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Bees as Biocarriers - Bee Based Entomovectoring Technology for Pest Control

K. Sri Ram*, Purushottam Sheshrao Neharkar, M. M. Sonkamble, A. G. Lad, F. S. Khan, Y. B. Matre and Leela Prasanna

Department of Entomology, College of Agriculture, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India

**Corresponding author*

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A B S T R A C T

The increasing global demand for sustainable agricultural production has intensified the search for Eco-friendly alternatives to synthetic pesticides. Entomovectoring has emerged as an innovative biological approach that integrates crop pollination with biological control by utilizing pollinating insects as carriers of beneficial microorganisms. In this technology, managed pollinators such as Honeybees (*Apis mellifera*), Bumble bees (*Bombus* spp.), Mason bees (*Osmia* spp.), and other floral visitors disseminate microbial biological control agents directly onto flowers during their natural foraging activities. This targeted delivery system enhances pollination efficiency while simultaneously suppressing important plant pathogens and certain insect pests. Compared with conventional pesticide application, entomovectoring requires lower quantities of biological control agents, minimizes environmental contamination, reduces labour costs, and ensures repeated deposition of microbial inoculum throughout the flowering period. Over the past three decades, the technology has been successfully implemented in several horticultural and field crops including strawberry, blueberry, tomato, sunflower, canola, pear, apple, raspberry, coffee, sweet pepper, cucumber, and cherry. Various microbial agents such as *Clonostachys rosea*, *Trichoderma harzianum*, *Gliocladium catenulatum*, *Beauveria bassiana*, *Metarhizium anisopliae*, *Bacillus subtilis*, and *Pantoea agglomerans* have demonstrated remarkable efficacy when delivered through pollinating insects. Recent advances in dispenser technology, microbial formulation, pollinator management, and integrated pest management have further improved the efficiency and commercial applicability of entomovectoring. However, challenges related to vector safety, microbial compatibility, environmental variability, regulatory approval, and large-scale adoption continue to limit widespread implementation, particularly in developing countries. This review synthesizes current knowledge on the historical development, principles, components, mechanisms, applications, and future prospects of entomovectoring. The review further highlights the role of entomovectoring as a sustainable crop protection strategy that complements ecosystem services, reduces dependence on chemical pesticides, and contributes to climate-resilient agriculture.

Introduction

Agriculture is currently challenged by the simultaneous need to increase food production while reducing environmental degradation caused by intensive farming practices. The global human population is projected to exceed 9.7 billion by 2050, thereby increasing demand for food, fibre, and feed. However, crop production continues to be constrained by numerous biotic stresses, particularly insect pests and plant diseases, which collectively account for substantial yield losses worldwide (Dharshini *et al.,* 2026). Historically, synthetic pesticides have served as the primary strategy for crop protection. Although these chemicals have significantly improved agricultural productivity, their indiscriminate use has resulted in pesticide resistance, contamination of soil and water resources, destruction of beneficial organisms, biodiversity loss, and concerns regarding human health and food safety (Carson 1962; Mahmood *et al.,* 2016).

Consequently, sustainable crop protection strategies have become increasingly important. Biological control, integrated pest management (IPM), conservation of natural enemies, and pollinator conservation are now recognized as essential components of environmentally friendly agriculture. Among these innovations, entomovectoring has attracted considerable attention because it integrates two fundamental ecosystem services pollination and biological control into a single technology (Kumar *et al.,* 2024).

Pollination is indispensable for the reproduction of approximately 75–80% of flowering plants and contributes significantly to the production of fruits, vegetables, oilseeds, spices, and several commercial crops. Bees account for the majority of insect-mediated pollination and provide ecosystem services valued at billions of dollars annually. Besides transporting pollen grains, bees naturally carry microscopic particles including fungal spores, bacterial cells, and viral particles on their body hairs during foraging. Scientists have successfully exploited this natural phenomenon by loading beneficial microorganisms onto pollinators before they leave the hive, allowing them to deliver microbial inoculum directly to flowers where infection by pathogens commonly begins (Temmermans & Smagghe, 2022).

The concept of using insects as carriers of beneficial microorganisms is collectively known as Entomovectoring, while the specific use of bees is commonly referred to as Apivectoring. Unlike conventional spraying methods, entomovectoring ensures precise, repeated, and targeted application of microbial agents onto floral tissues, thereby reducing wastage, minimizing non-target exposure, and lowering environmental contamination (Sharma & Sharma, 2024).

Entomovectoring has proven effective against numerous economically important diseases, including gray mold (*Botrytis cinerea*), fire blight (*Erwinia amylovora*), mummy berry disease, sunflower head rot, blossom blight, and brown rot. Similarly, microbial agents delivered by pollinators have shown promising activity against insect pests such as pollen beetles, coffee berry borer, western flower thrips, tarnished plant bugs, sunflower moth, cabbage seed weevil, pod borer, and *Drosophila suzukii*. Successful applications have been documented in strawberry, blueberry, tomato, sunflower, pear, coffee, canola, raspberry, cucumber, and greenhouse vegetable production systems (Dharshini *et al.,* 2026).

The efficiency of entomovectoring depends on the compatibility among four major components: the pollinator vector, the biological control agent, the delivery system (dispenser), and the target crop. Advances in microbial formulation, dispenser engineering, and pollinator management have improved the effectiveness of this technology over the last two decades. Moreover, increasing restrictions on pesticide use and growing demand for organic produce have accelerated research and commercial adoption of entomovectoring in Europe, North America, Australia, and several Asian countries.

Despite these developments, important challenges remain. Selection of appropriate pollinator species, optimization of microbial formulations, assessment of pollinator safety, registration of microbial products, large-scale commercialization, and farmer awareness continue to influence the successful implementation of entomovectoring. Furthermore, the technology remains underexplored in many developing countries, including India, where enormous potential exists due to the country's rich pollinator diversity and expanding protected cultivation systems.

This review provides a comprehensive synthesis of current knowledge regarding entomovectoring, covering its historical development, principles, mechanisms, biological components, applications, commercial progress, environmental significance, limitations, and future research priorities. By integrating pollination and biological control into a single sustainable technology, entomovectoring has the potential to transform modern crop protection while promoting ecological resilience and long-term agricultural sustainability.

History and Evolution of Entomovectoring

The idea of insects transporting microorganisms is not new. Long before the development of modern biological control, scientists recognized that bees naturally carry pollen grains, fungal spores, bacteria, and other microscopic particles between flowers. Early observations of bee- mediated transmission of the fire blight pathogen (*Erwinia amylovora*) demonstrated the remarkable efficiency with which pollinating insects transport microorganisms across flowering plants. These observations eventually inspired researchers to reverse this natural process by using pollinators to disseminate beneficial rather than harmful microorganisms (Temmermans & Smagghe, 2022).

The first successful scientific demonstration of entomovectoring was reported in 1992 by Peng and colleagues, who employed the western honeybee (*Apis mellifera*) to deliver the antagonistic fungus *Gliocladium roseum* to strawberry flowers for suppression of gray mold caused by *Botrytis cinerea*. Their pioneering study demonstrated that bees could effectively transport biological control agents directly to infection sites while simultaneously pollinating the crop. This landmark research established the scientific foundation of modern entomovectoring and stimulated extensive investigations worldwide.

During the late 1990s and early 2000s, additional studies expanded the technology to numerous crops, including blueberries, pears, tomatoes, cucumbers, sunflowers, canola, and raspberries. Researchers evaluated various microbial antagonists such as *Trichoderma harzianum*, *Bacillus subtilis*, *Pantoea agglomerans*, *Beauveria bassiana*, and *Metarhizium anisopliae*, demonstrating successful management of multiple plant diseases and insect pests under greenhouse and open-field conditions.

A major milestone occurred when Professor Heikki Hokkanen and collaborators formally introduced the term "Entomovector technology", emphasizing the deliberate use of insects as carriers of microbial biological control agents for crop protection. Subsequently, Finland became one of the first countries to commercialize entomovectoring through collaborations between researchers and industry, particularly in strawberry production systems where disease suppression comparable to conventional fungicide programs was achieved.

Since then, research has expanded rapidly across Europe, North America, Australia, South America, and Asia. Commercial dispenser systems such as BeeTreat®, Flying Doctors®, and BVT Inoculum Dispenser® have facilitated large-scale adoption of the technology. More recently, studies have focused on optimizing dispenser efficiency, microbial formulations, pollinator health, regulatory frameworks, and integration with integrated pest management (IPM), making entomovectoring one of the most promising innovations in sustainable agriculture.

Mechanism of Entomovectoring

Entomovectoring is an innovative crop protection technology that integrates pollination with biological control by exploiting the natural foraging behaviour of pollinating insects. The principle is based on the ability of bees and other flower-visiting insects to carry microscopic particles on their hairy bodies while moving from flower to flower. Instead of transporting only pollen grains, pollinators are deliberately loaded with beneficial microbial biological control agents (BCAs) before leaving their nests or hives. During subsequent floral visits, these microorganisms are deposited directly onto flowers, where they colonize floral tissues and suppress pathogens or insect pests. This process enables simultaneous pollination and targeted delivery of microbial agents, thereby improving crop productivity and reducing dependence on synthetic pesticides (Kevan *et al.,* 2008; Hokkanen *et al.,* 2015; Dharshini *et al.,* 2026).

The mechanism begins with the installation of a specially designed dispenser at the entrance or exit of a managed pollinator hive. The dispenser contains a formulated microbial inoculum in powder form. As pollinators leave the hive for foraging, they are gently coated with the biological control agent without affecting their normal flight behaviour or colony health. The quantity of inoculum adhering to the insect depends on the dispenser design, microbial formulation, body size of the vector, and grooming behaviour of the insect.

After leaving the hive, the pollinator visits flowers in search of nectar and pollen. During each floral visit, part of the microbial inoculum is transferred to floral structures such as stigmas, anthers, petals, and nectaries. These floral tissues are often the primary infection sites of economically important plant pathogens including *Botrytis cinerea*, *Erwinia amylovora*, *Monilinia* spp and *Sclerotinia* spp. The early deposition of antagonistic microorganisms enables them to establish before pathogen invasion, thereby preventing infection through mechanisms such as competition, antibiosis, mycoparasitism, induced systemic resistance, or direct pathogenicity toward insect pests (Mommaerts & Smagghe, 2011; Temmermans & Smagghe, 2022).

Unlike conventional foliar spraying, entomovectoring ensures repeated application of microbial agents throughout the flowering period because bees continuously revisit flowers several times each day. Consequently, fresh inoculum is deposited on newly opened flowers, improving disease suppression while minimizing wastage of microbial products. Since only floral tissues receive the biological agent, contamination of soil, water, and non-target vegetation is reduced.

Another important characteristic of entomovectoring is its dual ecological function. While transporting biological control agents, pollinators simultaneously perform pollination, resulting in improved fruit set, seed production, crop quality, and overall yield. Thus, a single biological process contributes to both crop protection and enhanced pollination efficiency, making entomovectoring an environmentally sustainable component of Integrated Pest Management (IPM).

The overall success of entomovectoring depends upon four interrelated factors: (i) selection of an efficient pollinator vector, (ii) compatibility of the biological control agent with the vector, (iii) an efficient dispenser system that ensures adequate loading without harming pollinators, and (iv) synchronization of pollinator activity with crop flowering. Any disruption in these components can significantly reduce delivery efficiency and biological control performance.

Components of Entomovectoring

A successful entomovectoring system consists of several interconnected biological and technological components. Each component plays a specific role in ensuring that microbial biological control agents are delivered efficiently to target flowers while maintaining pollinator health and maximizing crop productivity. The principal components include pollinator vectors, biological control agents, dispenser devices, microbial formulations, target crops, and favourable environmental conditions (Mommaerts & Smagghe, 2011; Dharshini *et al.,* 2026).

Pollinator Vectors

Pollinator vectors are the most critical component of entomovectoring because they act as biological carriers that transport microbial agents from the hive to crop flowers. An ideal pollinator vector should exhibit frequent floral visitation, high flower fidelity, efficient pollen transfer, compatibility with managed colonies, ease of domestication, and the capacity to carry adequate quantities of microbial inoculum.

Among all pollinating insects, honeybees (*Apis mellifera*) have been most extensively utilized because of their worldwide availability, large colony size, efficient communication system, and ability to forage over extensive areas. Commercial honeybee colonies can be easily managed throughout the flowering season, making them suitable for both open-field and orchard crops.

Bumble bees (*Bombus terrestris* and *Bombus impatiens*) represent another highly effective entomovector. Their ability to forage under low temperatures, cloudy weather, and greenhouse conditions makes them particularly valuable in protected cultivation. Bumble bees also perform buzz pollination, enabling efficient pollination of crops such as tomato, eggplant, and sweet pepper that require vibration-assisted pollen release (Temmermans & Smagghe, 2022).

Solitary bees belonging to the genus *Osmia* have also demonstrated considerable promise in entomovectoring. Species such as *Osmia cornuta*, *O. bicornis*, *O. cornifrons*, and *O. lignaria* possess excellent flower fidelity and are highly efficient pollinators of fruit crops including apple, pear, cherry, and almond. Because they forage short distances, microbial delivery remains concentrated within the target crop.

Recent studies have expanded entomovector research beyond bees. Stingless bees (Meliponini), leaf-cutting bees (*Megachile* spp.), alfalfa leaf-cutting bees (*Megachile rotundata*), certain ant species, predatory insects, fungus gnats, lacewings, and even mosquitoes have been experimentally evaluated as vectors under specific conditions. However, their commercial application remains limited due to difficulties in mass rearing, colony management, or restricted foraging behaviour.

Selection of the appropriate pollinator depends upon several factors including crop type, flowering period, greenhouse versus open-field cultivation, climatic conditions, floral morphology, flight range, and compatibility with microbial agents. Therefore, vector selection remains one of the most important determinants of successful entomovectoring.

Biological Control Agents

Biological control agents (BCAs) are beneficial microorganisms intentionally disseminated by pollinators to suppress plant pathogens or insect pests. They constitute the active component of the entomovectoring system and determine its effectiveness against target organisms.

An ideal microbial agent should possess several desirable characteristics. It must effectively colonize floral tissues, remain viable during storage and transport, adhere efficiently to the insect body, tolerate varying environmental conditions, and exhibit no harmful effects on pollinator health, humans, livestock, or non-target organisms. Furthermore, microbial formulations should maintain viability under field conditions while allowing gradual release from the insect body during repeated floral visits.

Among all microbial agents, fungi have received the greatest attention because they produce abundant spores, possess long shelf life, and exhibit broad-spectrum activity against both plant pathogens and insect pests. Frequently employed fungal antagonists include *Clonostachys rosea* (formerly *Gliocladium roseum*), *Gliocladium catenulatum*, *Trichoderma harzianum*, *Trichoderma atroviride*, *Beauveria bassiana*, *Metarhizium anisopliae*, and *Coniothyrium minitans*. These fungi suppress diseases through competition, mycoparasitism, antibiosis, production of hydrolytic enzymes, and induction of host resistance (Roy & Pell 2000; Dharshini *et al.,* 2026).

Several bacterial antagonists have also demonstrated remarkable efficacy in entomovectoring systems. *Bacillus subtilis*, *Pantoea agglomerans*, *Pseudomonas fluorescens*, and *Streptomyces griseoviridis* effectively suppress diseases such as fire blight, mummy berry, blossom blight, and bacterial infections through production of antimicrobial metabolites and competitive exclusion.

Entomopathogenic microorganisms targeting insect pests include *Beauveria bassiana*, *Metarhizium anisopliae*, *Bacillus thuringiensis* (Bt), and nucleopolyhedroviruses (NPVs). These pathogens infect susceptible insects after deposition on floral tissues or developing fruits, thereby reducing pest populations without harming beneficial organisms.

Compatibility between pollinators and microbial agents is of paramount importance. Excessive inoculum loads or incompatible microbial strains may alter pollinator behaviour, reduce foraging activity, or negatively affect colony development. Therefore, microbial formulations are rigorously evaluated to ensure pollinator safety before commercial deployment.

Dispenser Systems

The dispenser represents the technological interface between the pollinator and the microbial inoculum. It is specifically designed to coat insects with a predetermined quantity of biological control agent while allowing normal movement into and out of the hive. Efficient dispenser design ensures adequate microbial loading without causing stress, injury, or behavioural changes in pollinating insects.

Modern dispensers are classified into one-way dispensers and two-way dispensers.

One-way dispensers expose bees to microbial inoculum only while exiting the hive. As bees leave the colony for foraging, they pass through a chamber containing powdered microbial formulations that adhere to their body hairs. Returning bees enter the hive through an alternative route, thereby minimizing contamination within the colony. Although simple and inexpensive, one-way dispensers often produce variable microbial loading because insects contact the inoculum only once during each foraging trip.

Two-way dispensers require pollinators to pass through inoculum chambers during both exit and return to the hive. This design improves consistency of microbial loading, reduces inoculum loss, enhances delivery efficiency, and maintains a more uniform distribution of biological control agents among foraging bees. Recent comparative studies have demonstrated that two-way dispensers outperform one-way dispensers with respect to inoculum transfer efficiency and disease suppression (Dharshini *et al.,* 2026).

Commercially developed dispenser systems include BeeTreat® (Finland), Flying Doctors® (Belgium), and BVT Inoculum Dispenser® (Canada). These systems have been successfully adopted in strawberries, blueberries, tomatoes, peppers, raspberries, cherries, canola, and several greenhouse crops. Their design minimizes microbial wastage while ensuring continuous replenishment of inoculum during flowering. The effectiveness of dispensers depends on particle size, humidity, formulation characteristics, grooming behaviour of pollinators, flight frequency, colony strength, and environmental conditions. Future dispenser technologies are expected to incorporate smart materials, controlled-release formulations, automated inoculum replenishment, and digital monitoring systems to further improve delivery precision and commercial scalability.

Pollinator Species Used in Entomovectoring

The success of entomovectoring largely depends on the selection of an efficient pollinator vector. An ideal pollinator should exhibit high floral fidelity, frequent visitation rates, efficient pollen transfer, compatibility with managed colonies, and the ability to carry sufficient quantities of microbial biological control agents (BCAs) without compromising its health or foraging behaviour (Kevan *et al.,* 2008; Temmermans & Smagghe, 2022). Different pollinator species vary considerably in their foraging behaviour, flight range, environmental adaptability, and compatibility with specific crops. Therefore, careful selection of pollinator vectors is essential for maximizing both pollination efficiency and microbial delivery.

Honeybees (Apis mellifera)

The western honeybee (*Apis mellifera*) is the most widely used pollinator in entomovectoring because of its worldwide distribution, large colony size, efficient communication system, and ease of management. Honeybee colonies contain thousands of foraging workers capable of visiting millions of flowers during a flowering season, making them highly efficient vectors for microbial inoculum (Peng *et al.,* 1992; Kevan *et al.,* 2003).

Honeybees are particularly suitable for open-field crops such as strawberry, sunflower, canola, blueberry, apple, pear, raspberry, and cherry. During foraging, fungal spores or bacterial cells attached to their body hairs are deposited on floral reproductive structures where pathogen infection commonly occurs. Numerous studies have demonstrated successful delivery of *Clonostachys rosea*, *Trichoderma harzianum*, *Beauveria bassiana*, *Metarhizium anisopliae*, *Bacillus subtilis*, and *Pantoea agglomerans* using honeybees (Maccagnani *et al.,* 1999; Thomson *et al.,* 1992).

Despite these advantages, honeybees are sensitive to unfavourable weather conditions. Rainfall, low temperatures, and strong winds significantly reduce their foraging activity, thereby decreasing microbial delivery efficiency (Temmermans & Smagghe, 2022).

Furthermore, honeybees are less effective than bumble bees under greenhouse conditions because they require larger flight spaces and natural orientation cues (Velthuis & van Doorn 2006).

Bumble Bees (Bombus terrestris and Bombus impatiens)

Bumble bees have become increasingly important in commercial entomovectoring due to their superior performance in protected cultivation systems. Species such as *Bombus terrestris* in Europe and *Bombus impatiens* in North America are extensively reared for greenhouse pollination of tomato, sweet pepper, eggplant, cucumber, and berry crops (Velthuis & van Doorn 2006).

Unlike honeybees, bumble bees remain active under cloudy weather, lower temperatures, higher humidity, and light rainfall. They also possess the unique ability to perform buzz pollination, in which rapid thoracic vibrations release pollen from poricidal anthers, improving pollination efficiency in crops such as tomato and eggplant (Velthuis & van Doorn, 2006; Temmermans & Smagghe 2022).

Several studies have shown that bumble bees efficiently disseminate *Gliocladium catenulatum*, *Trichoderma harzianum*, *Beauveria bassiana*, *Clonostachys rosea*, and *Bacillus subtilis* against gray mold, blossom blight, whiteflies, western flower thrips, tarnished plant bugs, and aphids in greenhouse vegetable production (Kapongo *et al.,* 2008; Mommaerts & Smagghe 2011).

Their short foraging range also increases deposition of microbial agents within the target crop, reducing inoculum loss outside production fields.

Solitary Bees

Solitary bees have attracted increasing attention as potential entomovectors because many species exhibit exceptional floral constancy and high pollination efficiency. Important species include *Osmia lignaria*, *Osmia cornuta*, *Osmia bicornis*, *Osmia cornifrons*, and *Megachile rotundata* (Temmermans & Smagghe 2022).

Unlike social bees, solitary bees do not form large colonies. However, individual females make repeated visits to flowers while collecting pollen for nest provisioning, allowing effective dissemination of microbial agents. Their short flight distances ensure localized microbial deposition, making them particularly valuable for orchard crops such as almond, apple, pear, plum, peach, and cherry. Although commercial mass production of solitary bees has improved in recent years, their widespread use in entomovectoring remains limited because of higher management costs and shorter seasonal activity compared with honeybees and bumble bees.

Stingless Bees

Stingless bees (Meliponini) are abundant throughout tropical and subtropical regions, particularly in Central and South America, Southeast Asia, and parts of Africa. These bees possess several desirable characteristics, including gentle behaviour, year-round colony activity, and excellent adaptation to tropical environments (Slaa *et al.,* 2006).

Species such as *Nannotrigona perilampoides*, *Melipona quadrifasciata*, and *Tetragonula* spp. have shown promising results in greenhouse pollination of tomatoes and several fruit crops. Recent investigations suggest that stingless bees could serve as efficient entomovectors in tropical agriculture, although further research is required to optimize colony management and microbial delivery systems (Temmermans & Smagghe, 2022).

Other Potential Pollinator Vectors

Besides bees, several other insects have been experimentally evaluated as microbial vectors. These include hoverflies (*Syrphidae*), butterflies (*Lepidoptera*), predatory bugs, lacewings (*Chrysoperla* spp.), fungus gnats, ants, and certain parasitoids (Hokkanen & Menzler-Hokkanen 2007). However, their commercial application remains limited because of difficulties in mass rearing, lower flower fidelity, unpredictable foraging behaviour, or reduced microbial carrying capacity.

Future advances in insect rearing technologies and microbial formulation may broaden the diversity of pollinator vectors available for entomovectoring.

Biological Control Agents Used in Entomovectoring

Biological control agents are beneficial microorganisms deliberately transported by pollinators to suppress plant pathogens or insect pests. Their effectiveness depends upon successful colonization of floral tissues, compatibility with pollinator vectors, persistence under environmental conditions, and absence of adverse effects on bees or other beneficial organisms (Kevan *et al.,* 2008).

Fungal Biological Control Agents

Fungi constitute the most extensively utilized microbial group in entomovectoring because they produce abundant spores, remain viable under storage conditions, and possess multiple mechanisms of pathogen suppression.

Clonostachys rosea (formerly *Gliocladium roseum*)

Clonostachys rosea was the first fungal antagonist successfully delivered by honeybees for management of gray mold (*Botrytis cinerea*) in strawberries (Peng *et al.,* 1992). The fungus suppresses pathogens through competition, mycoparasitism, secretion of hydrolytic enzymes, and production of antifungal metabolites. Since its initial success, *C. rosea* has become one of the most extensively investigated biological control agents in entomovectoring systems.

Trichoderma harzianum

Trichoderma harzianum is widely recognized for its rapid growth, aggressive mycoparasitic activity, and ability to induce systemic resistance in host plants.

Honeybees and bumble bees have successfully disseminated *T. harzianum* for controlling gray mold in strawberry, cucumber fruit rot, sunflower head rot, and several greenhouse diseases (Maccagnani *et al.,* 1999; Sutton & Kevan 2012).

Beauveria bassiana

Beauveria bassiana is an entomopathogenic fungus used primarily against insect pests including coffee berry borer, whiteflies, aphids, western flower thrips, and tarnished plant bug. When delivered through pollinators, fungal spores establish on floral tissues where insect pests acquire infection during feeding (Kapongo *et al.,* 2008).

Metarhizium anisopliae

Metarhizium anisopliae has shown considerable promise against pollen beetles, cabbage seed weevils, and *Drosophila suzukii*.

Honeybee-mediated delivery significantly improves contact between fungal spores and target insects while minimizing environmental contamination compared with conventional spraying (Carreck *et al.,* 2007; Taning & Smagghe 2020).

Bacterial Biological Control Agents

Several bacterial antagonists have demonstrated high efficacy when disseminated by pollinating insects.

Bacillus subtilis

Bacillus subtilis suppresses plant pathogens by producing antibiotics, lipopeptides, and antimicrobial enzymes while competing effectively for nutrients and infection sites. Bee- mediated delivery has successfully controlled fire blight and mummy berry disease in fruit crops (Ngugi *et al.,* 2005).

Pantoea agglomerans

This epiphytic bacterium effectively suppresses *Erwinia amylovora*, the causal organism of fire blight in apples and pears. Honeybees carrying *P. agglomerans* efficiently colonize stigmatic surfaces before pathogen arrival, thereby preventing disease establishment (Vanneste *et al.,* 2002).

Pseudomonas fluorescens

Pseudomonas fluorescens has demonstrated antagonistic activity against numerous bacterial and fungal pathogens through antibiotic production, siderophore secretion, and induced systemic resistance. Bee-mediated dissemination has proven particularly effective against fire blight (Thomson *et al.,* 1992).

Viral Biological Control Agents

Although viral agents are less commonly used than fungi or bacteria, nucleopolyhedroviruses (NPVs) have shown considerable promise against lepidopteran pests. Honeybee-mediated dissemination of *Heliothis* NPV has successfully reduced corn earworm infestations, while *Helicoverpa armigera* NPV has demonstrated effectiveness against pod borer in pigeon pea (Gross *et al.,* 1994; Vakaliya & Borad 2017).

Characteristics of an Ideal Biological Control Agent

An effective biological control agent for entomovectoring should possess the following characteristics:

- High antagonistic activity against target pathogens or pests.
- No pathogenic effects on pollinators or humans.
- Excellent adherence to insect body hairs.
- Long shelf life under storage conditions.
- Stability under varying temperature and humidity.
- Compatibility with commercial dispenser systems.
- Ability to colonize floral tissues rapidly.
- Persistence throughout the flowering period.
- Minimal environmental risks and regulatory compliance.

Selection of suitable microbial agents remains one of the most critical factors determining the commercial success of entomovectoring systems.

Crop-wise Applications of Entomovectoring

Entomovectoring has been successfully implemented in numerous horticultural and field crops where flowers serve as the primary infection sites for pathogens or where insect pests exploit floral tissues. Because pollinators naturally visit flowers during nectar and pollen collection, they provide an ideal means of delivering microbial biological control agents (BCAs) directly to susceptible plant organs. Crop-specific selection of pollinator vectors and microbial agents is critical because floral architecture, flowering duration, environmental conditions, and pollinator preferences vary among crops (Kevan *et al.,* 2008; Temmermans & Smagghe 2022).

Strawberry (Fragaria × ananassa)

Strawberry is the most extensively studied crop in entomovectoring research. The crop is highly dependent on insect pollination for improved fruit size, uniformity, shape, and market quality. At the same time, strawberry flowers are highly susceptible to gray mold, caused by *Botrytis cinerea*, which can result in yield losses exceeding 50% under favourable environmental conditions (Peng *et al.,* 1992).

The first successful entomovectoring experiment employed honeybees (*Apis mellifera*) to disseminate *Gliocladium roseum* (currently *Clonostachys rosea*) onto strawberry flowers. The study demonstrated significant suppression of gray mold while maintaining normal pollination activity (Peng *et al.,* 1992). Subsequent investigations confirmed the effectiveness of *Trichoderma harzianum*, *Gliocladium catenulatum*, and *Clonostachys rosea* delivered by honeybees and bumble bees under both greenhouse and open-field conditions (Maccagnani *et al.,* 1999; Mommaerts & Smagghe 2011).

Compared with conventional fungicide applications, bee-mediated delivery provides repeated inoculation of newly opened flowers throughout the flowering period, thereby ensuring continuous protection while reducing pesticide use.

Economic analyses have further demonstrated increased profits due to improved fruit quality, reduced disease incidence, and lower pesticide costs (Temmermans & Smagghe 2022).

Blueberry (*Vaccinium* spp.)

Blueberry production depends heavily on insect pollination because effective fruit set requires repeated floral visitation. Entomovectoring has been successfully utilized to manage mummy berry disease (*Monilinia vaccinii-corymbosi*) and blossom blight using honeybees and bumble bees carrying *Bacillus subtilis* and *Streptomyces griseoviridis* (Ngugi *et al.,* 2005; Smith *et al.,* 2012). The floral morphology of blueberry promotes prolonged contact between pollinators and reproductive structures, thereby facilitating efficient deposition of microbial antagonists. Repeated pollinator visits throughout bloom enhance microbial colonization and suppress pathogen establishment before infection occurs (Kevan *et al.,* 2008).

Tomato (*Solanum lycopersicum*)

Tomato is one of the most economically important greenhouse crops worldwide. Commercial greenhouse tomato production relies exclusively on bumble bees because of their ability to perform buzz pollination. Entomovectoring has been integrated with greenhouse pollination by utilizing *Bombus terrestris* and *Bombus impatiens* to disseminate *Beauveria bassiana* and *Clonostachys rosea* against whiteflies (*Bemisia tabaci*), western flower thrips (*Frankliniella occidentalis*), green peach aphids (*Myzus persicae*), and tarnished plant bugs (*Lygus lineolaris*) (Kapongo *et al.,* 2008; Mommaerts & Smagghe 2011).

Greenhouse environments provide favourable conditions for entomovectoring because pollinator movement remains confined within enclosed structures, minimizing microbial loss and ensuring repeated inoculation of flowers. Furthermore, reduced pesticide applications improve pollinator survival and biological control efficiency.

Canola (*Brassica napus*)

Canola is an important oilseed crop benefiting from insect pollination. Honeybees have been used to disseminate *Metarhizium anisopliae* against pollen beetles (*Brassicogethes aeneus*) and cabbage seed weevils (*Ceutorhynchus* spp.). Experimental trials demonstrated reduced pest populations while maintaining seed yield and pollination efficiency (Butt *et al.,* 1998; Carreck *et al.,* 2007).

Although Brassicaceae flowers are highly attractive to honeybees, weather conditions strongly influence pollinator activity and microbial delivery. Therefore, successful implementation requires synchronization of flowering with peak pollinator foraging periods.

Sunflower (Helianthus annuus)

Sunflower is another crop where entomovectoring has demonstrated considerable promise. Honeybees have been employed to deliver *Trichoderma harzianum* for suppression of sunflower head rot, while *Bacillus thuringiensis* has been disseminated against banded sunflower moth (*Cochylis hospes*) (Joy *et al.,* 1999; Escande *et al.,* 2002).

Because sunflower flowers remain open for several days, repeated bee visits facilitate continuous deposition of microbial inoculum across developing florets, resulting in improved disease suppression and enhanced seed production.

Apple and Pear

Fire blight, caused by *Erwinia amylovora*, represents one of the most destructive bacterial diseases affecting apple and pear orchards. Honeybees and mason bees have successfully disseminated *Pantoea agglomerans*, *Pseudomonas fluorescens*, and *Bacillus subtilis* to stigmatic surfaces before pathogen infection (Thomson *et al.,* 1992; Vanneste *et al.,* 2002).

The floral biology of pome fruits favours early microbial colonization because bacterial pathogens initiate infection immediately after flowering. Consequently, pollinator-mediated delivery provides more precise disease suppression than conventional spraying.

Coffee

Coffee berry borer (*Hypothenemus hampei*) is one of the most economically damaging pests of coffee worldwide. Honeybees carrying *Beauveria bassiana* have demonstrated successful suppression of coffee berry borer populations by depositing fungal spores onto coffee flowers and developing berries (Urena & Chuncho 2003).

This approach reduces repeated insecticide applications while simultaneously improving pollination and berry quality.

Pigeon Pea

One of the first successful Indian applications of entomovectoring involved the dissemination of *Helicoverpa armigera* nucleopolyhedrovirus (HaNPV) by honeybees for management of pod borer in pigeon pea. Field studies reported significant reductions in larval populations and improved pod yield, demonstrating the feasibility of entomovectoring under Indian agro-climatic conditions (Vakaliya & Borad 2017).

Disease Management through Entomovectoring

Plant diseases often originate at flowers, making floral tissues ideal targets for biological control. Entomovectoring exploits this vulnerability by delivering antagonistic microorganisms directly to infection courts before pathogen establishment.

Compared with conventional spraying, bee-mediated delivery provides greater precision, repeated application, and reduced environmental contamination (Kevan *et al.,* 2008).

The mechanisms by which microbial antagonists suppress plant pathogens include:

- Competition for nutrients and infection sites.
- Production of antifungal and antibacterial metabolites.
- Mycoparasitism.
- Secretion of hydrolytic enzymes.
- Induction of systemic resistance.
- Biofilm formation on floral tissues.

These mechanisms collectively reduce pathogen establishment while minimizing chemical fungicide use (Harman *et al.,* 2004).

Major Diseases Successfully Managed

Numerous studies have demonstrated that entomovectoring often provides disease control comparable to conventional fungicide programs while requiring lower quantities of microbial products. Because pollinators repeatedly inoculate flowers throughout bloom, microbial populations remain active during the most susceptible stages of infection (Peng *et al.,* 1992; Sutton & Kevan 2012).

In addition to disease suppression, reduced pesticide application conserves beneficial arthropods, lowers production costs, minimizes chemical residues on harvested produce, and contributes to sustainable Integrated Pest Management programs (Mommaerts & Smagghe 2011; Temmermans & Smagghe 2022).

Table.1 Major Diseases Successfully Managed

Disease	Causal organism	Biological control agent	Pollinator
Gray mold	*Botrytis cinerea*	*Clonostachys rosea, Trichoderma harzianum*	**Honeybee, Bumble bee**
Fire blight	*Erwinia amylovora*	*Pantoea agglomerans, Bacillus subtilis*	**Honeybee**
Fire blight	*Erwinia amylovora*	*Pantoea agglomerans, Bacillus subtilis*	**Honeybee**
Mummy berry	*Monilinia vaccinii-corymbosi*	*Bacillus subtilis*	**Honeybee**
Blossom blight	Various fungi	*Streptomyces griseoviridis*	**Bumble bee**
Brown rot	*Monilinia fructicola*	*Clonostachys rosea*	**Honeybee**
Sunflower head rot	***Sclerotinia sclerotiorum***	***Trichoderma harzianum***	**Honeybee**

Insect Pest Management through Entomovectoring

Although entomovectoring was initially developed for managing plant diseases, recent research has demonstrated its considerable potential for insect pest management. The technology employs pollinating insects to disseminate entomopathogenic fungi, bacteria, or viruses onto flowers, where insect pests become infected during feeding, oviposition, or movement. Compared with foliar insecticide sprays, pollinator-mediated delivery provides highly targeted application, reduces pesticide residues, conserves natural enemies, and minimizes environmental contamination (Mommaerts & Smagghe 2011; Taning & Smagghe 2020).

The success of insect pest management through entomovectoring depends upon three essential factors: (i) effective dissemination of microbial propagules by pollinators, (ii) compatibility between the microbial agent and pollinator vector, and (iii) synchronization between pollinator activity and pest occurrence (Kevan *et al.,* 2008). Because most economically important insect pests attack flowers, young fruits, or reproductive tissues, pollinator-mediated delivery provides direct contact between the microbial pathogen and the target insect.

Coffee Berry Borer

Coffee berry borer (*Hypothenemus hampei*) is regarded as one of the most destructive insect pests of coffee, causing severe yield and quality losses throughout tropical coffee-growing regions. Researchers have demonstrated that honeybees carrying *Beauveria bassiana* effectively disseminate fungal spores onto coffee flowers and developing berries. Adult beetles acquire fungal spores while entering berries, leading to infection and mortality. This approach significantly reduces dependence on repeated insecticide applications while simultaneously improving pollination and coffee yield (Urena & Chuncho, 2003).

Western Flower Thrips

Western flower thrips (*Frankliniella occidentalis*) is an economically important pest of greenhouse vegetables and ornamentals. Bumble bees carrying *Beauveria bassiana* have been successfully employed to suppress thrips populations in greenhouse tomato and sweet pepper production. Spores deposited on flowers infect adult thrips during feeding, resulting in reduced pest populations and lower virus transmission (Kapongo *et al.,* 2008).

Tarnished Plant Bug

The tarnished plant bug (*Lygus lineolaris*) causes serious economic losses in strawberry production by feeding on developing flowers and fruits. Bumble bee-mediated dissemination of *Beauveria bassiana* has significantly reduced plant bug populations while maintaining effective pollination. This dual benefit makes entomovectoring particularly attractive for integrated management of berry crops (Al-Mazraawi *et al.,* 2006).

Pollen Beetle and Cabbage Seed Weevil

In canola production, pollen beetles (*Brassicogethes aeneus*) and cabbage seed weevils (*Ceutorhynchus* spp.) attack floral tissues, reducing seed yield. Honeybees transporting *Metarhizium anisopliae* have demonstrated significant suppression of these pests under experimental conditions. Because fungal spores are deposited directly onto flowers visited by adult insects, infection occurs naturally during feeding (Butt *et al.,* 1998).

Pod Borer (Helicoverpa armigera)

In India, one of the earliest successful demonstrations of insect pest management through entomovectoring involved the use of honeybees to disseminate *Helicoverpa armigera* nucleopolyhedrovirus (HaNPV) in pigeon pea. Bee-mediated virus delivery significantly reduced larval populations while improving pod yield and minimizing insecticide applications (Vakaliya & Borad 2017).

Drosophila suzukii

The spotted-wing drosophila (*Drosophila suzukii*) is a major pest of strawberries, raspberries, blueberries, and cherries. Recent studies have investigated the use of honeybees and bumble bees to disseminate *Metarhizium anisopliae* and *Beauveria bassiana*. Although commercial adoption is still under development, preliminary results indicate promising levels of pest suppression (Taning & Smagghe 2020).

Commercialization of Entomovector Technology

The transition of entomovectoring from laboratory research to commercial agriculture has accelerated during the past two decades. Advances in microbial formulation, dispenser engineering, pollinator management, and regulatory approval have facilitated large-scale implementation in several countries.

BeeTreat®

BeeTreat®, developed in Finland, represents one of the earliest commercial entomovectoring systems. The technology utilizes specially designed dispensers attached to honeybee colonies to deliver fungal biological control agents against gray mold in strawberries and several greenhouse crops (Hokkanen *et al.,* 2015).

Flying Doctors®

The Flying Doctors® system, developed in Belgium, utilizes bumble bees as vectors for microbial antagonists in greenhouse vegetables and berry crops. The system has been successfully employed against *Botrytis cinerea*, whiteflies, western flower thrips, and blossom diseases (Temmermans & Smagghe 2022).

BVT (Bee Vectoring Technologies)

Bee Vectoring Technologies (BVT), headquartered in Canada, has commercialized one of the world's most widely adopted entomovectoring systems. The company utilizes proprietary dispenser technology and the fungal biological control agent *Clonostachys rosea* (CR-7) to manage diseases in strawberries, blueberries, sunflowers, tomatoes, apples, and several other crops. Commercial adoption has expanded across Canada, the United States, Europe, South America, and Africa (Bee Vectoring Technologies 2023).

The BVT system reduces fungicide use, improves crop quality, and provides continuous microbial protection throughout flowering while maintaining effective pollination services.

Environmental and Economic Significance

Entomovectoring contributes significantly to sustainable agriculture by reducing pesticide use while conserving biodiversity and pollinator populations. Lower pesticide application decreases contamination of soil, water, and surrounding ecosystems, thereby protecting beneficial arthropods and improving ecosystem resilience (Pimentel 2005).

Economically, the technology reduces labour costs associated with pesticide spraying while improving pollination, fruit quality, and marketable yield. Several commercial trials have reported higher net returns because of improved crop quality and reduced pesticide expenditure (Bee Vectoring Technologies 2023; Temmermans & Smagghe 2022).

The integration of biological control with pollination also contributes to climate-smart agriculture by promoting environmentally sustainable crop production systems.

Future Prospects and Research Needs

Future research should focus on improving microbial formulations with enhanced shelf life, UV tolerance, and adherence to pollinator body hairs. Development of next-generation dispenser systems incorporating automated inoculum replenishment and digital monitoring could further improve delivery efficiency (Hokkanen *et al.,* 2015).

Additional priorities include:

- Identification of new pollinator species suitable for tropical agriculture.
- Development of multi-microbial formulations targeting both diseases and insect pests.
- Genetic improvement of microbial biological control agents.
- Evaluation of long-term ecological impacts.
- Expansion of entomovectoring to medicinal plants, spices, oilseed crops, and agroforestry systems.
- Development of cost-effective commercial technologies for smallholder farmers.
- Strengthening regulatory frameworks for microbial registration.

Countries such as India possess enormous potential because of their rich pollinator diversity, expanding protected cultivation, and increasing demand for sustainable crop protection technologies.

In conclusion, Entomovectoring represents one of the most promising innovations in sustainable crop protection by integrating pollination and biological control into a single ecological process.

The technology provides precise, repeated, and environmentally friendly delivery of microbial biological control agents while simultaneously enhancing pollination services.

Successful applications in strawberries, blueberries, tomatoes, peppers, canola, coffee, apple, pear, sunflower, and several greenhouse crops demonstrate its versatility across diverse agricultural systems.

Despite challenges related to pollinator management, environmental variability, and regulatory approval, advances in microbial formulation, dispenser technology, and integrated pest management continue to improve commercial feasibility. As concerns regarding pesticide resistance, environmental contamination, and pollinator conservation increase globally, entomovectoring is expected to play an increasingly significant role in climate-resilient and sustainable agriculture.

Author Contributions

K. Sri Ram: Investigation, formal analysis, writing—original draft. Purushottam Sheshrao Neharkar: Validation, methodology, writing—reviewing. M. M. Sonkamble:—Formal analysis, writing—review and editing. A. G. Lad: Investigation, writing—reviewing. F. S. Khan: Resources, investigation writing—reviewing. Y. B. Matre: Validation, formal analysis, writing—reviewing. Leela Prasanna: Conceptualization, methodology, data curation, supervision, writing—reviewing the final version of the manuscript.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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