SARPS - Journal of Advanced Research in Plant Science
January-June 2026 2(1)
https://journalofplantscience.com

Original Article

BIOPESTICIDES UTILIZATION SCENARIO IN INDIA: RECENT TRENDS IN BIOPESTICIDES IMPLEMENTED STRATEGIES FOR SUSTAINABLE HORTICULTURE

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ABSTRACT

The global horticultural sector is currently at a pivotal point, driven by the dual challenges of climate induced pest resurgence and the stringent regulatory laws to eliminate synthetic chemical residue. Although India contributes significantly to the global fruit and vegetable production, its shift towards biological control strategies present an inconsistent and fragmented implementation. As the global horticulture transition towards sustainable intensification, biopesticides have emerged as prime alternative to synthetic agrochemicals. Currently, Indian biopesticides market is undergoing enormous expansion, expected to exceed USD 285 million by 2026. This review examines biopesticides utilization within Indian horticulture system, sector crucial to country's nutritional and economic security. Despite having rich history of botanical pest controlling practices, Indian transition towards widespread implementation of biopesticides encounter several challenges, such as inconsistent field efficiency, regulatory complexities, and insufficient knowledge among farmers. In contrast the global arena is shifting towards transformative cutting edge technologies. This review consolidates the global breakthroughs including RNA interference (RNAi) biopesticides, nanoencapsulation delivery systems, and CRISPR-based biocontrol tactics, assessing their potential for incorporation into Indian horticultural practices. This review emphasize the connection between indigenous knowledge and global technical advancement, offering a strategic framework to improve dependability and scalability of biopesticides. Ultimately, it promotes a contemporary Integrated Pest Management (IPM) strategy to residue free horticultural output.

Keywords: Biopesticides, Indian Horticulture, Sustainable Horticulture, RNAI, Nano-Biopesticides, Integrated Pest Management (IPM)

INTRODUCTION

Horticultural crops constitute the backbone of food system worldwide, comprised of important fruits, vegetables and essential crops that are crucial to human sustenance and global agrarian economy. Horticultural activities encompasses the production of vegetables, fruits, ornamentals, spices and medicinal and aromatic plants. The acceleration of horticultural production has intensified dependence on pesticide to address pest, illness and weed, as cultivators endeavor to satisfy market need Gogoi et al. (2025), El-Sheikh et al. (2023). Nevertheless, the extensive use of pesticides poses health hazards for agricultural workers and consumers, in

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Received: 06 January 2026; **Accepted:** 23 February 2026; **Published** 31 March 2026
DOI: 10.29121/SARPS.v2.i1.2026.18
Page Number: 1-21
Journal Title: SARPS - Journal of Advanced Research in Plant Science
Journal Abbreviation: SARPS- J. Adv. Res. Plant Sci.
Online ISSN: 3108-2521
Publisher: Granthaalayah Publications and Printers, India
Conflict of Interests: The authors declare that they have no competing interests.
Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
Authors' Contributions: Each author made an equal contribution to the conception and design of the study. All authors have reviewed and approved the final version of the manuscript for publication.
Transparency: The authors affirm that this manuscript presents an honest, accurate, and transparent account of the study. All essential aspects have been included, and any deviations from the original study plan have been clearly explained. The writing process strictly adhered to established ethical standards.

addition to causing environmental contamination Food and Agriculture Organization of the United Nations, and World Health Organization (2025). Recent data reveals that global pesticide reliance for horticultural crops has escalated by 45%, with developing country experiencing an increase up to 65%. The worldwide economic influence of horticultural crops surpasses USD 500 billion, with pesticide expenditure constituting 8-15% of overall production Gogoi et al. (2025). In, India horticultural production has increased from 2, 68,845 metric tonnes in 2012-13 to 3, 69,055 metric tonnes in 2024-25 Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024). Unregulated pesticide use present considerable health hazards, the World health organization reports that around 25 million people in developing nations suffer from acute pesticide related ailments each year, resulting in approximately 11,000 fatalities due to accidental poisoning World Health Organization (2024). Pesticide usage in India is projected to attain 53,759.56 metric tons (MT) in 2024-25 Directorate of Plant Protection, Quarantine and Storage (2025). Biopesticide offer a sustainable alternative to chemical pesticide effectively, targeting pest while minimizing the ecological damage linked to conventional chemical pesticides Fenibo et al. (2021). In accordance with United Nations' 2030 Sustainable Development Goals (SDGs), biopesticides mediated sustainable agriculture seeks to alleviate poverty (SDG 1) and hunger (SDG 2). The effective management of natural resources is essential for sustainable utilization of environment to improve agricultural productivity (SDG6- Clean Water and Sanitation, SDG12: Sustainable Consumption and Production, SDG14- Life Under Water and SDG15: Life on Land). It further includes energy (SDG7), technology, and innovation (SDG9) Fenibo et al. (2021).

Considering all these aspects, the main objective of this review is to critically analyze the comprehensive idea of biopesticides, their integration into pest control systems, and their present utilization in sustainable horticulture. It also includes horticultural crop wise biopesticide applications, emphasizing contemporary trends and yield efficiency observed in the field. Additionally, this review summarizes the consumption of biopesticides within Indian horticulture systems and how this consumption has influence the horticultural production over the years.

BIOPESTICIDES UTILIZATION SCENARIO IN INDIA

Central Insecticide Board and Registration Committee (CIBRC) under Directorate of Plant Protection, Quarantine and Storage is India's leading authority for biopesticide, overseeing the registration of 970 products (https://ppqs.gov.in/en/divisions/cib-rc/bio-pesticide-registrant accessed on 29 Jan 2026). Despite global production reaching 3000 tonnes annually, biopesticides represent only 4.2% India's pesticide market Chakraborty et al. (2023). Out of registered products (970), fungal variants emerged as dominant player in biopesticides market accounting for 65% share in the total, indicating their commercial viability, likely due broad spectrum efficacy and ease of mass production. *Tricoderma, Beauveria, and Verticillium* are some impotent species in this group. Bacterial biopesticides make up to 24% of the market, with well-known agents like *Bacillus thurenginasis (Bt)*, however they are not as common as fungal products. The rest of the sectors are substantially smaller, suggesting specialized usages or barrier to adoption such as viral biopesticides accounted only 8% due high host specificities and intricate production. Botanical and biochemical pesticide possesses the smallest market share of 3% despite the historical application of plant derived insecticide like neem.

The registration and regulation of biopesticides in India are govern by insecticide act of 1968. This act has registered a total of 12 separate categories of biopesticide including Chakraborty et al. (2023):

1) *Bacillus thuringiensis var. israelensis*
2) *Bacillus thuringiensis var. kurstaki*
3) *Bacillus thuringiensis var. galleriae*
4) *Bacillus sphaericus*
5) *Trichoderma viride*
6) *Trichoderma harzianum*
7) *Pseudomonas fluorescens*
8) NPV *of Helicoverpa armigera*
9) *Beauveria bassianas*
10) *NPV of Spodoptera litura*
11) *Neem-based pe*sticides
12) *Cymbopogon*

The biopesticides market in India (as depicted in Figure 1) exhibited significant long term growth. Starting from baseline of 5151 Metric tonnes in 2010-11, consumption reached 7593 MT in 2024-25. Despite considerable annual fluctuation in recent years, long term growth from 2010 to 2025 indicates consistent growth, averaging 2.81% annually, resulting in an aggregate volume rise over 45%. The highest level of consumption reported was 9321 MT during 2021-22. Following a significant decline in 2022-23, a sector saw robust rebound in 2023-24, while the 2024-25 projections suggest possible market stability of corrections. As per the report published by Central Insecticide Board and Registration Committee (CIBRC) for period for 2024-25, West Bengal topped biopesticides adoption, with a reported consumption of 1575 MT, followed by Maharashtra and Rajasthan (Illustrated in Figure 2).

Maharashtra exhibits consistent consumption while Rajasthan demonstrate significant variability. Gujarat is considerably boosting its biopesticides utilization, nearly doubling from 307 MT in 2019-20 to 621 MT in 2024-25. Chhattisgarh demonstrates development, increasing from 607 to 791 MT. Bihar's consumption remained static at 360 MT for five years before decline to 133.5 MT in 2024-25. Uttarakhand had instabilsities, reaching a highpoint of 408.9 MT before seeing a decline. Numerous Union Territories, such as Chandigarh and Ladakh exhibit little biopesticides usage owing to restricted agricultural acreages and were omitted from principal chart to enhance clarity. These statistics elucidate the comparatively diminished efficacy of biocontrol efforts compared to those in southern states.

DEFINITION AND CLASSIFICATIONS OF BIOPESTICIDES

Biopesticides, derived from the Latin words pestis meaning 'scourge' and caedere implies 'to kill,' are pesticides of natural origin, mostly including bacteria, viruses, fungi, or active components sourced from plants. The mechanism of action of biopesticides relies on distinct biological effects rather than chemical extermination. Biopesticides utilized in horticulture are categorized according to their extraction sources and the explicit molecules or complexes employed in their formulation.

Figure 1

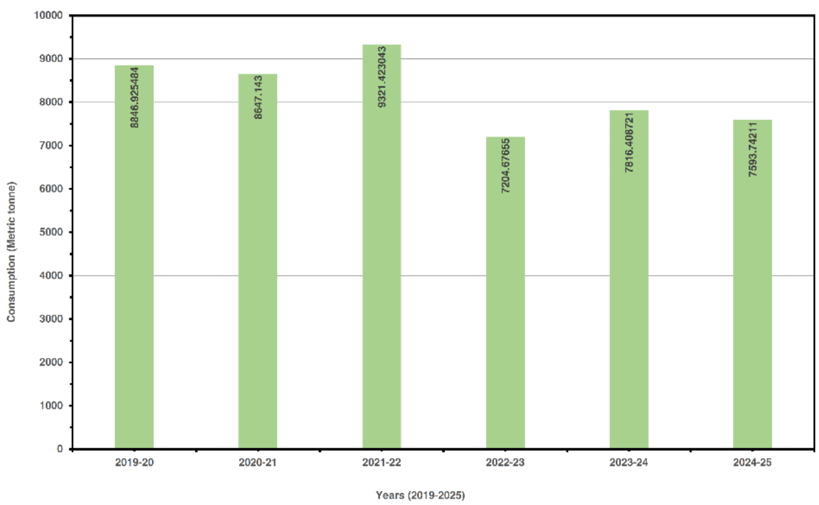

Figure 1 Indian Biopesticide Consumption Trends (2019-2025)

Figure 2

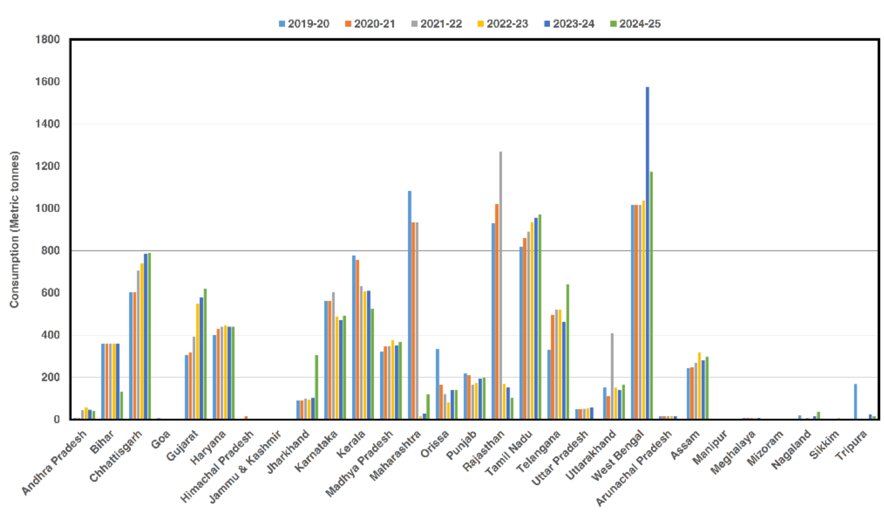

Figure 2 States Wise Biopesticide Utilization Trends (2019-2025)

MICROBIAL PESTICIDES

Microbial pesticides originate from microorganisms such as bacteria, fungi, and viruses, with a special focus on pest species. Bioinsecticides, including those derived from *Bacillus thuringiensis* (Bt), mitigate detrimental insect populations, whereas bioherbicides manage weed proliferation. In the past decade, several researchers have discovered new strains and toxins that have impelled the commercialization of biopesticides. Prominent bacterial entomopathogens are *Pseudomonas Yersinia, Bacillus* and *Chromobacterium*, whereas significant fungal agents include *Beauveria, Metarhizium, Verticillium, Lecanicillium, Hirsutella,* and *Paecilomyces*. Fungi, such as *Beauveria bassiana*, driven by enzymatic devastating the cuticle, infiltrating insect tissue, and secreting poisons such beauvericin to eliminate the host Fenibo and Matambo (2025).

Baculoviruses, distinguished by their species specificity, generate virions that specifically infect eating insects such as Lepidopteran caterpillars. Recombinant baculoviruses, such as ColorBtrus, comprise of a viral occlusion body that combines a virion with the Bt insecticidal Cry1Ac toxin protein. The combined strategy infects insects by ingestion, binding to receptors in the insect gut, creating holes that prompt cell rupture and eventually result in fatal septicemia, so disturbing vital cellular function efficiently and rapidly Kumar et al. (2021), Yadav et al. (2025), Fenibo and Matambo (2025).

Entomopathogenic nematodes (EPNs) from the genera *Heterorhabditis* and *Steinernema*, in association with the symbiotic bacteria *Photorhabdus* and *Xenorhabdus*, function as efficacious biocontrol agents. They are ecologically benign and ease in bulk production, enabling their marketable expansion and relieving them from rigorous registration obligations Kumar et al. (2021), Fenibo and Matambo (2025).

BIOCHEMICAL PESTICIDES

Biochemical pesticides are natural amalgams that manage pests using non-toxic practices, in contrast to manmade chemical pesticides that eliminate them directly. They can be categorized according to their mechanism of action, including the use of pheromones (semiochemicals), botanical extracts, or natural insect growth regulators for the management of pest infestations.

INSECT PHEROMONES

Insect pheromones are chemical substances produced by insects that can be artificially amalgamated for integrated pest control. They impede with mating activities, disturbing successful reproduction devoid of eradicating insects. Rather, they puzzle insects by altering their olfactory structures. Pheromones are absorbed by the antennae and diffuse into sensilla through cuticle pores. Internally, they occupy the pheromone-binding proteins (PBPs) sites and involve with certain receptors, modifying the signal into an electrical signal through a second messenger system Fenibo and Matambo (2025), Gurr et al. (1999), Kumar et al. (2025). A recent study focused on the production of sex pheromones to control Spodoptera exigua through an innovative RNA biopesticide (dsSepbanr). RNA interference (RNAi) silenced the Sepbanr gene, declining critical sex pheromones (Z9, E12–14:Ac and Z9–14:Ac), henceforth hindering reproducing incidence and restraining egg production He et al. (2025).

PLANT-DERIVED EXTRACTS AND ESSENTIAL OILS

In recent years, plant-derived extracts and essential oils have emerged as noteworthy substitutes to synthetic pesticides to control insect pests. These insecticides, derived from plants, enwrap varied bioactive elements that function as repellents, attractants, or antifeedants. They can hinder processes like as respiration, impede host plant recognition, and reduce adult emergence via ovicidal and larvicidal activities. Noticeable instances include neem oil and lemongrass oil, readily accessible in international herbal marketplaces. The essential oil market is projected at USD 700 million, with global manufacture of 45,000 tons Kumar et al. (2021). Commercial neem products comprise NeemBaan®, Margosom®, Anosom®, and Derisom®, whereas pyrethrum-based amalgam involve Pyrethrum 5EC®, EverGreen®, and Monterey Bug Buster-O® Fenibo and Matambo (2025). Halder et al. (2013) found that the blend of neem oil with the entomopathogenic microorganisms such as *Beauveria bassiana, Metarhizium anisopliae, Verticillium lecanii, and Pseudomonas fluorescens* effectively controls vegetable-imbibing pests. Specific dosage of azadirachtin is critical to guard non-target species.

INSECT GROWTH REGULATORS

Insect growth regulators (IGRs) obstruct critical biological processes vital for insect lifecycle, ensuing in death. They have pronounced selectivity and exhibit negligible impairment to non-target species. IGRs are classified as chitin synthesis inhibitors (CSIs) and disruptors of hormonal system, comprising juvenile hormone analogues and ecdysteroids (as shown in Figure 4d). These regulators can governor species such as fleas, cockroaches, and mosquitoes, nonetheless they generally do not decimate adult insects. Although IGRs unveil less toxicity to humans, they efficacious inhibit insect reproduction, obstruct egg hatching, and impede molting in young insects. When applied in combination with other insecticides, IGRs can expand treatment effectiveness against adult populations Kumar et al. (2021), Gurr et al. (1999).

TRANSGENIC BIOPESTICIDES (TBS)

Transgenic biopesticides are obtained from genetically modified organisms, wherein genetic material is incorporated into plants, allowing them to produce pesticidal elements known as plant-incorporated protectants (PIPs). Plant-Incorporated Protectants (PIPs) are genetically altered crops holding inherent defense systems. Cry proteins, derived from the soil bacteria *Bacillus thuringiensis* (Bt), establish the first generation of insecticidal PIPs Yadav et al. (2025). Continuous study is central to assess the environmental implications of these PIPs, particularly RNAi-based PIPs. RNA interference (RNAi) is a gene silencing method that employs double-stranded RNA (dsRNA) to abolish complementary messenger RNA (mRNA) as depicted in Figure 4h. Managed by the dicer (RNase III enzyme) into small interfering RNAs (siRNAs), these siRNAs are integrated into the RNA-induced silencing complex (RISC) to precisely slice target mRNA and diminish gene expression. RNA interference delivers novel pest management system by impeding vital genes in pests while reducing effects on non-target species. Two primary deployment strategies include: host-induced gene silencing (HIGS), wherein crops produce dsRNA that targets pest genes, and spray-induced gene silencing (SIGS), illustrated in Figure 4h, which utilizes nanoparticle enriched dsRNA to improve uptake and stability Yadav et al. (2025), Lim et al. (2026), Xu et al. (2025).

NANO BIOPESTICIDES (NBS)

The concept of 'nano' in biopesticides has transformed the market owing to the dimensions, content, and properties of materials contrived within a scale of 1–100 nm. These miniscule biologically active particles can hinder pathogen proliferation by exterminating or repelling them. Nanoencapsulation (shown in Figure 4e) and nanocontainers increase pest control effectiveness and stability, enabling the employment of reduced quantities of nanobiopesticides. Metallic nanoparticles (NPs) including zinc, gold, silver, nickel, and titanium have bactericidal characteristics that alleviate damage imposed by phytopathogens. They provide superior solubilization and targeted delivery comparative to conservative biopesticides, employing varied bacterial, fungal, and plant extracts for nanoparticle production Kumar et al. (2021), Anjaneyulu et al. (2024), Syahputra et al. (2025).

Figure 3

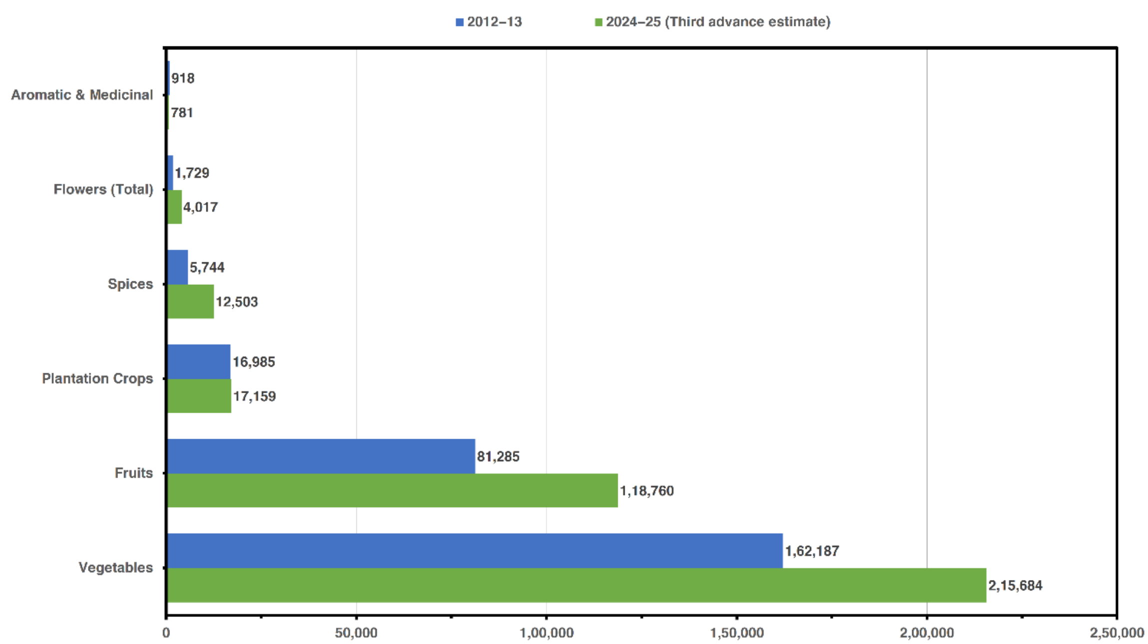

Figure 3 India's Horticulture Sector: A Decadal Leap in Production [2012-13 vs. 2024-25 Third Advance Estimate]

Horticultural crop wise biopesticide implementation studies including newer trends and field based yield efficiencies.

VEGETABLE CROPS

Vegetable crops account for 59.7% of the total horticulture production in India. The extent of Indian vegetable cultivation spans 11,707 hectares, yielding a total production of 215,684 metric tonnes (as depicted in the Figure 3), for the period 2024-2025, as provided by Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024) (https://agriwelfare.gov.in/en/StatHortEst viewed on 16 Feb 2026). In the financial year 2025, vegetable exports crossed USD 819 million; however, the United Nations Industrial Development Organization (UNIDO) Standards Compliance Analytics (SCA) tool unveils that edible vegetables and certain roots and tubers (Category 7) remain the most frequently rejected categories, with 101 consignments rejected for India in 2024-25 owing to pesticide level over Maximum Residue Limits (https://hub.unido.org/sca/#/countries/699?value_view=abs&product_exporter=504&product=123,7 accessed 19 Jan 2026). In India, vegetable crops are highly vulnerable to various pests, including borers (such as fruit and shoot borers in tomato and brinjal), sucking pests (like aphids, jassids, thrips, and whiteflies on okra, chili, and onion), and caterpillars/moths (notably the Diamondback Moth on cabbage), which significantly affect harvest. Additionally, major infections include fungal diseases such as Damping-off, Root Rot, Powdery and Downy Mildew, as well as viral infections like Mosaic and Leaf Curl, necessitating Integrated Pest Management (IPM) Fenibo and Matambo (2025). Vegetable crops impose rigorous pesticide application attributable to their substantial market returns, continuous production cycles, and susceptibility to numerous insect pests. These complications are exacerbated by climate change upshots the propagation of pest species, modifications in voltinism, and intensified pest pressure in vegetable cultivation practices Chhor et al. (2026), Majumder et al. (2024). The employment of biopesticides to address insect problems in Indian vegetable growing systems has risen in recent decades, as indicated by consumption figures of 853.35. Metric tonnes of biopesticides were utilized for vegetable cultivation in India during 2024-25 Directorate of Plant Protection, Quarantine and Storage (2025). This implies a link between the use of biopesticides and increased production over time as illustrated in Figure 3 The application and deployment of biopesticides in horticulture system are garnering significant interest from producers. Some onsite studies Table 1 are included in this section. Several research studies Amour et al. (2025) used field applications of *Beauveria bassiana, Akanthomyces lecanii*, and *Akanthomyces muscarius* in cassava, mostly aimed at controlling whitefly (*Bemisia tabaci*). Efficiencies ranging from 64% to 75% were observed in field-level applications utilizing insecticidal entomopathogenic fungi. The use of predatory mites (*Amblyseius swirskii* and *P. persimilis*) on cucumber crops, as reported by Adly and Sanad resulted in an 84.5% decline of aphids Adly and Sanad (2024). Mollah and Hassan (2023) utilized *Trichoderma harzianum* in Potato (*Solanum tuberosum*) fields formerly distressed by late and early blight. A field-based investigation conducted in Bangladesh clearly reduced *Leucinodes orbonalis* infections. This study resulted in an increased production from 14.8 to 21.7 tons per hectare, signifying a 46% enhancement in contrast to untreated control plots. The tendency was similarly noted in the utilization of plant biopesticides within sustainable horticulture. Neem-based extracts from *Azadirachta indica*, widely utilized in Indian agrarian systems. Some research studies lead to 75% reduction in insect populations, a 50% drop in synthetic pesticide application, and a 20% improvement in crop yields Ngegba et al. (2022). Munyore and Rioba (2020) documented a 65% reduction in insect infestations, a 45% drop in supplementary pesticide application, and an 18% improvement in marketable yields when garlic (*Allium sativum*) extracts were utilized in greenhouse vegetable growth. A reduction of up to 70% in pest infestations and a 55% decrease in pesticide reliance, coupled with a 20% increase in yield, were seen by the use of chili pepper (*Capsicum spp.*) extracts in integrated pest control systems for tomatoes and cucumbers in Southeast Asia and Africa Lengai et al. (2019). A significant way influencing the trend of insect loss percentage (↓I %), is the use of biocontrol agents, namely entomopathogenic nematodes (EPNs), across various horticultural cropping systems. A European case study in organic horticulture employed entomopathogenic nematodes (EPNs) such as *Heterorhabditis bacteriophora* and *Steinernema feltiae*, administered by drip irrigation in vegetable crops, achieving pest control efficacy of up to 90%, hence endorsing their suitability for field-based pest management Furmanczyk and Malusà (2023). Recent advancements in horticultural pest management have employed live pesticidal plants as repellents, banker, and trap crops (RBT plants) as shown in Figure 4i, notably inside push-pull frameworks. Push–pull frameworks exhibit twin tactical interventions: intercropped repellent species that inhibit pest establishment inside the field (push), and strategically planted perimeter attractant trap crops that divert pests away from the primary crop (pull). This dual strategy optimizes insect control while preserving crop yield. Cabbage fields in Tanzania utilized nightshade in conjunction with push–pull intercropping repellent and mustard as a trap crop, achieving up to 80% suppression of diamondback moth populations and resulting in yield increases of 20%–30% without synthetic pesticides Okoma et al. (2025).

In cruciferous vegetable cultivation, push–pull systems incorporating marigold and mustard resulted in a 70%–85% decrease in pest populations and increased beneficial parasitoid activity, as seen in Brazil da Silva et al. (2022). Similarly, Kenyan tomato systems employing Ocimum spp. as repellent intercrops and decoy trap plants achieved up to 78% control of *Tuta absoluta*, while also enhancing the bio diversity of natural enemies Chidawanyika et al. (2025). In addition to using non-crop living plants, crop plants have been enhanced with protectants, resulting in RNAi and Bt-crops. The RNA interference (RNAi) mechanism for gene silencing is a potential technique for pest management due to its selectivity, as described in earlier section. Current research seeks to refine dsRNA delivery, improve stability in field settings, and expand the spectrum of target pests while reducing off-target impacts Basso et al. (2025). With advancements in molecular biology and nanotechnology, RNA interference is poised to play a crucial role in sustainable pest management tactics within contemporary horticulture. Field trials in southern China utilized siRNA sprays against *Plutella xylostella* on cruciferous crops, resulting in larval mortality rates of up to 70%, thereby diminishing dependence on traditional pesticides Gong et al. (2013). In Brazil, the topical administration of nontransformative dsRNA targeting ATPase genes of *Spodoptera frugiperda* resulted in up to 80% larval mortality in field based case studies, demonstrating the viability of spray-based RNA interference Cagliari et al. (2019). A comparable study demonstrated the eradication of the flea beetle *Phyllotreta striolata*, a significant pest of Cruciferae crops, by a unique spray-induced gene silencing (SIGS) method. Two genes, psJHBP-like and psaaNAT-like, were identified as target candidates due to their elevated expression in the gastrointestinal tract. Administering double-stranded RNA (dsRNA) solutions to beetles resulted in successful gene silencing and increased mortality Xu et al. (2025). Subsequent study in the Philippines indicates that the use of Bt tomato (*Solanum lycopersicum*) and Bt eggplant in small-scale farming systems has resulted in decreased pesticide application and enhanced marketable fruit yields Ruane et al. (2023). Ghana has progressed from limited trials to complete governmental approval, resulting in the commercial launch of a pod-borer-resistant (PBR/Bt) cowpea (event 709A) between 2022 and 2024 Addae et al. (2019). Several studies Odón et al. (2020) have elucidated the application of biopesticides via UAVs as a clearly developing technique in horticultural systems. Site-specific administration enables the utilization of low yet effective dosages, thereby reducing runoff and off-target effects. Jenne (2025) has documented field case studies indicating that UAV-sprayed plots exhibited a 65% reduction in larval infestation in India. It also encompassed the integration of Artificial Intelligence (AI) and Machine Learning (ML) with drones for the most effective application of biopesticides. Looking at the global horticultural biopesticide implementation studies, Indian cultivators must incorporate wide array of practices to enhance the vegetable harvest in the field. Taking encouragement from Ghana based case studies government should employ field based trials to enhance the horizon of limited lab scale application of biopesticide.

FRUITS

India's diverse agro-climatic zones enable cultivation of a wide array of fruits, including mangoes, grapes, apples, apricots, oranges, fresh bananas, avocados, guava, lychee, papaya, sapodilla, and watermelons. Due to its extensive fruit output, India is designated as the global fruit basket, and fruit exports reached USD 999.55 million during the fiscal year 2025 (https://apeda.gov.in/FreshFruitsAndVegetables, accessed on 16 Fab 2026). According to the National Horticulture database, the area designated for fruit production in India for 2024-25 was 7,170 hectares, with a total production of 118,760 metric tons Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024). Indian fruit cultivation encounters various insect and pest challenges, including fruit flies, mango hoppers, mealybugs, thrips, aphids, scale insects, and borers, which cause damage through sapsucking, fruit destruction, and wilting. Additionally, significant infections such as fungal diseases like mango malformation, apple scab, powdery mildew, and bacterial cankers result in substantial quality harvest losses Fenibo and Matambo (2025). All these issues necessitate biopesticides for the management of these broad insect and pest concerns. As to the biopesticides usage data, India utilized 477.91 metric tonnes of biopesticide for fruit production in 2024-25 Directorate of Plant Protection, Quarantine and Storage (2025). Which indicates correlation between biopesticide usages and increased production over time as presented in Figure 3 Numerous on-field uses of biopesticides in fruit production have been documented globally Table 1., De et al. (2025) illustrated hybrid systems employing plant extract of Sachalinensis Reynoutria (Regalia), Double Nickel® (*Bacillus amyloliquefaciens* strain D747), RootShield Plus® (*Trichoderma harzianum* + *T. virens*), and Actinovate® (*Streptomyces lydicus*). RootShield Plus® exhibited a 56.4% increase in fruit quantity in the strawberry field. Likewise, pyrethrum-based formulations from Chrysanthemum species employed in African fruit orchards achieved an 85% reduction in pests, a 60% decrease in chemical pesticide usage, and a 25% increase in production Riyaz et al. (2022). Comparable research, as referenced in vegetable crop section, indicates that the treatment of entomopathogenic nematodes (EPNs) *S. feltiae* and *H. bacteriophora* in strawberry fields resulted in a 50%–90% reduction in pests, hence affirming the adaptation of EPNs to high-value crops and scalable operations Koppenhöfer et al. (2020). A different innovative method with semiochemical-enhanced trap crops surrounding strawberry fields demonstrated a 60%–70% reduction of the European tarnished plant bug (*Lygus rugulipennis*), a notable result attained without the use of synthetic pesticides Fountain et al. (2021). Entomopathogenic nematodes were employed in West Virginian plum orchards to manage the plum curculio, *Conotrachelus nenuphar*, attaining a pest reduction rate of 69.7% Piñero et al. (2020). The synergistic amalgamation of chitosan and biopesticides was assessed by DeGenring and colleagues in Pennsylvania and commercial orchards in New Hampshire. Researchers have discovered that chitosan diminishes apple scab (*Venturia inaequalis* (Cke.) Wint.) by up to 50%, concurrently reducing the occurrence of sooty blotch, flyspeck, and rust on fruit. The combination of chitosan (Tidal Grow and ARMOUR-Zen 15) and Bacillus subtilis QST 713 established superior disease reduction compared to the cultivator standard alone DeGenring et al. (2023). The use of Azadirachtin, orange oil, and potassium salts of fatty acids in pear orchards demonstrated insecticidal efficacy against the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), achieved a death rate of 50% Chierici et al. (2025). A field research on the management of Cyclamen mite (Phytonemus pallidus) with Captiva® Prime (capsicum oleoresin extract, garlic oil, canola oil), EcoTrol® EC rosemary oil, and peppermint oil via dip and foliar acaricide methods attained plant survival rates of 92.2% and 98.7%, respectively Renkema (2025). These case studies altogether validate the strategic use of hybrid systems as sustainable pest management interventions in fruit production methods.

PLANTATION CROPS

Plantation crops are prominent element of the Indian agrarian economy, particularly in fostering rural financial development throughout many Indian states. Rubber, tea, coffee, oil palm, cashew, coconut, and areca nut are regarded as primary plantation crops in the nation, beside cocoa and some spice crops, which are also categorized as plantation crops. Indian plantation crops encompass 4,586 hectares, with a total production of 17,159 metric tons, according to the National Horticulture Database Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024). Despite considerable export potential, the United Nations Industrial Development Organization (UNIDO) Standards Compliance Analytics (SCA) tool revealed that coffee and tea, along with other products in category 9, faced 358 consignment rejections for India in 2024-25 owing to pesticide residues (https://hub.unido.org/sca/#/countries/699?value_view=abs&product_exporter=504&product=123,7 as accessed on 16 Feb 2026). Noteworthy pests in Indian plantation crops include the tea mosquito bug (cocoa), stem borers (cashew, coffee), red palm weevil (coconut), and eriophyid mites. The primary diseases consist of root (wilt) disease, bud rot (coconut), blast, red rot, and fungal infestations such as leaf spots, powdery mildew, collar rot, and mosaic viruses, which adversely affect various crops, resulting in sizable harvest damages Fenibo and Matambo (2025). In response to these pests, biopesticides consumption data indicates that 166.71 metric tonnes of biopesticides were utilized for plantation crops in India year 2024-25 Directorate of Plant Protection, Quarantine and Storage (2025). Researchers primarily focus on on-field biopesticides applications Table 1 in horticultural fields to safeguard harvest. As, Manson and colleagues assessed on-field experiments (57 home gardens of coffee, Indonesia) to manage coffee berry borer (CBB; *Hypothenemus hampei*) using a biopesticides trap method as shown in Figure 4f, whereby Glumon™ (biopesticide) was sprayed on a yellow laminated surface affixed near the plant. Researchers observed an improved harvest yield of red berries following the augmentation (calculated model means (95% CI) and also concluded that the infestation of CBB and Colletotrichum spp. diminished with more shade cover. Approximately 87% of farmers considered it more effective than traditional insecticides Manson et al. (2022). Botanical pesticides such as α-elaeostearic acid and Citronellal, in conjunction with *Beauveria bassiana*, were utilized against pod borer (*Conopomorpha cramerella*), fruit suckers (*Helopeltis* spp.), and fruit rot (*Phytophthora palmivora*) in cocoa cultivation. A study conducted on a 10- hectare agricultural plot in South Sulawesi indicated a yield loss of less than 10% compared to a control group, which saw a loss of 36.5% Siswanto et al. (2020). Certain researchers have evaluated an aqueous extract from the plant *Clerodendrum viscosum* Ventenat (Verbenaceae) through field trials aimed at controlling two significant pests of tea, *Camellia sinensis* (L), precisely the tea mosquito bug, *Helopeltis theivora* Waterhouse (*Heteroptera: Miridae*), and the tea red spider mite, *Oligonychus coffeae* Nietner (Acarina: Tetranychidae) in India. The results indicated mite populations of 68–95% and 73–86%, respectively, together with infestations of the tea mosquito insect Roy et al. (2010). A recent study by Elrehawy and ElDoksch (2022) assessed the insecticidal and antifeedant properties of Calotropis procera latex and foliar extracts against the larvae of the red palm weevil, *Rhynchophorus ferrugineus* (Oliver). The results indicated that both leaf and latex extracts possess a substantial antifeedant activity, as evidenced by the reduction in mean larval weight. Recent research indicated the efficacy of serine protease inhibitors (SPIs) against the red palm weevil in palms Orfali et al. (2020). Serine protease inhibitors were extracted from various plant parts, and their effectiveness in vitro and in vivo against RPW was evaluated. A maximum of 39% protease inhibition activity was recorded for crude plant extracts suggesting its application for controlling red palm weevil. The strategic application of novel biochemical augmented with other hybrid systems (microbial and fungal) delivers viable pest management alternative in plantation crop cultivation.

SPICES

India is characterized by its wide-ranging spice resources, including black pepper, cardamom, and other Zingiberaceous species. Historically, India has been a crucial producer, user, and exporter of spices, acquired the designation of the "spice bowl of the globe". India is eminent producer of 60 out of the 109 spices acknowledged by the International Organisation for Standardisation, with nearly every state participating in the cultivation of at least one spice crop National Bank for Agriculture and Rural Development (2025). India is the forefront producer and exporter of spices, contributing 7.7% to the country's agrarian export returns and supplying to more than 185 nations. However, the nation has considerable difficulties with export rejections, with over 200 consignments refused each year owing to pesticide residues Thomas et al. (2024). As per the National Horticulture database, in the fiscal year 2024-25, the area allocated for spice cultivation in India covered 4694 hectares, with a total production of 12503 metric tonnes Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024). Critical pests impacting spice crops in India include thrips, stem and capsule borers, aphids, whiteflies, and root grubs, which inflict significant damage on crops such as chilies, pepper, cardamom, and cumin. Common infections consist of fungal diseases like Foot Rot (Quick Wilt), Powdery/Downy Mildew, Blight, and Wilt, typically spread by soil borne fungi or bacteria, leading to substantial yield reductions and necessitating integrated management strategies Fenibo and Matambo (2025). Certain field research Table 1 indicated the utilization of certain microbial and botanical pesticides to eliminate pests that impact spices. Choudhary et al. (2024) assessed the efficacy of *Beauveria bassiana*, *Metarhizium anisopliae*, *Verticillium lecanii*, and Azadirachtin in field applications against the cumin aphid, *Myzus persicae* (Sulzer). The highest reduction in aphid population (47.88%) among the biopesticides was observed with *Verticillium lecanii*, which resulted in a yield of 0.59 t ha^{-1} and a return of 22880.0 Rs ha^{-1} from increased yield. Janarjan and co-worker have assessed the efficacy of fermented botanical extracts from Titepati (*Artemisia vulgaris*), Banmara (*Ageratina* *adenophora*), Asuro (*Justicia adhatoda)*, Sisno (*Urticadiocia*), Onion (*Allium cepa*), Garlic (*Allium sativum*), and Chilly (*Capsicum frutescens*) in conjunction with cow urine for the management of ginger rhizome fly (*Calobata* sp.). The results indicated that fermented Asuro (*Justicia adhatoda*) extract resulted in the lowest incidence of rhizome fly (7.18%) and the maximum fresh rhizome yield (32.20 mt/ha) Janarjan and Ahmed (2020). A novel approach where, Kim et al. (2024) evaluated the efficiency of antifungal bacterial isolates from Bacillus velezensis strains GT227 and GT234, together with the microalga *Chlorella fusca* CHK0058, in relation to ginger rhizome rot disease. The synergistic use of *Bacillus velezensis* strains GT227 and GT234 alongside *Chlorella fusca* (CHK0058) markedly augmented fresh weight, highlighting its capacity to promote ginger development in organic farming settings. Innovative approach utilizing papaya waste (*Carica papaya* L.) as a biopesticides to manage aphid populations in chili (Capsicum annuum L.) Indratmi et al. (2025). Results indicated a 2.5-fold increase in chili output. A recent study shown that the entomopathogenic fungus, Lecanicillium psalliotae strain IISR-EPF-02, is infectious to cardamom thrips (Sciothrips cardamom) and enhances plant development in cardamom (Elettaria cardamomum). The isolated strain holds direct plant growth-promoting characteristics through the synthesis of indole-3-acetic acid and ammonia Kumar et al. (2022). The on-site study confirmed that initial crop sanitization with spinosad sprays, succeeded by soil treatment of the fungus L. psalliotae, efficaciously diminished capsule damage caused by thrips. In June 2025, the ICAR-Indian Institute of Spices Research (ICAR-IISR) in Kozhikode declared the development and commercialization of a biopesticides derived from the fungus Lecanicillium psalliotae to control cardamom thrips (Sciothrips cardamomi) (https://www.pib.gov.in/PressReleasePage.aspx?PRID=2139534®=3&lang=2, accessed on 16 Fab 2026). Lal et al. (2019) described many hybrid methodologies for the organic cultivation of seed spices utilizing fungal, bacterial, botanical, and essential oil-based biopesticides.

MEDICINAL AND AROMATIC PLANTS

Aromatic crops are vital to the worldwide market for essential oils, fragrance amalgams, and medications. India's varied environment accommodates several fragrant plants, such as Citronella grass, Palmarosa, vetiver, sweet flag, lavender, geranium, patchouli, mint, and holy basil. Medicinal plants are integral to India's ancient systems, such as Ayurveda and Homeopathy. Approximately 6,000 to 7,000 species holding therapeutic characteristics, of which 960 are routinely traded, including Long Pepper, Periwinkle, and Belladonna. The diminishing supply of wild plants has led to an increasing interest in organic farming National Bank for Agriculture and Rural Development (2025). The global market for goods produced from medicinal plants is presently valued at roughly USD 60 billion. The market is seeing an annual growth rate of seven percent Singh (2006). The National Horticulture Board indicates that the area designated for medicinal and aromatic plants in India expanded to 942 hectares, yielding an output of 781 metric tons in the 2024-25 fiscal year Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024). Principal pests impacting these crops comprise sap-sucking insects (aphids, mealybugs, thrips, mites) and defoliators (beetles, caterpillars such as *Spodoptera litura*, leaf rollers), whereas significant infections entail fungal diseases (root rot, leaf spots, powdery mildew, blight, anthracnose) and viral impediments like yellows/witches' broom (phytoplasmas) and Cucumber Mosaic Virus Fenibo and Matambo (2025). These variables significantly influence output and quality, underscoring the necessity for comprehensive management solutions for sustainable agriculture. As previously noted about horticultural crops, medicinal and aromatic crops have also demonstrated Table 1 an increasing tendency in the utilization of microbial control agents in field applications. Trends indicate an increase in the utilization of botanical biopesticides, such as leaf and seed extracts in aqueous solutions, seed cakes, crude oils, or essential oils, which have shown helpful in managing sap-sucking pests, foliar diseases, and root-knot nematodes. Medicinal crops frequently utilize traditional and commercial products, particularly those sourced from neem (*Azadirachta indica* A. Juss.) leaf or kernel Gahukar (2012). Sandeep et al. (2024) assessed the on-field bioefficacy of Bacillus thuringiensis var. kurstaki, *Beauveria bassiana, Metarhizium anisopliae*, Azadirachtin, Neem oil, and NSKE (Neem Seed Kernel Extract) for the management of the tobacco cutworm, *Spodoptera litura* Fab., in mint cultivation. The results indicated a mean larval population decline of 42.92 percent, the maximum observed. In a similar manner, Rhioui et al. (2024) assessed local agroecological strategies employed in Moroccan mint cultivation systems. A survey involved 264 mint cultivators showed that biological pest management is implemented using black soap, neem oil, Melia azedarach (L.) extract, and *Bacillus thuringiensis*. Tamil Nadu Agricultural University (2026) recommended the application of insecticidal soaps, 3% plant oils, or 0.2% pyrethrin, together with the preservation of indigenous predators for the sustainable growth of Aloe vera (L.) Burm. (Aloe barbadensis Mill.) (Aloe). Meshram et al. (2015) employed botanical (neem-based Gronim) and microbial (*Bacillus thuringiensis* and *Beauveria bassiana*) to manage *Polytela gloriosae*, *Anomis flava*, *Earias vitella*, *Dysdercus cingulatus*, and *Aphis gossypi*, which predominantly impact medicinal plants such as *Abelmoschus moschatus*, *Gloriosa superba*, and *Withania somnifera* in India. Results indicated a maximum bug reduction of 83.01% compared to the control in the on-site research Prakash (2012) recommended application of spinosad (0.5 WP at 0.25 ml l^{-1}) for the total eradication of the gooseberry aphid, *Schoutedenia emblica*. Certain researchers have assessed the efficacy of a formulation including 2% *Trichoderma viride*, derived from shelled maize cob powder and neem cake, for the management of Fusarium wilt induced by *Fusarium oxysporum* Schlecht in Isabgol (*Plantago ovata*). The results indicated an approximate 96.80% increase in net yield of Isabgol following treatment.. Munnysha et al. (2025). Figure 3 illustrates the diminished output of medicinal and aromatic plants in the Indian horticulture system in recent years, attributed to many problems, including restricted collaboration among research institutes, producers, and the industry. The studies carried out by these groups are detached from industrial requirements. A lack of communication between farmers and research institutions on industrial demands, coupled with inadequate cooperation within these institutions, results in a deficiency of awareness of historical and contemporary research, hence causing unwanted duplication of efforts.

ORNAMENTAL PLANTS

The cultivation of potted plants, landscape plants, palms, trees, topiary plants, seeds, planting materials, turf grass, and value-added goods is a significant aspect of the ornamental industry. The floriculture sector in India possesses cultural importance and includes the cultivation of loose and cut flowers in open fields as well as controlled environs. The enactment of the Seed Act in the 1990s facilitated export-oriented protected cultivation and promoted to commercial agriculture. Ornamentals propagation occurs in both open field system and sophisticated polyhouses and greenhouses National Bank for Agriculture and Rural Development (2025). The National Horticulture Database indicates that the area allocated for floriculture production in India for the year 2024-25 was 389 hectares, resulting in a total output of 4,017 metric tons. This comprises 3,046 metric tons of loose flowers and 971 metric tonnes of cut flowers Figure 3 Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (2024). India's overall floriculture exports amounted to USD 88.58 million in 2024-25 (https://apeda.gov.in/FloricultureAndSeeds, accessed 16 Jan 2026). Major pests impacting ornamentals in India comprise sucking insects like aphids, mealybugs, thrips, and whiteflies, with chewing pests comprising caterpillars (such as semi-loopers, tobacco caterpillars, and hairy caterpillars) and beetles (notably blister beetles and flea beetles). Common illnesses in these plants frequently include fungal infections such as powdery mildew, leaf spots, and root rot, as well as viral infections such the Cucumber Mosaic Virus (CMV) in gladiolus Fenibo and Matambo (2025). Mites, especially red spider mites, are notable pests that inflict damage to widely cultivated plants such as roses, chrysanthemums, hibiscuses, and gerberas. A variety of methods are employed to manage different pests and diseases in ornamentals, including bacterial agents, nematodes, botanical substances, and innovative RNA interference technologies Table 1. Entomopathogenic nematodes (EPNs) were employed to manage *Temnorhynchus baal* Reice and Saulcy (Coleoptera: Scarabaeidae) on Egyptian golf courses Hussein et al. (2025). The results indicated over 90% mortality, signifying the use of entomopathogenic nematodes (EPNs) for managing *Temnorhynchus baal* in grass management. A novel practice was employed to assess the simultaneous biocontrol and biostimulant properties of entomopathogenic fungi (EPF), specifically *Metarhizium anisopliae* and *Beauveria bassiana*, applied to seeds for the growth and development of turfgrasses, namely *Lolium arundinaceum* (syn. *Festuca arundinacea*) and *Poa pratensis* Swoboda et al. (2025). The results showed a substantial treatment impact, with *M. anisopliae*-treated seeds provided a 17.8% enhancement in turfgrass coverage comparative to the control group. Ponpandian et al. (2019) described bacterial endophytes (BEs) to mitigate pine wilt disease (PWD) caused by the pine wood nematode (PWN) *Bursaphelenchus xylophilus*. Among 44 nematicidal bacteria, *Stenotrophomonas* and *Bacillus* species shown considerable inhibitory effects against the pine wood nematode (PWN) isolated from the needle, stem, and root tissues of *Pinus densiflora*, *Pinus rigida*, *Pinus thunbergii*, and *Pinus koraiensis*. Lim et al. (2026) employed a spray induced gene silencing (SIGS) technique to manage dollar spot in creeping bentgrass (*Agrostis stolonifera* L.) affected by *Clarireedia jacksonii*. Of the 32 double-stranded RNAs (dsRNAs) assessed for gene targeting, 8 dsRNAs have diminished infection severity by roughly 34.7–45.5% compared to the control. Perveen and colleagues assessed the effectiveness of plant-based essential oils (PEOs); mint (*Mentha piperita*), eucalyptus (*Eucalyptus camaldulensis*), and lemongrass (*Cymbopogon citratus*) were studied against the rose sawfly, *Arge ochropus* (Gmelin) (Hymenoptera: Argidae). The findings revealed a maximum larval death rate of 85.9% Perveen et al. (2025). The effectiveness of three terpene-based biopesticides was assessed for the control of two aphid species, *Myzus persicae* and *Aphis gossypii*, on ornamental crops Smith et al. (2018). Orange oil, a botanical extract from *Chenopodium ambrosioides*, and azadirachtin A derived from neem were employed as biopesticides. Results showed that all products decreased aphid populations by at least 85%. Gahukar (2011) elucidated the efficacies of neem and several plant-derived biopesticides in floriculture. Calidonio and co-workers have assessed biorational solutions for the treatment of botrytis blight induced by *Botrytis cinerea* in floriculture crops Calidonio et al. (2025). The results indicate that certain biorational agents attained a maximum decrease of 79% in disease severity, and their combinations shown efficacy against botrytis blight on ornamental flowers. Brownbridge and Buitenhuis (2019) collated research studies on the incorporation of microbial pesticides in greenhouse floriculture in Canada. Control strategies for several pests were addressed, including whitefly, thrips, aphids, spider mites, Lepidoptera, numerous sucking and chewing insects, mites, and the pupal stages of western flower thrips. Lecomte and co-researchers have provided comprehensive biological management strategies for controlling *Fusarium oxysporum* infections and described various microbial, botanical, and biological control agents to mitigate of ornamental infections Lecomte et al. (2016).

Figure 4

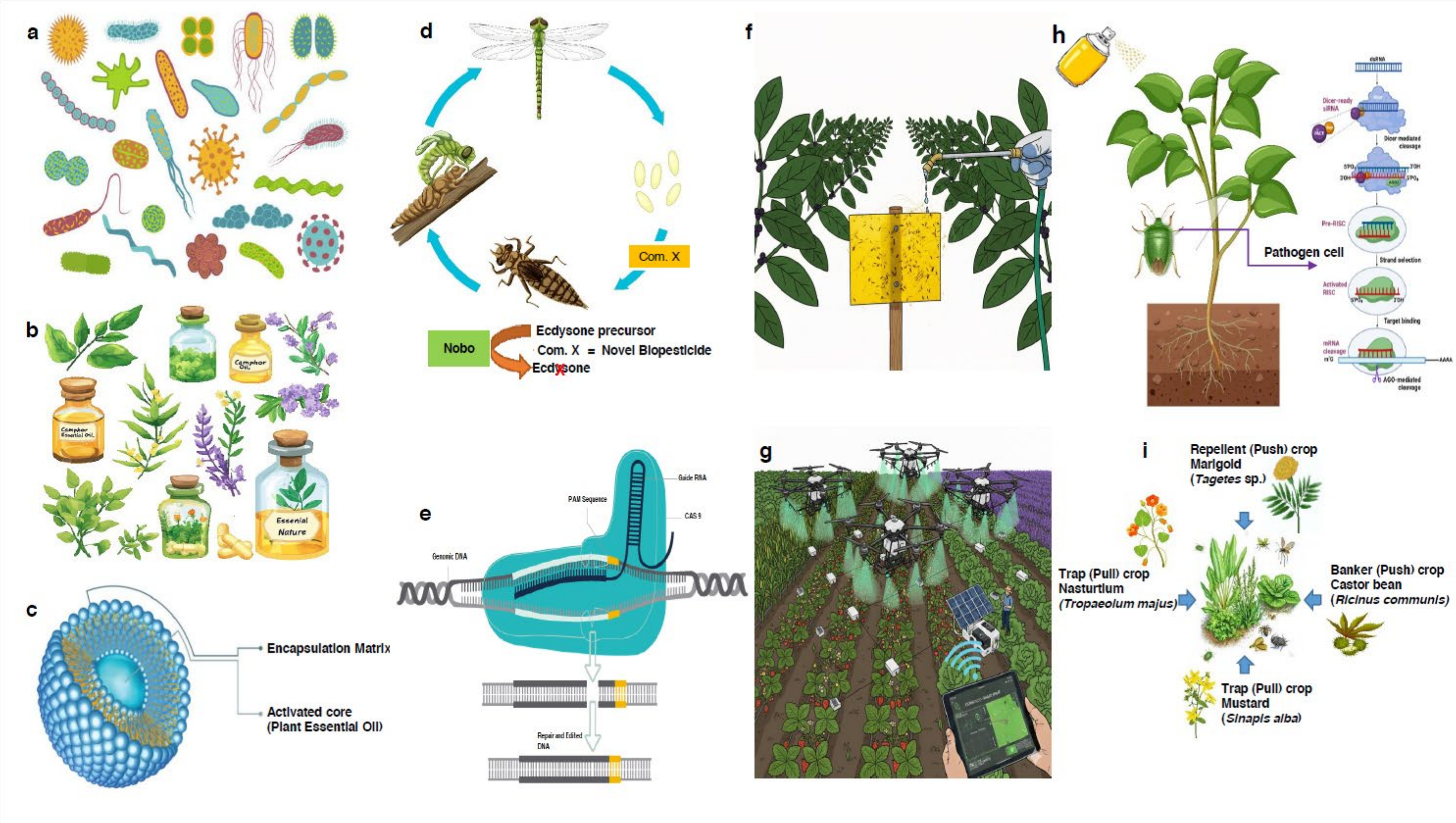

Figure 4 Innovative biopesticide approaches in horticulture system. a Microbial biopesticide(e.g. *Pseudomonas fluorescens*, works through antibiotic production (2,4-DAPG), siderophores). b Essential oils(e.g. Thymol from *Thymus vulgaris* imparts membrane disruption, fumigant action). c Nanoencapulated plant extract (e.g. Encapsulated Azadirechtin efficiently target pest destruction via antifeedant activities). d Insect growth regulators (IGRs) (e.g. Compounds inhibiting Noppera-bo, a Glutathione S-transferase blocks Ecdysteroid biosynthesis (disruption of molting). e Genome editing based on CRISPR/Cas 9 (e.g. *Bacillus thurengenesis* (Bt) enhance expression of Cry & Vip proteins killing insect larva via midgut epithelium lysis. f Strip applied biopesticide (e.g.strip applied Glumon™, effectively control of pest via direct toxicity). g Internet of Things and Artificial Intelligence integrated application (e.g.On-field drone spraying of biopesticide provide precision based targeted delivery). h Spray Induced Gene Silencing (SIGS) (e.g. Application of exogenous dsRNA/siRNA mediate cleavage of the complementary mRNA transcripts, and transcriptional or post-transcriptional gene silencing). i Repellent, banker and trap crop (e.g. Live plant biopesticide which discourage pest establishment & draw pests away from the main crop

Table 1

Table 1 Efficiencies of Certain Biopesticides Implementation Studies Along with Pest Targeted in Horticultural Cropping Systems

Source	Type	Organisms/ botanical compounds	Pest type	Target crop	Efficiency/Yield	References
			Vegetable Crop			
Anamorphic fungus	Fungicide	*Ampelomyces quisqualis 2.0% WP*	Powdery mildew, (Erysiphe cichoracearum)	Okra	N/A	Majumder et al. (2024)

Entomo-pathogenic fungi	Insecticide	*Beauveria bassiana*, *Akanthomyces lecanii*, *Akanthomyces muscarius*	whitefly, (*Bemisia tabaci*)	Cassava	35%–86% at lab scale, 64%–75% at field level	Amour et al. (2025)
Endophytic fungi	Insecticide	*Clonostachys spp*. and *Beauveria bassiana*	The tomato leaf miner, *Tuta absoluta* (Meyrick) (*Lepidoptera: Gelechiidae*)	Tomato	Maximum 100% mortality rates after 72 hours	Mahmoud et al. (2021)
Entomopathogenic fungi	Insecticide	*Beauveria bassiana*, *Isaria fumosorosea* and *Pupureocillium lilacinum*	The tomato leaf miner, *Tuta absoluta* (Meyrick) (*Lepidoptera: Gelechiidae*)	Tomato	Maximum 100% mortality rates after 7 dyas	Karaca et al. (2022)
Fungi and Bacteria	Insecticide and fungicide	*Beauveria bassiana* and *Bacillus subtilis*	whitefy (*Trialeurodes vaporariorum* Westwood) and tomato powdery mildew (*Oidium neolycopersici*)	Tomato	Greenhouse whitefy (78.9–88.3%) and tomato powdery mildew (47.2–81.0%)	Komagata et al. (2024)
Fungi	Insecticide	*Metarhizium anisopliae* and	Melon Fly	Winter squash *Cucurbita moschata*	Maximum mortalities of 94% with 5 days post-exposure	Onsongo et al. (2022)
		Beauveria bassiana	(*Zeugodacus cucurbitae*)	Duch. (Violales: Cucurbitales)		
Bacteria	Fungicide	*Peudomonas fluorescens 1.0% WP*	Wilt (*Fusarium oxysporum*)	Brinjal	N/A	Majumder et al. (2024)
Plant	Bactericide	Guarda®	*Xanthomonas*	Tomato, Pepper,	N/A	Giovanardi et al. (2025)
		(Thyme oil, Thymol chemotype)	spp., *Peudomonas* spp.	Brassicaceae, Fabaceae		
Plant	Bactericide	Sporan EC2® (Rosemary, clove, peppermint, and thyme oils)	*Xanthomonas* spp., *Peudomonas* spp.	Tomato, Pepper, Brassicaceae, Fabaceae	N/A	Giovanardi et al. (2025)
Virus	Bactericide	AgriPhage®	*Xanthomonas* spp., *Peudomonas* spp.	Tomato, Pepper	N/A	Giovanardi et al. (2025)
Virus	Bactericide	*Bacteriophage DB1*	Black rot *Xanthomonas campestris*	Cabbage	N/A	Orynbayev et al. (2020)
			Fruit Crops			
Bacteria	Fungicide	Serenade ASO(*Bacillus subtilis* QST 713)	Apple scab, (*Venturia inaequalis* (Cke.) Wint.)	Apple	Reduced severity up to 55%	DeGenring et al. (2023)

Plant, Virus, Fungi and Bacteria	Bactericide	Blossom Protect (*Aureobasidium pullulans* strains DMS14940 and DSM14941), Agriphage, Bacteriophage (A, B, C), Double Nickel (*Bacillus amyloliquefaciens* strain D747), Serenade Opti (*Bacillus subtilis* QST 713), Serenade ASO(*Bacillus subtilis* QST 713) Thyme and cinnamon extracts	Fire blight (*Erwinia amylovora)*	Apple and Pear	Maximum 86% Control	DuPont et al. (2023)
Plants	Insecticide	Azadirachtin, orange oil, potassium salts of fatty acids	The brown marmorated stink bug, *Halyomorpha halys* (*Hemiptera: Pentatomidae*)	Pear orchards	more than 50% mortality	Chierici et al. (2025)
Plant	Insecticide	Neem oil, Garlic oil, citrus oil, castor oil	Papaya mealybug, *Paracoccus marginatus* Williams and Granara de Willink (Hemiptera: Pseudococcidae)	Papaya	Maximum (95.5%) after 72 h	Mwanauta et al. (2023)
Plant	Fungicide	*Moringa oleifera* leaves extracts (Methanolic and aqueous) and *Cymbopogon citratus*, *Ocimum gratissimum* and *Eucalyptus citryodera* essencial oil	Stem-end rot (*Lasiodiplodia theobromae*)	Mango	100% growth inhibition	Yeo et al. (2023)
Fungi	Insecticide	*Isaria fumosorosea* (PFR-97)	Asian citrus (psyllid, *Diaphorina citri)* (Hemiptera: Liviidae)	Citrus	Maximum 100% psyllid mortality	Kumar et al. (2017)
Fungi, Bacteria, Plant	Fugicide and Insecticide	Regalia (Extract of *sachalinensis Reynoutria)*, Double Nickel (*Bacillus amyloliquefaciens* strain D747), RootShield Plus	N/A	Strawberries	Highest 56.4% more fruit numbers	De et al. (2025)

		(*Trichoderma harzianum* + *T. virens*) and Actinovate (*Streptomycens lydicus* WYEC 108)				
		Plantation crops				
Plant, bacteria, virus and fungi	Insecticide	Glumon™ (*Bacillus thuranginasis*, *Trichoderma* sp., Nuclearpoihydrosis, Azadirachtin	coffee berry borer (CBB; *Hypothenemus hampei*)	coffee	95% higher red berries proportion	Manson et al. (2022)
Plant	Insecticide	*Clerodendrum viscosum* Ventenat (Verbenaceae)	tea mosquito bug, *Helopeltis theivora* Waterhouse, (Heteroptera: Miridae) and the tea red spider mite, *Oligonychus coffeae* Nietner, (Acarina: Tetranychidae)	Tea	68–95% and 73–86% reduction in mite population as well as infestation	Roy et al. (2010)
Plant	Insecticide	Calotropis procera latex and foliar extracts	*Rhynchophorus ferrugineus* (Oliver)	Oil Palm	high antifeedants index and the decreased mean larval weight	Elrehawy and ElDoksch (2022)
		Spices				
Fungi, plant	Insecticide	*Beauveria bassiana*, *Metarhizium anisopliae*, *Verticillium lecanii* and Azadirachtin	Cumin aphid, *Myzus persicae* (Sulzer)	Cumin	47.88% maximum aphid population reduction provided 0.59 yield t ha^{-1}	Choudhary et al. (2024)
Plant	Insecticide	fermented botanical extracts of Titepati *(Artemisia vulgaris)*, Banmara *(Ageratina adenophora*, Asuro *(Justicia adhatoda)*, Sisno *(Urticadiocia)*, Onion *(Allium cepa)*, Garlic *(Allium sativum)* and Chilly *(Capsicum frutescens)*	Ginger rhizome fly (*Calobata* sp.)	Ginger	Rhizome fly incidence (7.18%), highest fresh rhizome yield (32.20 mt/ha)	Janarjan and Ahmed (2020)
Microalga, bacteria	Fungicide	*Bacillus velezensis* strains GT227 ,GT234 *Chlorella fusca* CHK0058	Ginger rhizome rot	Ginger	Increased the fresh weight	Kim et al. (2024)
Plant	Insecticide	Papaya waste (Carica papaya L.)	Aphid	Chilli	2.5 times increased chilli production	Indratmi et al. (2025)

			Medicinal and aromatic crops			
Bacteria, fungi,plant	Insecticide	*Bacillus thuringiensis var. kurstaki, Beauveria bassiana Metarhizium anisopliae,* Azadirachtin, Neem oil and NSKE (Neem Seed Karnel Extract)	Tobacco cutworm, *Spodoptera litura* Fab	Mint	highest 42.92 per cent mean larval population reduction	Sandeep et al. (2024)
Plant, bacteria, Fungi	Insecticide	Gronim (*Azadiracta indica*), *Bacillus thuringensis* and *Beauveria bassiana*	*Polytela gloriosae, Anomis flava, Earias vitella, Dysdercus cingulatus* and *Aphis gossypi*	*Abelmoschus moschatus, Gloriosa superba* and *Withania somnifera*	maximum 83.01 % bug reduction	Meshram et al. (2015)
Fungi	Insecticide	*Trichoderma viride* 2%	Fusarium wilt caused by *Fusarium oxysporum*	Isabgol	96.80 % net yield increase	Munnysha et al. (2025)
Plant, bacteria	Insecticide, Fungicide	Black soap, neem oil, *Melia azedarach* (L.) extract, and *Bacillus thuringiensis.*	N/A	Mint	N/A	Rhioui et al. (2024)
Plant	Insecticide	Azadirachtin	red spider mite, *Tetranychus ludeni*	Sarpagandha	maximum cost benefit ratio (1 : 7.90)	Kumar et al. (2025)
			Ornamentals			
Fungi	Insecticide	*Metarhizium anisopliae* and *Beauveria bassiana*	N/A	(*Lolium arundinaceum* (syn. *Festuca arundinacea*) and *Poa pratensis*	17.8% increase in turfgrass coverage	Swoboda et al. (2025)
Bacteria	Nematicide	*Stenotrophomonas* and *Bacillus sp.*	pine wilt disease (PWD) *Bursaphelenchus xylophilus*	Pine	N/A	Ponpandian et al. (2019)
RNAi	Fungicide	Spray-induced gene silencing s (SIGS)	dollar spot *(Clarireedia jacksonii)*	Creeping bentgrass (*Agrostis stolonifera* L.)	reduced disease severity by approximately 34.7–45.5%	Lim et al. (2026)
Plant	Insecticide	Orange oil, *Chenopodium ambrosioides* Extract and azadirachtin A	Aphids (*Myzus persicae*) and (Aphis gossypii)	Flowering plants	more than 85% reduction in adhids	Smith et al. (2018)

FUTURE DIRECTIONS

Indian biopesticide adoption framework requires more focus on enhancing the commercial viability of botanical and viral biopesticides, which currently account for minimal market shares of about 8% and 3%, respectively. Additionally, implementation measures are required to broaden the market in underserved areas, particularly in northern Indian states and Union Territories, where usage rates are much lower than in southern regions. In, Indian horticulture particularly vegetable crops centric biopesticide adoption requires governmental policies and field based trials to enhance prospect of limited lab scale application. Despite having huge export potential Indian spices and plantation crops encounter cross borders consignment rejections which necessitate more stringent measure to adopt organic based cultivation practices among Indian horticultural systems. Reduction in medicinal and aromatic plants production demands more focus on collaborative research and developments among research institutes, producers, and the industry. Cultivation practices based on industrial demands may fulfil the market gaps and hence improve the statistics of productions. The advancement of hybrid systems, especially synergistic combinations of microbial agents such as *Bacillus subtilis* with natural elicitors like chitosan, may provide superior protection against diseases relative to conventional single-agent therapies. Amalgamation of botanical and microbial agents also provided promising results to mitigate infections. Furthermore, there is an urgent necessity to concentrate on the proliferation of nano-biopesticides applications. Investigations into nanoencapsulation and the creation of nanocontainers might improve the stability and targeted distribution of bioactive particles, thereby decreasing the required dosage of biopesticides while enhancing their effectiveness against phytopathogens. The consolidation of Artificial Intelligence (AI) and Machine Learning (ML) with Unmanned Aerial Vehicles (UAVs) is essential for facilitating site-specific and precise application of biopesticides, thereby alleviating runoff and diminishing the environmental complications linked to pesticide usage. Additionally, further investigations should focus on enhancing RNA interference (RNAi) technologies. Enhancing delivery mechanisms for double-stranded RNA (dsRNA) via techniques such as spray-induced gene silencing (SIGS) and host-induced gene silencing (HIGS) is crucial to maintain dsRNA stability across diverse environmental conditions and to reduce unwanted off-target effects. Expanding the array of pest management techniques accessible to horticulturists can markedly improve agricultural sustainability and pest control methods.

CONCLUSION

Indian horticulture production has shown significant expansion, reached a total output of 367.72 million tonnes in 2024-25. This advancement is offset by a growing reliance on chemical pesticides, which pose considerable health and environmental hazards. Biopesticides represent a vital sustainable alternative, corresponding with many United Nations Sustainable Development Goals (SDGs), such as poverty reduction (SDG 1) and responsible consumerism (SDG 12). India has attained 92.4% rise in biopesticides usage from 2009-10, with fungal types like *Trichoderma* and *Beauveria* prevailing in the market. Implementation studies in several horticultural sectors, including vegetables, fruits, and plantation crops, have shown that biopesticides provided superior pest reduction and increased harvest outputs. Innovative methodologies, like as push-pull methods and RNAi-mediated gene silencing, are further revolutionizing pest management by offering accurate and environmentally sustainable control mechanisms. Ultimately, shifting from traditional chemical-dependent methods to integrated biopesticide focused management systems is essential for assuring the long-term sustainability and resilience of the global horticulture sector.

AUTHORS' CONTRIBUTIONS

SS and HO conceptualized the manuscript. SS wrote the manuscript. HS provided suggestions, reviewed and corrected the manuscript. All authors reviewed and approved the final version.

ACKNOWLEDGMENTS

Authors are grateful to the Head of the Department, Prof. Dr. Hitesh Solanki for their insightful feedback on drafts of this work.

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