected fields (Sridhar *et al*., 2021).

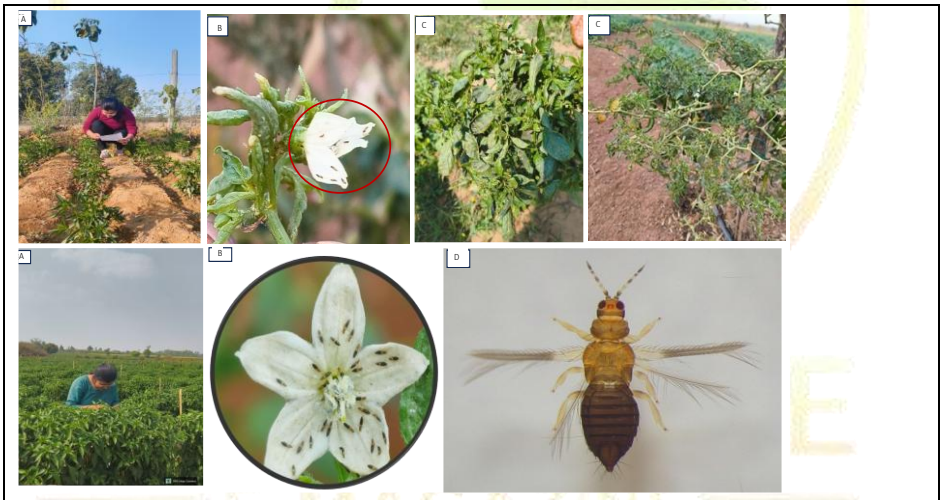


Figure 2. Field occurrence and damage symptoms of *Thrips parvispinus*: (A) field survey, (B) infestation in flowers, (C) plant damage and characteristic symptoms, and (D) adult thrips.

Integrated Pest Management of *T. parvispinus* in chilli and vegetable Crops

The concealed feeding behaviour, broad host range, rapid multiplication, short life cycle and increasing risk of insecticide resistance make *T. parvispinus* difficult to manage through insecticides alone. Therefore, sustainable management requires an integrated, monitoring-based approach combining cultural, mechanical, physical, biological and need-based chemical tactics.

11. Cultural Management

- Use healthy, pest-free planting material and resistant/early-maturing varieties where available.
- Practise deep summer ploughing, regular inter cultivation and soil raking to destroy soil-inhabiting pupae.
- Maintain field sanitation by removing weeds, crop residues, volunteer plants and alternate hosts.
- Apply neem cake @ 500 kg ha^{-1} + vermicompost @ 1.5-2.0 t ha^{-1} and maintain balanced plant nutrition.
- Avoid excessive nitrogen fertilization and maintain recommended spacing (60 × 30 or 45 × 45 cm).
- Use silver mulch (25-30 µm) to reduce thrips pupation.
- Grow 2-3 border rows of maize, sorghum or bajra; chilli + maize/sorghum + cowpea (10:3:1) can support natural enemies.
- Practise crop rotation with non-host/cereal crops and monitor neighbouring crops and alternate hosts.

2. Mechanical and Physical Management

- Remove and destroy severely infested shoots, leaves, buds, flowers and plants.
- Install blue sticky traps @ 20-25 ha^{-1} for monitoring and 65–75 ha^{-1} for mass trapping.
- Use glue-coated blue tarpaulin sheets where locally practiced.
- Prefer sprinkler irrigation to disturb thrips populations.
- In protected cultivation, use insect-proof nets and maintain strict sanitation.

3. Biological Management

- Conserve natural enemies such as *Orius* spp., *Chrysoperla* spp. and *Amblyseius* spp. by minimizing indiscriminate insecticide use.
- Incorporate entomopathogenic fungi such as *Beauveria bassiana, Metarhizium anisopliae* and *Lecanicillium lecanii*.
- Use *Pseudomonas fluorescens* and *Bacillus albus* as microbial biocontrol agents.
- Apply entomopathogenic nematodes such as *Steinernema carpocapsae* and *Heterorhabditis indica* where appropriate.

4. Botanical and Organic Management

- Apply 5% NSKE/neem seed extract, 0.5% neem oil, 0.5% pongamia oil or 5% *Vitex negundo* extract.
- Use azadirachtin 3000 ppm @ 2 ml L^{-1}.
- Apply 2% fish oil rosin soap, alone or with NSKE.
- Use *Kappaphycus alvarezii* extract @ 2 ml L^{-1} to enhance plant tolerance**.**

5. Monitoring and Decision-Based Management

- Regularly inspect tender leaves, growing points, buds and flowers for early infestation.
- Combine direct plant inspection, blue sticky traps and surveillance of alternate hosts.
- Record population trends over time and initiate control based on locally validated action thresholds.
- Integrate cultural, mechanical, biological and botanical measures with need-based insecticides to reduce resistance risk and conserve natural enemies

5. Chemical management and insecticide resistance management

Chemical control should be used judiciously when *T. parvispinus* populations reach economically important levels or locally recommended thresholds.

Insecticide	Dose per hectare
Spinosad 45% SC	160 g ha^{-1}
Spirotetramat 15.31% OD	400 g ha^{-1}
Tolfenpyrad 15% EC	1 L ha^{-1}
Imidacloprid 17.80% SL	250 ml ha^{-1}
Thiamethoxam 25 WG	75 g ha^{-1}
Fluxametamide 10 EC	200 ml ha^{-1}
Cyantraniliprole 10.26% OD	290 ml ha^{-1}

To delay insecticide resistance:

- rotate insecticides belonging to different IRAC mode-of-action groups rather than repeatedly using the same chemistry;
- avoid unnecessary prophylactic and repeated broad-spectrum applications;
- apply insecticides only when monitoring indicates the need;
- ensure adequate coverage of young leaves, growing points, buds and flowers where thrips commonly occur;

- follow the recommended label dose and pre-harvest interval; and
- avoid insecticide mixtures unless officially recommended and compatible.

Pesticide selection, dose, product registration and pre-harvest interval should always follow the current CIB&RC-approved label and the latest recommendations of the concerned agricultural university or state agriculture department. Thus, chemical intervention should be considered as one component of an integrated programme rather than the primary or sole management strategy.

Conclusion

T. parvispinus has emerged as an important invasive pest of chilli and other agricultural, horticultural and ornamental crops in India due to its rapid development, broad host range, concealed feeding behaviour and high reproductive potential. Since its detection in India in 2015, it has become widespread, with severe outbreaks highlighting its potential to cause significant crop losses. Sustainable management requires a preventive, monitoring-based and integrated approach combining field sanitation, regular surveillance, physical and mechanical measures, conservation of natural enemies, botanical and microbial products, and judicious insecticide use with mode-of-action rotation. Early detection and timely intervention, along with improved surveillance, host-range documentation and development of region-specific economic thresholds and IPM strategies, are essential for effective long-term management**.**

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From Emasculation to Pollination: Why Tomato Hybridization Demands Expertise

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Abstract

Tomato (*Solanum lycopersicum* L. 2n = 2X = 24) is one of the most important vegetable crops worldwide and hybrid cultivars dominate commercial production due to their superior yield, uniformity, quality, and resistance to biotic and abiotic stresses and also provide quick and convenient way of combining desirable characters. Unlike open-pollinated varieties, hybrid seed production in tomato relies on controlled crossing between selected parental lines. The process involves delicate operations such as flower selection, emasculation, pollen collection, hand pollination, tagging, and maintenance of genetic purity. Since tomato flowers are naturally self-pollinated, successful hybridization requires precision, timing and trained personnel. Hence, it requires lot of skilled labours as a result of which, seed production has become costly. This article discusses the critical role of technical expertise in each stage of tomato hybridization and explains why skilled workers remain indispensable in hybrid seed production.

Introduction

Hybrid breeding has transformed tomato cultivation by enabling the development of cultivars with improved productivity, adaptability and fruit quality. The production of F_1 hybrid seed depends on controlled pollination between genetically distinct parental lines. However, the self-pollinating nature of tomato flowers makes artificial hybridization technically challenging. Any mistake during crossing may result in selfed seeds, contamination or poor seed set, leading to economic losses.

Therefore, tomato hybridization is not merely a routine agricultural operation but a specialized skill requiring extensive training and experience.

Equipment Required for Tomato Hybridization

1. Fine Forceps (Tweezers)

- Used for removing anthers during emasculation without damaging the stigma.

- Stainless steel forceps are preferred.

2. Needle or Fine-pointed Scalpel

- Helps in opening flower buds and removing floral parts carefully.

3. Magnifying Lens or Dissecting Microscope

- Useful for observing small floral structures and ensuring complete anther removal.

4. Cotton swab or small cotton plug

- The crossed flower is covered with a cotton swab to prevent contamination and unwanted cross-pollination.

5. Tags or Labels -Essential for recording:

- Date of emasculation
- Date of pollination
- Crossing number

6. Camel Hair Brush or Soft Brush/ Pollinating ring

- For pollen transfer in tomato hybridization a **fine camel hair brush of size 0 or 00** is commonly used because it allows gentle and precise handling of pollen grains without damaging the stigma or floral parts.
- A Tomato Pollination Cup cum Ring is a wearable plastic tool used during manual hand pollination.

7. Petri Dishes or Small Containers

- Anthers from the male parent are collected in Petri dishes for pollen extraction.



1.Male flower collection 2. Separation of anther cone 3. Pollen extraction

8. Marker Pen or Waterproof Pen

- For writing information on tags and labels.

9. Scissors

- Used for trimming flower parts or cutting bags and tags.

10. Notebook or Field Record Sheet

- For maintaining detailed records of crosses and fruit set.

11. Seed Extraction Equipment

- Sieves or strainers
- Plastic containers or beakers
- Drying trays

Key Steps Requiring Expertise in Tomato Hybridization

1. **Understanding Floral Biology**

A successful hybridization programme begins with a thorough understanding of tomato floral biology, including:

- Flower morphology and reproductive structures- The inflorescence is extra axillary cymes with dichotomous or polycotomous branching. It is lateral and arises from the stem opposite to the leaf. It may be terminal or may continue with the vegetative shoot. The plant produces bright yellow flowers. The flowers are pentamerous, bisexual, regular, complete, ebracteate, and hypogynous. The pistil has two to several carpels. The anthers connate appearing in the throat of the corolla and their dehiscence is introrsely **longitudinal** and occurs soon after or during the corolla opening. Usually, the style is shorter than anther therefore, a high degree of self-pollination takes place.
- Timing of anthesis and anther dehiscence- The anthesis of flowers starts around 6 a.m. and the flower continues to open until 11 a.m. The peak period of anther dehiscence is between 8 to 11 a.m. depending upon the initiation of sunshine, atmospheric temperature, and humidity.
- Pollen viability period- At temperatures ranging between 18° to 25°C, the pollen remain viable from 2 to 5 days.
- Stigma receptivity duration- The stigma becomes receptive 16 to 18 hours before
- anthesis and retains the receptivity up to 6 days after anthesis.

Knowledge of these factors allows breeders to perform crossing operations at the optimum time for maximum fruit set and seed recovery.

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2. **Selection of Suitable Flower Buds**



Fig. Different stages of flowering in tomato.

Choosing flower buds at the correct developmental stage is crucial.

- After initiation of flowering about 30-35 days after transplanting flowers were manually emasculated at the right stage.
- The buds to be opened the next day are selected in the female parent.
- Overmature flowers may already have undergone self-pollination.

3. **Precision During Emasculation**



Emasculation involves removing anthers from the female parent without damaging the stigma, style, or ovary. This step demands:

- Steady hands and careful manipulation.
- Proper use of forceps and dissecting tools.
- Ability to avoid accidental pollen contamination.

Even minor injuries to floral organs can reduce fruit set significantly.

4. **Collection of Viable Pollen**

Pollen must be collected from freshly opened flowers of the male parent at peak viability. Skilled workers are required to:

- For pollination, fully opened flowers were plucked in afternoon from pollen parents and anther cones were separated from sepals and spread over newspaper or Petri Dishes for drying overnight at ambient temperature. The petri dish is shaken vigorously by holding tightly by hand to separate pollen from the anthers. The pollen was then collected by fine brush. This pollen was used for pollination in next morning.
- Protect pollen from excessive moisture and temperature.
- Prevent contamination from foreign pollen sources.

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5. **Accurate Hand Pollination**

Pollination is to be carried out with utmost care and it is done 24 to 72 hours after emasculation. Early in the morning, hold the emasculated bud in one hand and apply pollen to the stigma using camel hair brush. Fertilisation occurs around 24 to 50 hours after pollination.

The transfer of pollen to the receptive stigma is one of the most critical operations in hybrid seed production. Successful pollination depends on:

- Proper pollen load on the stigma.
- Pollination at the right time of day
- Favorable environmental conditions.



1. Pollination with brush 2. Tagging 3. Covered with cotton plug

6. **Tagging and Record Keeping**

Hybrid seed production requires meticulous documentation, including:

- Cross combinations.
- Date of emasculation and pollination.
- Parent line information.

Errors in labeling may compromise the identity and value of hybrid seed lots.

7. **Maintenance of Genetic Purity**

Commercial hybrid seed production demands high genetic purity standards. Skilled personnel ensure:

- Isolation from unwanted pollen sources- For seed production the tomato varieties should be 50 m for foundation seed and 25 m for certified seed. For Hybrid seed production the distance should be 200 m for foundation seed and 100 m for certified seed.
- Roguing of off-type plants.
- Proper field sanitation and monitoring.

Maintaining genetic purity directly influences the commercial success of hybrid cultivars.

8. **Environmental Management**

Temperature, humidity, and light conditions strongly influence pollination success. Experienced hybridizers adjust crossing schedules according to prevailing environmental conditions to maximize seed set and reduce flower drop.

Why Skilled Personnel Are Indispensable

Tomato hybridization combines biological knowledge with manual dexterity. Unlike mechanized agricultural operations, many stages still depend heavily on human precision and judgement. A trained hybridizer can:

- Increase fruit set percentage.
- Improve hybrid seed recovery.
- Reduce contamination and selfing.
- Ensure uniform and high-quality seed production.

Thus, the success of tomato hybrid seed production largely depends on the expertise of the personnel involved.

Conclusion

From selecting the right flower bud to ensuring genetic purity of harvested seed, every step in tomato hybridization requires technical competence and experience. The self-pollinating nature of tomato makes controlled crossing particularly demanding, emphasizing the importance of skilled labour in hybrid seed production systems. Investment in training and capacity building of hybridization personnel is therefore essential for improving efficiency, seed quality, and profitability in tomato breeding programmes.

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The Orchid That Lives in the Dark: Ghost Orchid Reappears in Kinnaur After Several Decades

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It has no green leaves, no chlorophyll and no conventional way of making its own food. Hidden beneath the Himalayan forest floor, the elusive Ghost Orchid has resurfaced in Kinnaur—revealing yet another secret of the Western Himalaya.

Imagine walking through a Himalayan forest and finding a flower that seems almost too delicate to be real.

There are no broad green leaves announcing its presence. No lush foliage surrounds it. It does not turn its leaves towards the sunlight. For most of its existence, it remains hidden beneath the forest floor, invisible to the human eye.

And then, for a brief period, it appears.

This is the Ghost Orchid, *Epipogium aphyllum* Sw., one of nature's most unusual orchids. Recently, this elusive species was recorded again in Kinnaur, Himachal Pradesh, after several decades without a contemporary record from the region. The rediscovery was reported from the Rakchham area of the Rakchham–Chitkul Wildlife Sanctuary, where only four individuals were observed.

The discovery is remarkable not simply because the orchid is rare. It is remarkable because of how this plant lives.

It survives without chlorophyll.

It survives without photosynthesis.

And for much of its life, it remains hidden underground.

A flower that behaves like a ghost

The Ghost Orchid is a perennial terrestrial orchid with an extraordinary life strategy. Its above-ground shoot is delicate, pale and ephemeral, while its major phase of existence occurs beneath the soil.

According to the detailed biological account by Taylor and Roberts (2011), the plant has a highly reduced above-ground structure with leaves represented largely by small scales. Its subterranean rhizome is much more important to its survival than its short-lived flowering stem.

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Fig. 1: *Epipogium aphyllum* (Source: Pedra Espiga)

This is where the orchid's ghost-like character begins. For years, a forest may appear to contain no Ghost Orchids at all. Then, under suitable conditions, a slender flowering stem can suddenly emerge from the forest floor. The flowering itself is unpredictable. The species may remain unseen above ground for several successive years, and historical observations have documented remarkably long periods between appearances. Taylor and Roberts (2011) noted that *E. aphyllum* has even reappeared at some sites after decades of apparent absence.

The recent Kinnaur report similarly describes the flowering stem as visible for only around 10–12 days after which the plant disappears from view again. For a field botanist, therefore, finding the Ghost Orchid is almost a matter of timing. You have to be there when the ghost decides to appear.

The plant that does not need chlorophyll!

Perhaps the most fascinating question is also the simplest:

How does a plant survive without chlorophyll?

Chlorophyll is the green pigment that allows most plants to capture light energy and use photosynthesis to produce organic compounds from carbon dioxide and water. The Ghost Orchid has abandoned this conventional strategy.

Epipogium aphyllum is achlorophyllous and obligately mycoheterotrophic. In simple terms, it cannot photosynthesize and instead obtains its nutrition through fungi associated with its underground tissues. Taylor and Roberts (2011) describe the species as completely dependent on its fungal symbiont throughout its life cycle. This is not parasitism on decaying leaves, despite the older term "saprophytic orchid" sometimes being used for such plants. The distinction is important. The Ghost Orchid does not simply feed on dead organic matter. It obtains nutrients through a living fungal relationship. Its secret is hidden beneath the soil.

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The key to understanding the Ghost Orchid lies in the microscopic world beneath our feet.

Its rhizome is closely associated with fungi, particularly fungi belonging to the genus *Inocybe*. Roy et al. (2009) used molecular techniques to investigate the fungal partners of *E. aphyllum* and found strong associations with ectomycorrhizal *Inocybe* species. Their work demonstrated that the orchid's nutrition is intimately connected with its fungal partners.

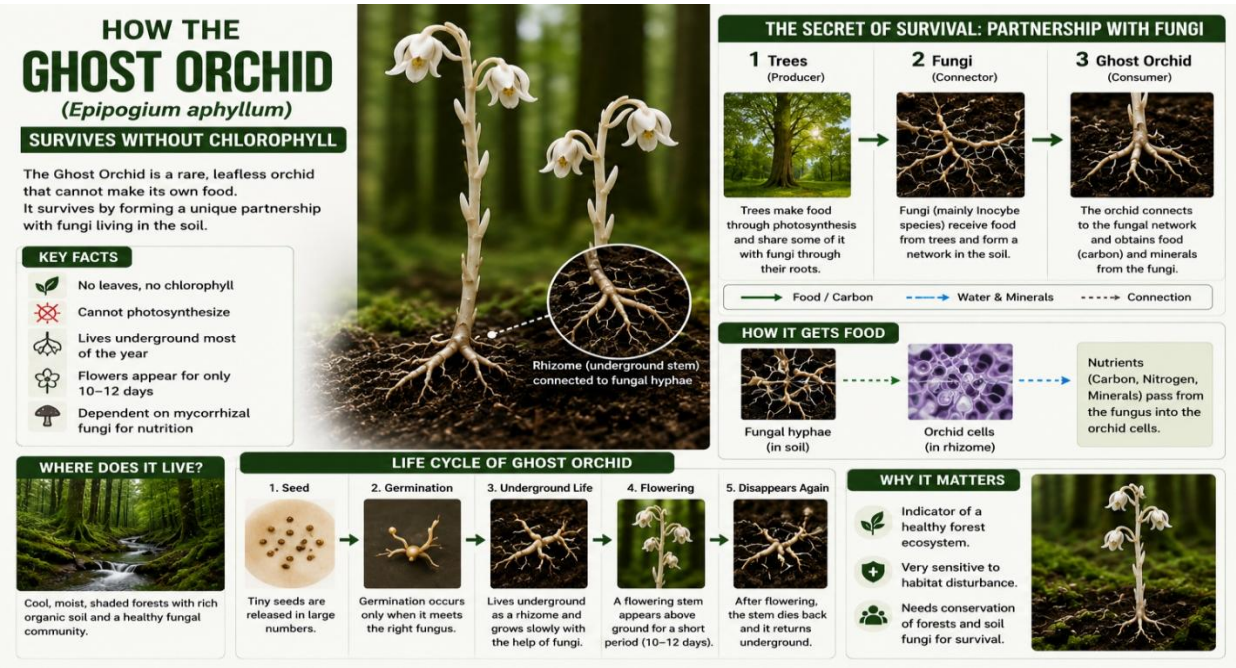


Fig. 2: The survival mechanism of *Epipogium aphyllum*

The exact ecological pathway is more complicated than this simplified diagram suggests, but the central idea is fascinating: the Ghost Orchid obtains organic carbon and mineral nutrients through its fungal association rather than producing its own carbon through photosynthesis.

Modern research on mycoheterotrophic orchids shows that this evolutionary transition from photosynthesis to fungal dependence involves major changes in plant metabolism and genome function. *E. aphyllum* is one of the completely mycoheterotrophic orchids investigated in this context. In other words, the Ghost Orchid has not merely lost its green colour. It has evolved an entirely different way of living.

The forest is more than what we see! This unusual lifestyle also changes the way we should think about conservation. When we look at a forest, we see trees, shrubs, herbs and flowers. But beneath that visible landscape exists another ecosystem, the one made up of roots, fungi, microorganisms, organic matter and complex nutrient exchanges.

The Ghost Orchid belongs to this hidden ecosystem. Its survival therefore depends on more than protecting the four flowering plants observed in Kinnaur. The forest habitat and the underground

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fungal community that support the species are equally important.

Taylor and Roberts (2011) suggested that the availability of suitable fungal partners may be a critical factor controlling the establishment and persistence of *E. aphyllum*. They also highlighted the vulnerability of these relationships to habitat fragmentation and environmental change. This makes the orchid a powerful reminder that conservation is not always about protecting what we can see. Sometimes, it means protecting what we cannot see.

Kinnaur's botanical secret

The recent Kinnaur observation is particularly significant because the documented history of *E. aphyllum* in Himachal Pradesh is limited. The 2026 reports state that historical records include a report from Fagu in Shimla district by Henry Collett in 1921, a collection by Dr Rau in 1959 and another collection attributed to Dr. Vaid from the 1980s, although the date of the latter record is reportedly still being verified. The new Kinnaur record therefore adds another important location to the state's botanical history.

A discovery that expands the map

The importance of the Kinnaur record goes beyond adding one more orchid to a species list. A recent 2026 checklist of orchids of Himachal Pradesh documents *Epipogium aphyllum* among the state's unusual leafless mycoheterotrophic orchids and records the remarkable diversity of orchids across the region. The checklist documents 97 orchid species in Himachal Pradesh, highlighting the state's substantial but still incompletely understood orchid diversity. (Verma et al., 2026).

The Kinnaur finding therefore fits into a much larger story. The Western Himalaya still holds many botanical secrets with plants that are rare, flower only briefly, remain hidden underground or depend on microscopic organisms that often go unnoticed. The Ghost Orchid belongs to all these categories, making its rediscovery a remarkable reminder of the hidden botanical diversity that still exists within the Himalayan forests.

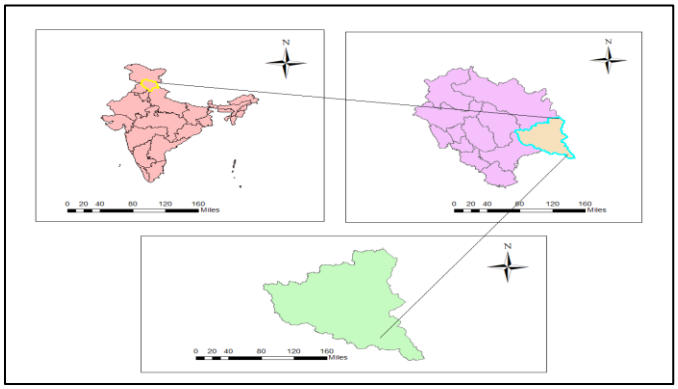


Fig 3. Location map of Kinnaur district

Why this discovery matters

Finding only four individuals might sound disappointing. For conservationists, it is the opposite. Four plants are evidence that the species persists in the landscape. They provide an opportunity to document its habitat, flowering period, associated vegetation and fungal relationships. They also provide a starting point for future surveys. The appropriate response to such a discovery, however, is not to collect the plants or disturb their habitat. It is to observe, document and protect.

Photographic records, GPS-based observations, phenological monitoring and repeated surveys can help scientists understand the species without removing it from its natural habitat. The 2026 field team itself encountered the orchid during routine monitoring and photographed the plants in their natural surroundings. That is precisely how rare species should increasingly be studied.

The Himalaya still has secrets

The rediscovery of the Ghost Orchid offers a humbling lesson. We often imagine that discovering a new species or rediscovering a rare one requires travelling to an untouched corner of the planet. But sometimes the secret is already there. It is simply hidden. A plant may spend years beneath the soil. A fungus may form an invisible network around roots. A flowering stem may emerge for little more than a week and then disappear. The forest continues functioning whether or not we notice. And every now and then, it gives us a glimpse.

In Kinnaur, that glimpse came in the form of four pale, delicate Ghost Orchids rising from the forest floor. They cannot make their own food. They do not remain visible for long. They may disappear for years. Yet they survive. Perhaps that is the most remarkable thing about the Ghost Orchid. It reminds us that absence is not always disappearance and that some of nature's most extraordinary stories are happening where we cannot see them.

The ghost beneath our feet

The next time we walk through a Himalayan forest, it may be worth looking beyond the obvious. The tallest tree may not be its most fascinating resident. The brightest flower may not be its rarest. And the greenest plant may not be the one with the most extraordinary story. Somewhere beneath the forest floor, connected to a world of fungi and roots, a Ghost Orchid may be waiting. It waits for the right season, the right conditions, and the perfect moment to appear. And when it does, the forest may reveal its ghost for only a few days before quietly taking it back into the darkness.

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Sugar Import Policy and Domestic Market Stability in India: Implications for Farmers and the Sugar Industry

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ABSTRACT

India's sugar industry is closely connected with sugarcane farmers, sugar mills, ethanol producers, food processors and consumers. Market stability is influenced by production, stocks, consumption, trade, ethanol use and government policies. In 2026, the Government permitted duty-free imports of 1 million tonnes of raw sugar until 31 October to improve domestic availability and control prices. By 1 September, 797,450 tonnes had been allocated, while dealer stock limits were reduced from 4,000 to 2,000 quintals to discourage hoarding. Sugarcane production increased from 405.399 million tonnes in 2020–21 to 475.614 million tonnes in the first advance estimate for 2025–26, while Fair and Remunerative Price (FRP) rose from ₹285 to ₹365 per quintal. Ethanol blending reached 20% in Ethanol Supply Year (ESY) 2025–26. Temporary imports may stabilize supply and prices, but frequent policy changes can create uncertainty. Long-term stability requires predictable trade policies, higher productivity, efficient water use, timely cane payments and diversified mill operations.

Keywords: Sugarcane, sugar imports, price stability, farmers, sugar industry, ethanol, FRP, trade policy, India

INTRODUCTION

Sugarcane is a major commercial crop supporting sugar mills, ethanol plants, cogeneration units, rural employment and related industries. India's sugar sector is strongly regulated through Fair and Remunerative Price (FRP) and government controls on production, stocks, domestic sales and international trade. The Sugar (Control) Order, 2025 provides the regulatory framework for these interventions. Sugar production is cyclical. High production can create surpluses and lower prices, whereas reduced production or low stocks can increase prices. Therefore, policy must balance farmer returns, mill viability and affordable sugar supply. The 2026 import decision

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illustrates this challenge, as India shifted from export management to duty-free imports and stock restrictions to support domestic market stability.

IMPORTANCE OF SUGARCANE AND THE SUGAR INDUSTRY

Sugarcane provides livelihoods to millions of farm households and supports substantial rural employment. Government data indicate around 5 crore farmers and 5 lakh workers are associated with the sector. Production increased from 405.399 million tonnes in 2020–21 to 454.611 million tonnes in 2024–25, with the first advance estimate reaching 475.614 million tonnes in 2025–26.

Year	Production (million tonnes)	FRP (₹/quintal)
2020–21	405.399	285
2022–23	—	305
2023–24	—	315
2024–25	454.611	340
2025–26*	475.614	355
2026–27	—	365

*First advance estimate for 2025–26.

Source: Government of India, Ministry of Agriculture & Farmers Welfare and PIB.

The growing importance of sugarcane for ethanol has expanded its role from a sugar crop to a food, energy and industrial resource.

EVOLUTION OF SUGAR POLICY

India's sugar policy responds to changes in production, consumption, stocks and global markets. Major measures include FRP, import-export regulation, supply management, stock limits, ethanol support, mill viability measures and monitoring of cane-payment arrears. Sugar exports have fluctuated considerably, reaching about 110 lakh tonnes in 2021–22 but declining to around 9 lakh tonnes in 2024–25. Exports generally support mills during surplus periods, while restrictions or imports may be used when domestic supplies become tight.

RECENT SUGAR IMPORT POLICY, 2026

In 2026, the Government permitted duty-free imports of up to 1 million tonnes of raw sugar until 31 October 2026 to improve domestic availability and moderate price pressures. By 1 September,

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797,450 tonnes had been allocated, leaving 202,550 tonnes.

Indicator	Policy position
Import quota	1 million tonnes
Allocated by 1 Sept. 2026	797,450 tonnes
Remaining quota	202,550 tonnes
Eligible applicants	Sugar millers/refiners
Validity	31 October 2026
Objective	Improve supply and moderate prices

Source: Directorate General of Foreign Trade/Reuters reporting on the September 2026 allocation.

The measure is better viewed as a supply-management intervention during relatively tight market conditions rather than proof of an absolute shortage.

DOMESTIC SUGAR AVAILABILITY AND PRICE STABILITY

Sugar availability depends on production, opening stocks, imports, consumption, exports and ethanol diversion.

Opening stocks + Production + Imports − Consumption − Exports − Ethanol diversion = Closing stocks

Low projected stocks can increase price pressure, whereas excess stocks may reduce prices and weaken mill profitability. Therefore, policy decisions should consider production forecasts, stocks, recovery, consumption, ethanol diversion, trade commitments and domestic and international prices.

SUGAR–ETHANOL LINKAGE

Ethanol has become an important component of India's sugar and energy policies. Petrol blending reached 20% during ESY 2025–26. Ethanol procurement and production capacity have expanded substantially, creating an additional revenue source for sugar mills. Sugar diversion towards ethanol declined from about 12% in 2022–23 to 9% in 2025–26, while grains, particularly maize, supplied a major share of ethanol. Thus, sugar prices are influenced by several factors beyond ethanol diversion, including production, stocks, weather, consumption and trade policy.

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Selected indicators of India's ethanol programme

Indicator	Earlier position	Recent position
Ethanol blending	<1.5% in 2013–14	20% in ESY 2025–26
Ethanol procurement	38 crore litres, 2013–14	>1,200 crore litres projected, 2025–26
Ethanol production capacity	421 crore litres, 2014	~2,000 crore litres, 2026
Sugar-mill ethanol revenue	—	>₹1.29 lakh crore over the past decade

Source: Government of India/PIB.

FAIR AND REMUNERATIVE PRICE (FRP) AND FARMER WELFARE

The FRP for sugarcane increased to ₹365 per quintal for 2026–27 at a basic recovery rate of 10.25%. Although higher FRP provides greater price assurance, farmer welfare also depends on productivity, input costs, recovery and timely payments. Government data indicate that about 99.5% of 2024–25 cane dues had been paid by 20 April 2026, compared with about 88.6% for 2025–26.

Increase in sugarcane FRP

Sugar season	FRP (₹/quintal)
2020–21	285
2022–23	305
2023–24	315
2024–25	340
2025–26	355
2026–27	365

Source: Government of India

EFFECTS OF SUGAR IMPORTS ON FARMERS

Imports can improve supply, reduce excessive price increases and lower shortage risks. Greater market stability may improve mill liquidity and support timely cane payments. However, excessive or poorly timed imports can lower domestic sugar prices and mill realisations, potentially affecting mill profitability and payment capacity.

Imports → Higher supply → Possible lower sugar prices → Lower mill realisation → Possible pressure on cane payments

The actual impact depends on import volume, timing, international prices, demand and mill inventories.

IMPLICATIONS FOR THE SUGAR INDUSTRY

Imports may create short-term competition, lower prices and margin pressure, while also reducing shortage risks and extreme price volatility. Long-term mill viability will increasingly depend on diversification into ethanol, cogeneration, molasses, bagasse, press-mud, bio-CNG and other value-added products.

IMPLICATIONS FOR CONSUMERS

Imports aim to improve availability and moderate price increases. Sugar prices influence households as well as food-processing sectors such as confectionery, bakery, beverages and pharmaceuticals. However, imports do not automatically reduce retail prices because consumer prices also reflect import, refining, transport, wholesale and retail costs.

STOCK LIMITS AND ANTI-HOARDING

From 15 September to 30 November 2026, the sugar dealer stock limit was reduced from 4,000 to 2,000 quintals. The measure aims to discourage hoarding and speculative accumulation during the festive season. Together, imports, stock restrictions and mill inventory management form a broader strategy for maintaining market stability.

SUGAR TRADE: EXPORTS TO IMPORT INTERVENTION

India's sugar trade reflects changing domestic supply conditions. Exports help manage surpluses and improve mill returns, whereas imports can support domestic availability during tighter periods. Exports reached about 110 lakh tonnes in 2021–22 but were around 8 lakh tonnes in 2025–26. The key challenge is to replace frequent reactive decisions with a more predictable, rules-based trade system.

SUGAR MARKET STABILISATION FRAMEWORK

A stable policy framework should link:

Production + Opening stocks → Total availability → Domestic consumption + Ethanol use + Export commitments → Projected closing stocks → Price assessment → Export or Import decision → Market stabilisation

Such a system could improve predictability for farmers, mills, traders and consumers.

MAJOR TRENDS

Three major trends are evident: sugarcane production has increased, FRP has risen substantially, and sugar exports have fluctuated according to domestic availability. Therefore,

future policy should focus not only on production but also on processing, storage, trade, consumption and alternative uses.

MAJOR CHALLENGES

Key challenges include:

- Policy uncertainty
- High water requirements of sugarcane
- Variable productivity and sugar recovery
- Delayed cane payments
- Competition between sugar and ethanol
- International price volatility
- Climate variability

POLICY RECOMMENDATIONS

1. **Introduce predictable import-export triggers** based on stocks, production, consumption, ethanol diversion and prices.
2. **Improve production forecasting** using remote sensing, satellite data, AI and field surveys.
3. **Promote water-efficient cultivation** through drip irrigation, fertigation and suitable varieties.
4. **Ensure timely cane payments** by improving mill liquidity.
5. **Maintain strategic sugar stocks** to manage temporary shortages.
6. **Balance sugar and ethanol utilisation** according to domestic requirements.
7. **Promote mill diversification** into ethanol, cogeneration and bio-based products.
8. **Improve market transparency** through timely information on production, stocks, imports, exports and policy changes.

FUTURE OUTLOOK

India's sugar sector is increasingly shaped by food, energy, climate and trade considerations. Ethanol has expanded the role of sugarcane in national energy security, while population growth and food processing will sustain domestic sugar demand.

Future policy must balance:

Farmer income + Consumer affordability + Mill viability + Ethanol demand + Environmental sustainability + Trade competitiveness

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CONCLUSION

India's 2026 sugar import policy demonstrates the difficulty of balancing farmer interests, consumer prices, mill viability, ethanol demand and trade. The 1 million-tonne duty-free import quota and reduced dealer stock limit were intended to strengthen domestic availability and control price pressures. While temporary imports can stabilize markets, excessive reliance on trade interventions may create uncertainty. A sustainable approach requires a predictable, data-driven import-export mechanism, supported by higher sugarcane productivity, efficient water use, timely farmer payments, mill diversification and coordinated sugar–ethanol policies. India's long-term sugar-sector stability will depend on achieving a balance between affordable sugar for consumers, remunerative farmer returns, financially viable mills and national energy security.

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The Hidden Enemy of Rice: From Panicle Rice Mite Infestation to Integrated Pest Management

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Abstract

The panicle rice mite, *Steneotarsonemus spinki* Smiley (Acari: Tarsonemidae), is a minute and cryptic pest of rice that can cause substantial yield and grain-quality losses. The mite predominantly inhabits the inner leaf sheath and may subsequently colonize developing panicles, where feeding can cause sterility, poor grain filling and malformed grains. Its importance is further increased by its association with sheath rot caused by *Sarocladium oryzae* and bacterial panicle blight associated with *Burkholderia glumae*. Parthenogenetic reproduction, temperature-dependent development, continuous rice cultivation, ratoon and volunteer rice, crop residues and movement of contaminated machinery can favour population persistence and spread. Its concealed habit also makes early detection and conventional contact control difficult. Sustainable management therefore requires an integrated approach combining early detection, sanitation, crop rotation, management of ratoon and volunteer rice, host plant resistance, conservation of natural enemies and judicious use of registered acaricides. This review summarizes the biology, ecology, distribution, damage and integrated management of *S. spinki*, with emphasis on early detection and preventive suppression.

Keywords: *Steneotarsonemus spinki*, panicle rice mite, rice tarsonemid mite.

Introduction

Rice (*Oryza sativa* L.) is a major cereal crop and is attacked by numerous insect and mite pests. Among them, the panicle rice mite, *Steneotarsonemus spinki* Smiley (Acari: Tarsonemidae), is an important pest in several tropical and subtropical rice-growing regions. The mite is exceptionally small and primarily inhabits the protected space between the leaf sheath and stem, making early detection difficult. As populations increase, mites may move towards developing panicles, causing poor grain development, sterility and malformed grains. Infestations have also been associated with sheath rot caused by *S. oryzae* and bacterial panicle blight associated with *B. glumae*, increasing the complexity and potential severity of damage.

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Identification

Adults of *S. spinki* are approximately 250 µm long and are not readily visible to the unaided eye. They are transparent to straw-coloured; females are ovoid, whereas males are active and possess elongated hind legs with prominent spines. Because of their minute size and concealed habit, detection requires magnification and examination of the inner leaf sheath.

Biology and Life History

S. spinki exhibits facultative parthenogenesis. Virgin females can produce male progeny, allowing establishment from a small founding population; following mating, females produce additional offspring. A female may produce approximately 55 eggs, although fecundity varies with temperature and experimental conditions.

Development is strongly temperature-dependent, with warm conditions favouring faster multiplication. The mite can also persist between rice crops in stubbles and ratoon rice, allowing populations to bridge successive cropping cycles.

Conditions favouring population increase

- Warm temperatures
- Relatively dry periods
- Continuous rice cultivation
- Ratoon and volunteer rice
- Infested crop residues
- Repeated rice cultivation without rotation
- Movement of contaminated farm machinery

Distribution and Host Association

S. spinki is recognized as a pest of rice in tropical Asia, Central America and the Caribbean. Major outbreaks have been documented in Central America and the Caribbean, and its detection in the United States demonstrated its occurrence beyond historically recognized pest regions.Rice is the principal cultivated host. The mite has also been reported from wild and weedy plants associated with rice production, including *Oryza latifolia* and other grasses and sedges. Such alternate hosts may provide refuges between rice crops and contribute to off-season persistence.

From Infestation to Damage

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The mite initially colonizes the inner leaf sheath, where feeding produces brown to chocolate-coloured discoloration. As the plant develops, populations may move through successive sheaths towards the developing panicle. Because colonies remain concealed, external inspection may underestimate infestation.

During reproductive development, feeding can result in:

- Spikelet sterility and partial panicle infertility
- Poor grain filling
- Grain discoloration
- Chaffy and malformed grains
- Reduced grain quality and yield

The severity of damage varies with mite density, crop stage, cultivar and environmental conditions. Reported yield losses differ considerably among regions, partly because mite damage may occur together with associated pathogens.



Panicle Rice mite and damaging symptoms (Source- google web)

The Mite-Disease Complex

The economic importance of *S. spinki* extends beyond direct feeding. The mite is frequently associated with *Sarocladium oryzae*, the causal agent of sheath rot, and *Burkholderia glumae*, associated with bacterial panicle blight. Feeding injury can damage plant tissues and may facilitate pathogen invasion. The mite has also been associated with the carriage of fungal propagules. Consequently, diagnosis of affected fields should consider both mite infestation and associated diseases rather than attributing all symptoms to a single causal factor.

Why Management Is Difficult

Management is complicated by three interacting characteristics of the pest: microscopic size, rapid multiplication and a protected feeding site. Parthenogenetic reproduction and

favourable temperatures can accelerate population growth, while the position beneath the leaf sheath limits exposure to contact acaricides. Therefore, management should begin before severe panicle symptoms become evident, making early detection the critical intervention point.

From Detection to Management

Surveillance and Early Detection

Fields should be monitored particularly during booting and reproductive stages. Suspected plants should be examined by carefully removing the outer leaf sheath and inspecting the inner surface with a hand lens or stereomicroscope. A useful surveillance programme should record mite presence, infestation frequency, location within the plant, sheath symptoms, panicle and grain symptoms, cultivar, crop stage and field history. Reliable sampling procedures and economic thresholds remain important research needs because concealed populations are difficult to estimate through visual scouting alone.

Cultural Management

Management should target population carry-over between crops through:

- Removal or management of ratoon and volunteer rice
- Appropriate management of infested crop residues
- Crop rotation with suitable non-host crops
- Avoidance of unnecessary continuous rice cultivation
- Cleaning of machinery before movement from infested to uninfested fields
- Management of alternate hosts where they contribute to pest persistence

These practices reduce refuges and interrupt population continuity between cropping cycles.

Biological Control

Predatory mites and fungal pathogens may contribute to natural suppression of *S. spinki*. Their practical value, however, depends on field efficacy, predator-prey relationships, environmental compatibility and compatibility with other management practices. Conservation of naturally occurring predatory mites should therefore be encouraged through avoidance of unnecessary broad-spectrum pesticide use.

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Natural enemy	Type / group	Feeding or role	Importance in rice ecosystem
Spiders	Generalist predators	Actively prey on small, soft-bodied arthropods, including mites and other insect pests	Help naturally suppress pest populations in paddy fields
Predatory mites	Acari;mainly Phytoseiidae	Feed directly on plant-feeding mites and their immature stages	Potentially useful biological control agents; their use in rice is less developed than in orchard systems
Amblyseius spp.	Predatory mites; Phytoseiidae	Hunt and consume phytophagous mites and other small arthropods	Important group of predatory mites with potential for mite management
Endoparasitoid wasps	Hymenoptera	Develop inside suitable insect hosts and contribute to suppression of pest populations	May contribute to overall biological control within the crop canopy, although they are not specific predators of rice mites

Chemical Management

Chemical control should be used judiciously when mite populations reach economically important levels. At this stage, any one of the recommended acaricides should be applied at the appropriate label-recommended dose:

S. no.	Insecticides/ formulation	Dose/L
1	Spiromesifen 22.9% w/w SC	1.0 ml
2	Propargite 57% EC	1.0 ml
3	Fenpyroximate 5% EC	1.0 ml
4	Ethion 50% EC	3.0 ml
5	Diafenthiuron 50% WP + Propiconazole 25% EC	1.5 g + 1.0 ml
6	Propargite 57% EC + Propiconazole 25% EC	1.5 ml + 1.0 ml
7	Profenofos 50% EC + Propiconazole 25% EC	2.0 ml + 1.0 ml

Integrated Pest Management Strategy

An effective IPM programme can be organized around four sequential steps: This approach shifts management from responding to visible damage towards preventing population establishment and limiting carry-over.

Detect: Inspect inner leaf sheaths and monitor susceptible crop stages.

Disrupt: Manage ratoon and volunteer rice, crop residues and alternate hosts; clean farm machinery.

Reduce: Use suitable cultivars, crop rotation and conservation of natural enemies.

Intervene: Where damaging infestation is confirmed, apply an effective, locally registered acaricide as part of an integrated programme.

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Weekly Market System as a Rural Livelihoods and Local Economic Development in Garo Hills, Meghalaya

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Introduction

Meghalaya is an eastern hilly state that experiences humid subtropical weather, with rainfall ranging from 2,500 mm to 5,000 mm per year and temperatures between 4 and 30 °C. The state's undulating topography and predominantly acidic red and lateritic soils support diverse agricultural and horticultural activities. Tribal farmers, mainly belonging to the Garo, Khasi, and Jaintia communities, cultivate crops such as rice, maize, millets, and a variety of indigenous tubers, along with horticultural crops like pineapple, Khasi mandarin, oranges, banana, jackfruit, and arecanut. Spices are another major production in Meghalaya, including turmeric, ginger, black pepper, and bay leaf, while livestock rearing, such as piggery, goatery, and backyard poultry farming, plays a vital role in sustaining rural livelihoods and nutritional security.



The Garo Hills region of Meghalaya, comprising the districts of West Garo Hills, South Garo Hills, East Garo Hills, South West Garo Hills, and North Garo Hills, is home to the Garo community and other tribes, including Koch, Hajong, Rabha, and Banai. The rural economy depends on agriculture as the main source of income, and farmers have relied on the traditional farming system for their livelihoods. Some of the most significant indigenous institutions underpinning rural livelihoods in the area are the Weekly Markets (*Antini Bazar*). These markets have existed as centres of business and economic development for ages. These markets, which were initially restricted to local trade, have now become widespread in the rural Garo Hills. The weekly market is much more than a place to buy and sell; it is an arena for earning money, sharing information, purchasing household necessities, and building connections in the community. In most villages of the Garo Hills, farmers

plant crops such as turmeric, ginger, arecanut, banana, colocasia, tapioca, yam, elephant foot yam, sweet potato, and various vegetables. However, due to a lack of proper market facilities, farmers have difficulty selling their produce. This system of weekly markets is an ideal solution to this problem. Each market is held on a particular day of the week, drawing a large number of farmers and buyers from nearby villages. The farmers eagerly wait for the market day to sell their goods and earn money to cover their expenses. Among all weekly markets, the *Garobadha weekly market* is one of the largest, followed by the *Chibinang weekly market*, which is held every Tuesday. In this weekly market, most fresh vegetables are sold by farm women using the *bhaga* system instead of by kilogram. Depending on the type of vegetable or edible item, they are sometimes wrapped in banana or turmeric leaves to preserve their freshness.

The Story of Rural Farmers

Before Market Day

One day before the market schedule, the farmers harvest produce from their farm. The turmeric rhizomes are cleaned, the ginger is segregated, and the tuber crops are harvested carefully. Both women and men work in tandem to make the harvest ready for selling purposes. However, bamboo shoots are harvested early in the morning on the very day of the market, since customers tend to prefer freshly harvested shoots. This tradition reflects the importance of freshness and quality in indigenous food systems. Many farmers carry their produce on foot, on a motorcycle, in an auto-rickshaw, in a pick-up (Mahindra or Bolero), or in shared vehicles to reach the market early in the morning. Most people in remote areas reach the bazaar in a Mahindra or Bolero pickup, and when returning, they carry their purchases.

Activities in the Weekly Market

The rural weekly market, locally referred to as an *Antini bazar*, forms an integral part of the socio-economic activities of the tribal communities of Garo Hills. Weekly markets usually start at 7:00 AM and continue until approximately 2:00 PM, while some rural markets get over by 12:30 PM. The weekly market serves as an important meeting point for farmers, traders, and villagers for business and other social and cultural activities. There are several purposes for which the market is used in the lives of the Garo communities. The farmers come to the market with their produce to earn money for their families' needs. It also serves as a venue for villagers to purchase basic necessities and exchange seeds and other planting materials. There are also livestock and poultry trading at the market. Apart from economic activity, the weekly market also serves as a centre for social interaction, the exchange of indigenous agricultural knowledge, cultural

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exchange, and community networking. Several products cultivated by the tribal people are sold at the market. They include turmeric, ginger, arecanut, banana, colocasia, tapioca, yam, elephant foot yam, sweet potato, bamboo shoots, and several other seasonal fruits and vegetables cultivated locally. Many of these products are produced through traditional methods (*Jhum* or plain land cultivation) and hold high value for both household and commercial use. In turn, the farmers procure essential household products like dry fish, salt, chilli, pulses, vegetables, cloth, household goods, and writing materials. In this way, the weekly market acts as an important link between the rural producers and consumers. The income earned from the weekly market plays a significant role in covering the weekly needs of the tribal families in the Garo Hills region.

During festival seasons, the market committee occasionally reschedules the weekly market day when it coincides with a major festival. In such cases, the market is usually held on an earlier or alternative day to facilitate the festival's celebration and ensure maximum participation by traders and villagers.



Economic Impact

The weekly market system has become a crucial driving force behind rural economic development.

- **Benefit farmers:** Weekly market provides a venue to sell their products and helps sustain their livelihood
- **Direct produce marketing:** Farmers do not need intermediaries in selling their products
- **Instant money flow:** Produce is instantly turned into money
- **Less post-harvest losses:** The fresh produce gets sold fast and avoids any losses.
- **Markets for traditional crops:** The traditional crops, like colocasia, yams, and bamboo shoots, have plenty of buyers as they are all grown organically.
- **Livestock marketing facility:** The poultry birds and livestock are exchanged as well as sold on a regular basis
- **Exchange of seeds and planting material:** Farmers get good-quality planting material for the next season.
- **Social and cultural importance:** People from various villages gather at a single point. This helps them create strong social links and maintain their cultural identity. Market days are considered recreation days for many elders and women. The culture, language, and traditions remain alive thanks to these markets. The exchange of farming knowledge among farmers helps preserve their agricultural tradition.

Challenges

However, despite their significance, weekly markets experience certain difficulties, which include:

- Insufficient market facilities
- Inadequate storage facilities
- Lack of proper transport during the rainy seasons
- Inadequate facilities for value addition
- Price fluctuation
- Limited access to digital marketing facilities

Overcoming these hurdles would further increase the role of weekly markets in rural development.

Way Forward

For improving the efficiency of the weekly markets, the following strategies can be adopted:

- Construction of better market sheds

- Development of storage and grading centres
- Value-added products promotion
- Improved road connectivity
- Market information through digitization
- Empowerment of women entrepreneurs and farmers' associations.
- Branding of local products of Garo Hills

Conclusion

In the Garo Hills, the age-old tradition of weekly markets remains a vital means of sustaining the livelihoods of farming tribes. This is an effective intermediary between producers and consumers, providing food security, generating income, and preserving indigenous agriculture. The weekly market means much more for numerous rural communities than just another commercial venue, as it signifies the resilience of their culture and economic independence. With modernization underway, it is vital to preserve and improve this special foundation in the Garo Hills of Meghalaya.

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Storage behaviour of forest orthodox and recalcitrant seeds

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ABSTRACT

Ex situ seed bank conservation of forest genetic resources requires knowledge on the seed storage behaviour in terms of either orthodox or recalcitrant type. Orthodox seeds of many forest species including *Pinus* and *Tectona* possess physiological and biochemical mechanisms enabling them to endure desiccation to 2-5% moisture content, while the desiccation sensitivity of recalcitrant seeds like *Quercus* and *Shorea* restricts their moisture content at high level (30-70%). Hence, while orthodox seeds can be conserved ex situ for decades to centuries, the recalcitrant species are unable to form persistent soil seed banks, threatening their long-term conservation in the backdrop of forest degradation and climate change. Thus, special efforts including tissue culture, maintaining live gene banks, and cryopreservation of embryonic axes at ultra-low temperatures are necessary for conservation of recalcitrant species.

Keywords: Orthodox seeds, Recalcitrant seeds, Tissue culture, Cryopreservation

Introduction

Forest ecosystems are the foundation of biodiversity, climate regulation, and ecological integrity. In this regard, ex situ conservation of forest tree genetic resources in the form of seed banks, as a measure of species conservation, reforestation, and restoration, has become a compelling practice. Not all forest tree species have seeds that are amenable to seed banking. There is a need to understand the basic science of forest tree seed storage behaviour to adopt appropriate conservation strategies.

The categorization of seeds according to their tolerance of desiccation and response to storage was proposed by Roberts (1973) and modified by Ellis *et al*. (1990). Seeds are classified into different categories based on their physiological responses to drying and low temperature during storage. Knowing if a particular forest tree species has orthodox or recalcitrant seeds is the first step towards developing conservation strategies.

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Orthodox seeds

Orthodox seeds are capable of withstanding desiccation (drying) and exhibit an increase in desiccation tolerance during the late stages of development. They usually lose viability rapidly upon storage at ambient temperatures, but this process can be slowed down by lowering the temperature and moisture content. Orthodox seeds can endure desiccation down to a moisture content (MC) of 2-5%. According to Harrington's rule, for orthodox seeds, the lifespan can be predicted for a given level of MC or temperature; for every 1% reduction in MC or 5ºC reduction in storage temperature, the lifespan of the seeds doubles. The Orthodox seeds can be stored in conventional gene banks at –18 to –20ºC for long-term conservation. The few forest tree species that are orthodox include the pines (*Pinus spp*.), teak (*Tectona grandis*), acacia (*Acacia spp.),* and eucalyptus (*Eucalyptus spp.).*

Recalcitrant seeds

Recalcitrant seeds are exceptionally sensitive to desiccation and cannot tolerate exposure to low temperatures. Compared to orthodox seeds, they do not tolerate desiccation and are typically shed at a relatively high moisture content (30-70%). Desiccation sensitivity occurs during the later stages of their development. A major proportion of recalcitrant forest tree species including *Shorea* and *Quercus* exhibit extreme sensitivity to low temperatures especially below 10-15ºC. For example, the seeds of *Shorea* species contain very little moisture and cannot be conserved in gene banks. The longevity of recalcitrant forest tree species is usually short, ranging from days to months.

Parameter	Orthodox Seeds	Recalcitrant Seeds
Moisture content at shedding	Low to moderate (10-20%)	High (30-70%)
Desiccation tolerance	High	Low
Optimum storage temperature	–18 to –20ºC	15ºC (tropical) and 0-5ºC (temperate)
Lifespan/Longevity	Decades to centuries	Days to months
Primary damage mechanism	Aging Desiccation, DNA degradation	Desiccation damage, chilling injury, metabolic arrest
Common forest tree species	Pines (Pinus), Teak (Tectona)	Oaks (*Quercus*), Sal (*Shorea*)

Physiological mechanisms of storage behaviour

Mechanisms in orthodox seeds

Orthodox seeds exhibit unique physiological adaptions such as the synthesis of Late Embryogenesis Abundant (LEA) proteins and accumulation of sugars during the maturation phase so that they normally tolerate desiccation down to a MC of 2-5%. At low moisture and temperature, the cytoplasm of orthodox seeds is vitrified into a glass-like consistency that prevents any reaction occurring in the cells. Orthodox seeds also have antioxidant defense mechanisms that help in detoxifying reactive oxygen species that may accumulate during desiccation.

Mechanisms in recalcitrant seeds

Recalcitrant seeds normally do not undergo the maturation drying process on the mother plant. Due to their inability to adjust membrane lipid phase transitions, water removal from these seeds causes cessation of metabolic processes, resulting in the accumulation of toxic metabolites such as reactive oxygen species. The seeds also have decreased production of LEA proteins and oligosaccharides, and their cellular membranes transition to a liquid state when dehydrated, leading to loss of cellular content upon rewetting. Additionally, in tropical regions, the cellular membranes of the recalcitrant seeds are vulnerable to cold temperatures and undergo phase transition which causes significant cellular damage.

Forest seed examples

Orthodox forest tree species: Orthodox forest tree species are predominantly found in temperate conifers and the dry tropical region. For example, the seeds of Pinus spp. can be desiccated to a very low moisture content and subsequently stored in gene banks for long-term conservation. The seeds of *Acacia* and *Eucalyptus* species are also highly tolerant to desiccation. Many *Acacia* species have hard seed coats that induce physical dormancy. Another good example of a forest tree species that produces orthodox seeds is *Tectona grandis*. Being highly valuable tropical timber, Tectona provides an excellent opportunity for international trade of its seeds.

Recalcitrant forest tree species: Recalcitrant forest tree species are largely confined to the canopy of tropical rainforests, but some species also occur in temperate climax forests. For example, *Quercus* and *Castanea* spp. are temperate trees that produce recalcitrant seeds. The majority of their seeds mature in late summer or autumn and should be stored in a moist forest for winter. These seeds are sensitive to desiccation but resistant to near-freezing temperatures.

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Meanwhile, in the tropics, trees of the genus *Shorea* are keystones species of dipterocarps. The seeds of *Shorea* spp. are short-lived and germinate soon after falling from the tree to the ground. Moreover, they die at temperatures below 15ºC and a moisture content of less than 35%. By contrast, the genus *Theobroma* is a representative of Amazonian understory species with recalcitrant seeds.

Management, practical storage techniques & conservation strategies

Strategies for orthodox seeds

Due to the predictable nature of orthodox seed physiology and their ability to withstand desiccation, they can be stored in conventional gene banks. The first step to this process is appropriate seed processing. This involves drying the cleaned seed lots at a controlled environment (15ºC, 15% RH) to reduce the moisture content (MC) to 3-5%. Seeds with stabilized moisture can then be stored in moisture-proof containers (glass jars or laminated bags) in gene banks. To store such seeds for a longer period, the containers can be placed in a deep freeze (walk-in freezer) set at –20ºC.

Strategies for recalcitrant seeds

Since recalcitrant seeds cannot be stored in gene banks, special measures such as short-term moist storage, cryopreservation, and live gene banks (ex situ arboreta) are needed for their conservation. For short-term conservation, recalcitrant seeds may be stored at an optimal temperature and moisture content mixed with appropriate media (peat or sawdust) for a few weeks to months. As far as long-term conservation is concerned, cryopreservation of embryos or embryonic axes appears to be the most promising technique for the conservation of recalcitrant forest tree seeds. In this process, the embryonic axis is cut out from the seed and subjected to rapid drying to a specified moisture content followed by cryoprotection and ultra-rapid freezing by plunging them into liquid nitrogen at –196ºC. Another conservation option includes the maintenance of live gene banks. Here, the gene bank curator maintains a collection of plants of desired species in botanical gardens under appropriate environmental conditions. Alternatively, tissue culture can be undertaken to maintain plantlets of desired species in vitro under aseptic conditions.

Ecological and conservation implications

Seed storage behaviour plays a critical role in ecology and conservation. For instance, dipterocarps are termed ‘recalcitrant’ species because they ‘mast seed’ to guarantee that enough seeds reach the ground to produce the required number of seedlings for new forest growth to occur. This is an

adaptation that makes them highly vulnerable to anthropogenic disturbances such as logging; it means that any human activity that affects the forest cover will affect their ability to regenerate. Moreover, climate change poses a serious threat to these species because changes in rainfall patterns can affect germination and establishment of these species. It has been postulated that the majority of critically endangered plant species are recalcitrant and thus not amenable to conventional seed banking. In fact, it is estimated that 36% of endangered species and over 90% of climax forest tree species are recalcitrant and thus require specialized downstream conservation approaches. Therefore, more research is needed to bridge the gap between conservation needs and the actual practice of ex situ seed bank conservation for recalcitrant forest tree species.

Conclusion

The concept of orthodox and recalcitrant seeds and their conservation approaches are of utmost importance to forest genetic resources conservation. Due to the presence of LEA proteins and physiological adaptations enabling cells to withstand desiccation, orthodox seeds can be stored in gene banks at ultra-low temperatures for long-term conservation. Recalcitrant seeds, on the other hand, require special approaches such as tissue culture, live gene banks, and cryopreservation techniques to overcome desiccation and low-temperature injuries. With the current threat to forest ecosystems across the globe due to climate change, conservation of recalcitrant forest tree species appears to be a major challenge for the seed technologists and conservation biologists in the near future.

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