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BIOLOGICAL CONTROL OF AGRICULTURAL INSECT PESTS: PARASITOIDS, PREDATORS, ENTOMOPATHOGENIC FUNGI, AND MICROBIOME-MEDIATED SUPPRESSION IN INTEGRATED PEST MANAGEMENT SYSTEMS

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ABSTRACT

Agricultural insect pests account for pre-harvest crop losses estimated at 10 to 40% globally, representing a critical threat to food security for an expanding human population. The near-exclusive reliance on synthetic insecticides for pest management has generated pervasive problems including the evolution of insecticide resistance, disruption of non-target organisms, environmental contamination, and escalating economic costs to farmers. Biological control, the deliberate exploitation of natural enemies including parasitoids, predators, entomopathogenic fungi, and microbiome-based agents, offers a sustainable alternative and complement to chemical pesticides within Integrated Pest Management (IPM) systems. This review synthesizes current knowledge on four principal categories of biological control agents, examining their mechanisms of action, host specificity, efficacy under field conditions, commercial development status, and compatibility within IPM frameworks. We highlight the emerging frontier of microbiome-mediated pest suppression, including the roles of plant microbiomes in induced resistance, insect gut microbiome disruption as a biocontrol target, and synergistic interactions between microbial biocontrol agents. Key challenges including inconsistent field performance, regulatory barriers, climate change impacts, and non-target effects are critically evaluated. We identify priority research directions including omics-assisted biocontrol agent discovery, nanotechnology-enhanced delivery, and AI-driven precision deployment, and conclude with recommendations for accelerating the adoption of biological control within sustainable agricultural systems.

Keywords:

Biological control, parasitoids, entomopathogenic fungi, predatory insects, IPM, Beauveria bassiana, Metarhizium anisopliae, Bacillus thuringiensis, gut microbiome, sustainable pest management.

INTRODUCTION

Global agricultural production faces a mounting crisis driven by the damage inflicted by insect pests on crops from sowing to harvest and beyond. The Food and Agriculture Organization of the United Nations estimates that insects and other invertebrate pests are responsible for pre-harvest losses of 10 to 40% of global crop

production annually, with the financial cost to agriculture exceeding hundreds of billions of dollars [1, 2]. These losses are compounded by post-harvest pest damage to stored grains and food products, which disproportionately affects food security in low- and middle-income countries. The challenge is intensifying under climate change, which is expanding the geographic ranges of many pest species and altering the phenological synchrony between crops, pests, and their natural enemies [3].

Synthetic insecticides have constituted the primary response to agricultural pest pressure for more than seven decades, and their efficacy in protecting crops is undeniable. However, the costs and externalities of chemical-intensive pest management have become increasingly apparent. More than 600 insect species have evolved resistance to at least one insecticide class, and resistance to multiple classes simultaneously is now widespread in economically significant pests including Helicoverpa armigera, Bemisia tabaci, Spodoptera frugiperda, and Aedes aegypti [4]. Environmental contamination from insecticide runoff and spray drift has contributed to the documented decline of non-target insect communities, including pollinators and natural enemies, with cascading effects on ecosystem services [5]. Growing consumer demand for pesticide residue-free food products, tightening regulatory frameworks for insecticide registration, and mounting evidence of insecticide effects on human health are collectively driving a structural shift toward biologically-based pest management [6].

Biological control, the use of living organisms or their products to suppress pest populations below economically damaging thresholds, represents one of the most ecologically rational approaches to pest management. The discipline encompasses three broad strategies: classical biological control, which involves the importation and establishment of co-evolved natural enemies from the pest's region of origin; augmentative biological control, which involves the mass rearing and periodic release of natural enemies; and conservation biological control, which involves habitat and management modifications that enhance the abundance and effectiveness of naturally occurring enemies [7]. These strategies are not mutually exclusive and are most effective when deployed within comprehensive IPM frameworks that integrate biological, cultural, physical, and chemical control methods [8].

The global market for biopesticides, which includes microbial biocontrol agents, has grown at annual rates exceeding 15% over the past decade, driven by regulatory pressures on conventional insecticides, rising farmer awareness of resistance issues, and expanding retail demand for sustainably produced food [9]. This market trajectory reflects a genuine and accelerating transition in pest management philosophy, supported by an expanding base of scientific evidence for the efficacy, selectivity, and environmental safety of biological control agents across diverse cropping systems and geographies. Investment in the research and development of new biocontrol agents and formulation technologies has grown correspondingly, with national and multilateral funding agencies increasingly prioritizing biopesticide innovation as a component of sustainable food systems strategies.

The history of biological control contains both spectacular successes and instructive failures that collectively define our current understanding of when and why natural enemies reliably suppress pest populations. Early classical biocontrol programs, including the successful use of the vedalia beetle (Rodolia cardinalis) to suppress cottony cushion scale (Icerya purchasi) in Californian citrus orchards in the 1880s, demonstrated the transformative potential of the approach and inspired a century of subsequent work [10]. More recent programs have refined the conceptual and practical toolkit of biological control substantially, incorporating molecular tools for natural enemy identification, population genetics for understanding enemy dispersal and establishment, and behavioral ecology for optimizing release strategies and habitat design.

This review examines four categories of biological control agents in detail: parasitoid insects and

their mechanisms of host suppression; predatory arthropods and their deployment in conservation and augmentative programs; entomopathogenic fungi and the rapidly expanding commercial sector of mycoinsecticides; and microbiome-mediated pest suppression, encompassing both classical microbial agents such as Bacillus thuringiensis and emerging approaches that target insect gut microbiomes or exploit plant microbiome-induced resistance. We evaluate the evidence base for each category, identify key limitations, and propose research priorities for advancing biological control in the context of sustainable agriculture [11].

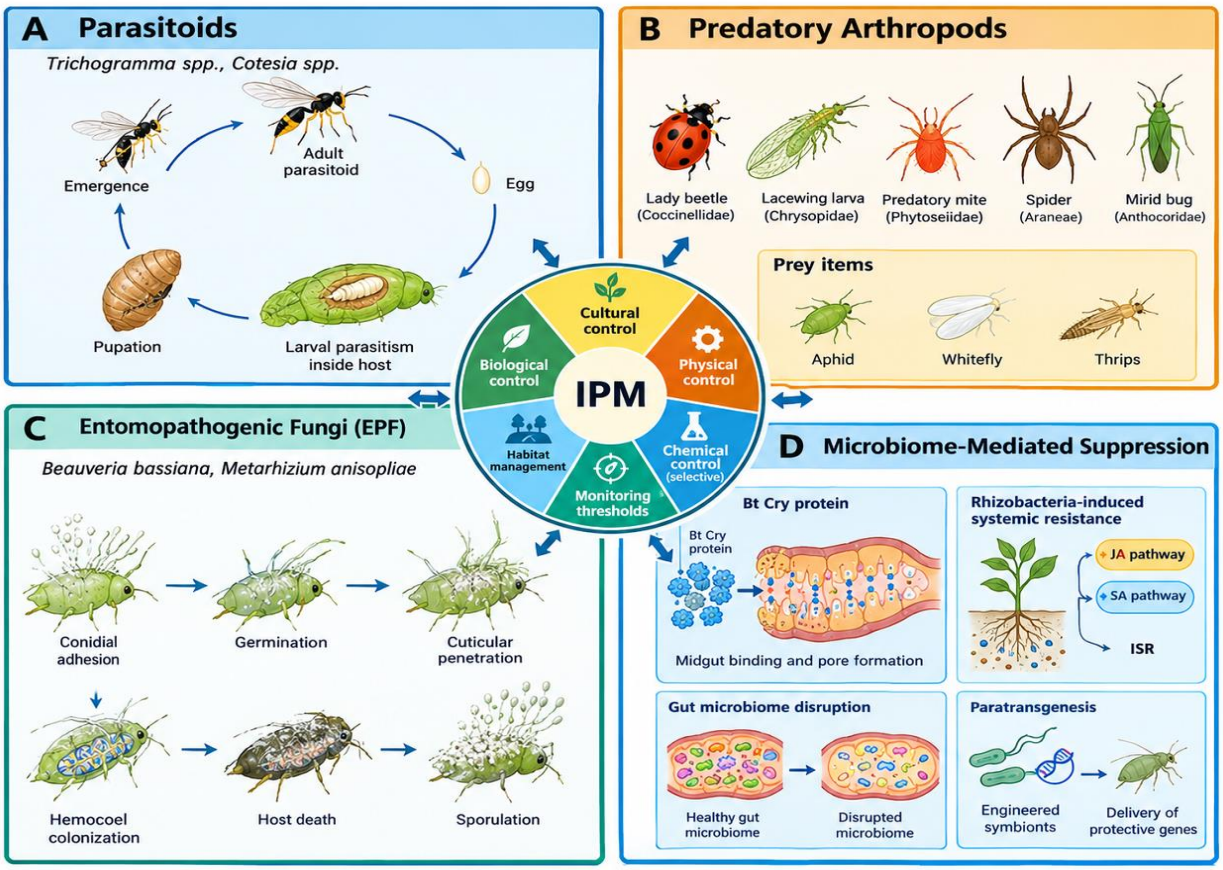


Fig. 1 Conceptual framework of biological control agent categories and their integration within Integrated Pest Management (IPM) systems. A Parasitoid life cycle (Trichogramma spp., Cotesia spp.); B Predatory arthropod guild and prey spectra; C Entomopathogenic fungal infection cascade (Beauveria bassiana, Metarhizium anisopliae); D Microbiome-mediated suppression (Bt Cry proteins, rhizobacteria-induced systemic resistance, gut dysbiosis, paratransgenesis). Central hub depicts IPM components interacting synergistically with biological control, with bidirectional arrows indicating integration pathways.

2. Parasitoid Insects as Biological Control Agents

Parasitoids, insects that develop by feeding on a single host organism and ultimately killing it, represent the largest and most taxonomically diverse group of biological control agents in agricultural use. The majority of parasitoid species used in biological control are wasps belonging to the orders Hymenoptera, principally in families Braconidae, Ichneumonidae, Eulophidae, and Trichogrammatidae, with a smaller contribution from parasitoid flies in the

family Tachinidae [12]. Parasitoids can be ectoparasitic, developing externally on the host, or endoparasitic, developing internally; they can be larval, pupal, or egg parasitoids, targeting different life stages of the host. This diversity of life history strategies enables parasitoid-based biocontrol programs to target pest insects at multiple developmental stages, often sequentially within a single crop growing season.

Egg parasitoids of the genus Trichogramma are among the most widely deployed biological control agents in global agriculture, with augmentative releases used on more than 32 million hectares annually, primarily targeting lepidopteran pests in maize, cotton, sugarcane, and vegetable crops [13]. Trichogramma species parasitize host eggs before larval feeding damage can occur, making them particularly effective for crops where early-season damage is critical. Mass rearing technology for Trichogramma is well-developed, enabling cost-effective production at scales sufficient for inundative release programs. However, the effectiveness of Trichogramma releases is sensitive to field conditions including temperature, humidity, host egg density, and the presence of competing hyperparasitoids [14].

Larval parasitoids including Cotesia glomerata, Cotesia plutellae, and Apanteles spp. provide important natural regulation of caterpillar pests including the diamondback moth (Plutella xylostella) and various Spodoptera species in vegetable and row crops [15]. Tritrophic interactions, encompassing the crop plant, the herbivorous pest, and its parasitoid natural enemies, play a central role in determining parasitoid efficacy under field conditions. Plants under herbivore attack emit volatile blends that attract parasitoids to locate their hosts, and the composition of these herbivore-induced plant volatiles can be influenced by plant genotype, herbivore species, and abiotic conditions [16, 17]. Breeding crop varieties with enhanced volatile production represents a promising avenue for conservation biological control that remains underexplored in most major crops.

Classical biological control programs have produced some of the most dramatic success stories in pest management history. The introduction of Cotesia flavipes from Pakistan to control the spotted stem borer (Chilo partellus) in East Africa, the use of Aphelinus mali to control woolly apple aphid (Eriosoma lanigerum) globally, and the suppression of cassava mealybug (Phenacoccus manihoti) by Anagyrus lopezi across sub-Saharan Africa exemplify the potential for lasting, self-sustaining pest suppression through classical biocontrol [18]. However, classical biocontrol programs also carry risks including non-target effects on native insect species, which necessitate rigorous host specificity testing before agent release [19].

The mass production of parasitoids for augmentative release programs has benefited substantially from advances in artificial diet formulations, controlled environment rearing facilities, and quality control protocols for assessing the vigor and parasitism capacity of commercially produced parasitoids. Ensuring that commercially released parasitoids retain adequate fitness for field establishment, foraging, and parasitism following mass rearing under artificial conditions is a persistent quality assurance challenge, particularly as production scales increase [20]. Genetic diversity management in mass-reared parasitoid colonies is increasingly recognized as a critical factor in maintaining the long-term fitness and adaptability of biological control agent populations.

Venom proteins produced by endoparasitoid wasps play a pivotal role in regulating host physiology and immune responses during parasitism. Parasitoid venoms and polydnaviruses disrupt host hemocyte function, suppress melanization responses, and modulate host endocrine signaling in ways that create a permissive internal environment for parasitoid larval development. Characterization of these immune-suppressive mechanisms at the molecular level is revealing new targets for biotechnological manipulation of host-parasitoid interactions and may ultimately enable the engineering of parasitoid strains with enhanced capacity to overcome host immune defenses under diverse field conditions [21].

Table 1. Comparative profile of major biological control agent categories: taxonomy, mode of action, host specificity, deployment strategy, optimal conditions, commercial status.

Parameter	Parasitoids	Predatory Arthropods	Entomopathogenic Fungi (EPF)	Microbiome-Mediated Agents
Representative taxa	Hymenoptera: Braconidae, Ichneumonidae, Eulophidae, Trichogrammatidae; Diptera: Tachinidae	Coleoptera: Coccinellidae; Neuroptera: Chrysopidae; Acari: Phytoseiidae, Stigmaeidae; Araneae; Hemiptera: Miridae	*Beauveria bassiana*, *Metarhizium anisopliae*, *Isaria fumosorosea*, *Lecanicillium muscarium*, *Akanthomyces lecanii*	*Bacillus thuringiensis*, *Chromobacterium subtsugae*, *Serratia entomophila*, baculoviruses, rhizobacteria (*Bacillus* spp., *Pseudomonas* spp., *Trichoderma* spp.), engineered gut symbionts
Mode of action	Larval/pupal/egg parasitism; venom proteins and polydnaviruses suppress host immunity, melanization, and endocrine signaling	Direct predation (consumption of multiple prey items); generalist and specialist foraging strategies	Cuticular adhesion → germination → enzymatic and mechanical penetration → hemocoel proliferation → host death via nutrient depletion, toxins, and tissue destruction; endophytic systemic protection	Bt Cry proteins form midgut pores disrupting osmotic balance; rhizobacteria induce JA/SA-mediated systemic resistance; gut microbiome disruption causes dysbiosis; paratransgenesis delivers insecticidal effectors
Host specificity	Generally narrow to moderate; co-evolved host ranges; some species highly specific	Broad to moderate; generalist predators consume diverse prey; risk of intraguild predation and non-target effects	Broad host range for *B. bassiana* (hundreds of species); *M. anisopliae* effective against soil-dwelling pests; some strains more specific	Bt subspecies vary in specificity (Lepidoptera, Coleoptera, Diptera); baculoviruses highly host-specific; *S. entomophila* highly specific to grass grub
Deployment strategy	Classical (importation), augmentative (mass rearing	Augmentative releases (e.g., *Hippodamia*	Inundative and augmentative spray applications;	Bt sprays and transgenic crops; seed/soil inoculation with rhizobacteria consortia; dsRNA-mediated RNAi; bait stations for

	and release), conservation (habitat management)	*convergens*, *Harmonia axyridis*, *Chrysoperla* spp.); conservation biological control via field margins, beetle banks, hedgerows, insectary strips; banker plant systems	seed treatment; root inoculation; foliar application; endophytic colonization	paratransgenesis; baculovirus sprays
Optimal conditions	Temperature 20–30°C; RH 50–80%; adequate host egg/larval density; presence of floral resources and shelter; low hyperparasitoid pressure	Diverse landscape with semi-natural habitat; moderate temperatures; alternative prey and floral resources; reduced tillage; low broad-spectrum insecticide use	RH >90% for conidial germination; moderate temperatures (20–28°C); protection from UV radiation; oil-based formulations for moisture retention; endophytic strains for systemic protection	Soil moisture and organic matter for rhizobacteria; appropriate gut pH and microbial community for Bt and RNAi; UV protection for baculoviruses; stable temperature for paratransgenesis
Commercial status	Widely commercialized; *Trichogramma* spp. used on >32 million ha annually; numerous augmentative release products globally	Extensively commercialized; coccinellids, lacewings, and predatory mites available globally; banker plant systems increasingly adopted in greenhouse horticulture	Numerous registered mycoinsecticide products globally; *B. bassiana* and *M. anisopliae* dominate; >USD 2 billion annual biopesticide market share	Bt is the most commercially successful microbial insecticide (>USD 2 billion annually); *C. subtsugae* commercialized in USA; *S. entomophila* registered in New Zealand; baculoviruses registered in multiple countries

3. Predatory Arthropods in Agricultural Pest Suppression

Predatory arthropods, including beetles, bugs, lacewings, lady beetles, spiders, and predatory mites, constitute a functionally diverse and

ecologically important guild of natural enemies in agricultural systems. Unlike parasitoids, predators typically consume multiple prey items throughout their lives and often have broader prey ranges, which both extends their utility as biocontrol agents and introduces complexity regarding intraguild predation and non-target effects [22]. The effectiveness of predatory arthropods as biocontrol agents depends on prey density, predator foraging behavior, and the structure of the agricultural landscape in which they operate.

Coccinellid beetles (lady beetles) are among the most familiar and widely recognized predatory biocontrol agents, consuming large numbers of aphids, scale insects, and other soft-bodied pests during both larval and adult life stages [23]. Commercial augmentative releases of coccinellids, particularly Hippodamia convergens and Harmonia axyridis, have been widely used, though their effectiveness in field settings is often limited by emigration from release sites and displacement of native coccinellid species by invasive congeners. Green lacewings (Chrysopidae), whose voracious larvae consume aphids, thrips, whiteflies, and small caterpillars, are commercially produced for augmentative release in greenhouse and field crops, with established efficacy against a range of soft-bodied pest species [24].

Conservation biological control strategies that enhance predator populations through habitat management have gained substantial research attention and practical adoption in recent decades. Flowering field margins, beetle banks, hedgerows, and insectary plant strips within and around crop fields provide shelter, overwintering sites, and alternative prey and food resources for predatory arthropods during periods when pest density is low [25, 26]. A meta-analysis of 132 studies found that habitat management interventions significantly increased predator abundance and diversity in adjacent crops, with downstream effects on pest suppression and crop yield in the majority of cases. The spatial configuration of semi-natural habitats relative to crop fields modulates these effects, with greater benefits observed when natural habitats are distributed throughout the landscape rather than concentrated at field boundaries.

Predatory mites of the families Phytoseiidae and Stigmaeidae are indispensable components of biological control programs in greenhouse horticulture and perennial fruit crops, where they suppress populations of phytophagous mites, thrips, and whiteflies [27]. Amblyseius swirskii, Phytoseiulus persimilis, and Neoseiulus californicus are among the most commercially successful predatory mite species, widely deployed in augmentative biocontrol programs. The compatibility of predatory mites with selective pesticides and other biocontrol agents is a key consideration in IPM program design, as predatory mites are highly sensitive to many broad-spectrum insecticides and acaricides [28].

The role of spiders as generalist predators in agricultural systems has historically been underestimated relative to more conspicuous natural enemies. Spiders are among the most numerically abundant predatory arthropods in most agricultural habitats and collectively consume substantial numbers of herbivorous pest insects through both web-based and active hunting strategies. Conservation measures that maintain structural habitat complexity, including reduced tillage, retention of crop residues, and maintenance of field margins with diverse vegetation, support spider community diversity and abundance, with measurable effects on aphid and leafhopper pest suppression in cereal and vegetable crops [29].

Mirid bugs of the family Miridae have attracted increasing research interest as predatory biocontrol agents in fruit and vegetable crops, where species such as Macrolophus pygmaeus and Nesidiocoris tenuis play important roles in suppressing whitefly and other pest populations in tomato and pepper cultivation [30]. These zoophytophagous species, which feed on both prey insects and plant tissue, can sustain populations in the absence of prey by consuming plant sap, enabling them to persist in crops at low pest densities when other obligate predators would emigrate or starve. This characteristic makes them particularly valuable as early-season

biocontrol agents capable of preventing pest population establishment rather than merely reacting to outbreak conditions.

Banker plant systems, in which commercially produced plants infested with non-pest prey species are deployed within crops to sustain predator and parasitoid populations between pest outbreaks, represent an innovative application of conservation biological control principles in protected horticulture. Barley plants infested with bird cherry-oat aphid (Rhopalosiphum padi) have been used to maintain Aphidius colemani parasitoid populations in tomato greenhouses, while pepper plants infested with Ephestia kuehniella eggs serve as banker plants for Orius spp. predators in sweet pepper crops. The cost-effectiveness and scalability of banker plant systems have been demonstrated across multiple crop-pest-natural enemy combinations, and their adoption in commercial greenhouse production is growing [31].

4. Entomopathogenic Fungi: Mechanisms, Formulations, and Field Applications

Entomopathogenic fungi (EPF) are among the most diverse and promising biological control agents available for insect pest management. Unlike bacterial and viral entomopathogens, EPF infect insects through the cuticle rather than requiring ingestion, enabling them to target sucking insects and other pests that are difficult to control with stomach poisons [32]. The infection process begins with adhesion of fungal conidia to the host cuticle, followed by germination, penetration of the integument through mechanical force and enzymatic degradation, proliferation within the hemocoel as blastospores, and ultimately host death through a combination of nutrient depletion, toxin production, and physical destruction of tissues [33].

Beauveria bassiana and Metarhizium anisopliae are the most extensively studied and commercially developed EPF species, with numerous registered mycoinsecticide products available globally [34]. B. bassiana has a broad host range encompassing hundreds of insect and mite species and has been commercialized for control of whiteflies, thrips, aphids, weevils, and various lepidopteran larvae in both greenhouse and field settings. M. anisopliae is particularly effective against soil-dwelling pests including white grubs (Coleoptera: Scarabaeidae) and has shown efficacy against adult mosquitoes when applied to resting sites [35]. Additional species including Isaria fumosorosea, Lecanicillium muscarium, and Akanthomyces lecanii are registered for use against specific pest groups in several countries [36].

The efficacy of EPF under field conditions is strongly influenced by abiotic factors, particularly temperature, relative humidity, and ultraviolet radiation. Optimal conidial germination and infection for most EPF species requires relative humidity above 90%, and conidial viability is rapidly reduced by exposure to ultraviolet radiation and desiccation [37, 38]. Formulation technology plays a crucial role in extending the field persistence and efficacy of EPF products. Oil-based formulations provide substantially better UV protection and moisture retention than aqueous suspensions, while encapsulation in polymer matrices can extend shelf life and improve environmental stability. The development of EPF strains with enhanced tolerance to heat and UV radiation through selection and mutagenesis programs represents a promising strategy for improving field performance under challenging environmental conditions.

An emerging and particularly promising dimension of EPF research concerns their capacity to act as plant endophytes. Several Beauveria and Metarhizium strains can colonize plant tissues systemically following seed treatment, root inoculation, or foliar application, providing systemic protection against herbivorous insects without direct contact between the fungus and the pest [39]. Endophytic EPF have been shown to reduce herbivore feeding, growth, and reproduction across a range of crop-pest combinations, and may also prime plant immunity against other biotic stressors [40]. The ecological implications of widespread EPF

endophytism in agricultural systems are not yet fully understood, but the phenomenon opens transformative possibilities for integrated pest and disease management.

The compatibility of EPF with other pest management tools is a critical consideration in IPM program design. Several studies have demonstrated synergistic effects when EPF are combined with parasitoids or sublethal doses of selective insecticides, with combined treatments providing pest suppression exceeding that of either agent alone [41]. Conversely, many broad-spectrum fungicides are incompatible with EPF, and their indiscriminate use can eliminate EPF inoculum from agricultural soils. Systematic assessment of EPF compatibility with commonly used agrochemicals is therefore essential for the rational integration of EPF into existing crop protection programs [42].

The genus Metarhizium has attracted particular attention in recent years because of its dual role as both an insect pathogen and a rhizosphere colonizer that can promote plant growth and nutrient acquisition. Strains of M. robertsii and M. brunneum have been shown to colonize plant roots, transfer nitrogen from insect cadavers to host plants, and induce systemic resistance against both insect herbivores and fungal pathogens [43]. This multifunctionality positions Metarhizium as an exceptionally versatile component of biological pest management programs that simultaneously deliver plant health benefits beyond direct insect suppression.

Sexual recombination and genetic improvement of EPF strains through both classical breeding approaches and modern genetic tools are active areas of research aimed at enhancing the efficacy, environmental stability, and host range of commercial mycoinsecticide candidates. Protoplast fusion between strains with complementary traits, including high virulence and UV tolerance, has produced hybrid strains with improved performance profiles in laboratory evaluations. CRISPR-based gene editing is beginning to be applied to EPF to modify virulence factors, secondary metabolite profiles, and stress tolerance genes, though regulatory acceptance of genetically modified biocontrol agents remains a significant constraint on commercial development [44].

5. Microbiome-Mediated Pest Suppression

The recognition that microbial communities associated with both plants and insects play fundamental roles in mediating pest-plant interactions has opened new frontiers in biological control research. Microbiome-mediated pest suppression encompasses several distinct mechanisms: the direct entomopathogenic action of bacteria such as Bacillus thuringiensis; the indirect suppression of insect pests through plant microbiome-mediated induction of plant defenses; and the disruption of insect gut microbiomes to impair pest physiology, immunity, or pesticide detoxification [45]. These mechanisms operate at different scales and can be harnessed in complementary ways within IPM systems.

Bacillus thuringiensis (Bt), a spore-forming bacterium that produces crystal (Cry) proteins toxic to specific insect orders, remains the most commercially successful microbial insecticide in history, with global sales exceeding USD 2 billion annually [46]. Cry proteins bind to specific receptors in the midgut epithelium of susceptible insects, forming pores that disrupt osmotic balance and cause rapid larval death. Different Bt subspecies and strains produce distinct Cry protein profiles with different host ranges, enabling relatively selective targeting of lepidopteran, coleopteran, or dipteran pests depending on the product used [47]. The expression of Bt Cry genes in transgenic crops has enabled season-long pest suppression without spray applications, but has also accelerated the evolution of resistance in target pests where refuge strategies have been inadequately implemented [48].

The soil microbiome represents a powerful but underexploited resource for the biological suppression of soil-dwelling insect pests and for priming plant immunity against foliar pests. Rhizosphere bacteria including plant growth-promoting rhizobacteria in genera such as

Bacillus, Pseudomonas, and Trichoderma can induce systemic resistance in host plants against herbivorous insects, reducing their fitness through the activation of jasmonic acid and salicylic acid signaling pathways [49, 50]. Inoculation of seeds or soil with rhizobacteria consortia has been shown to reduce aphid, whitefly, and caterpillar damage in field crops while simultaneously enhancing nutrient acquisition and abiotic stress tolerance.

The insect gut microbiome has emerged as a critical determinant of insect physiology, immunity, detoxification capacity, and fitness. Gut microbiome disruption, through the ingestion of compounds that alter microbial community composition or function, represents a novel and potentially highly selective approach to pest management [51]. Recent research has demonstrated that dsRNA-mediated RNA interference can induce dysbiosis of the insect gut microbiome, with secondary microbial overgrowth contributing substantially to insect mortality beyond the direct effects of gene silencing [52]. These findings suggest that RNAi and microbiome manipulation may be more deeply intertwined than previously appreciated, with implications for both the development of RNAi-based pesticides and the interpretation of their field efficacy [53].

Entomopathogenic bacteria beyond Bt are attracting growing research interest as potential biocontrol agents. Chromobacterium subtsugae produces multiple insecticidal compounds with activity against diverse pest species including whiteflies and fall armyworm, and has been commercialized in the United States [54]. Serratia entomophila is registered in New Zealand for the control of grass grub (Costelytra zealandica) and represents an example of a highly host-specific bacterial biocontrol agent developed for a soil pest niche where EPF and other agents are less effective [55]. The expanding application of metagenomics and synthetic biology to the soil and insect gut microbiome is expected to accelerate the discovery of novel biocontrol-relevant microorganisms and compounds in the coming decade.

Viral entomopathogens, particularly baculoviruses, occupy an important niche in biological control programs targeting caterpillar pests of forest and horticultural crops. Nucleopolyhedroviruses and granuloviruses are highly host-specific, with no known adverse effects on non-target vertebrates or beneficial invertebrates, and several products including *Helicoverpa armigera nucleopolyhedrovirus* and Cydia pomonella granulovirus are registered for commercial use in multiple countries [56]. Advances in baculovirus formulation, including encapsulation to protect occlusion bodies from UV degradation, and the identification of synergistic compounds that enhance baculovirus virulence, are improving the cost-effectiveness and reliability of viral biocontrol agents in field applications.

Paratransgenesis, the use of genetically modified symbionts to deliver biocontrol effectors to pest insects via their native microbiome, represents a frontier approach to microbiome-mediated pest management with particular promise for vector control. In this strategy, gut bacteria naturally associated with the target pest are engineered to express insecticidal peptides, enzyme inhibitors, or pathogen-blocking molecules, and are then reintroduced into pest populations through bait stations or environmental inoculation. Proof-of-concept studies in mosquitoes and sand flies have demonstrated the technical feasibility of paratransgenesis for vector control, and the approach is advancing toward field trials in several research programs globally [57].

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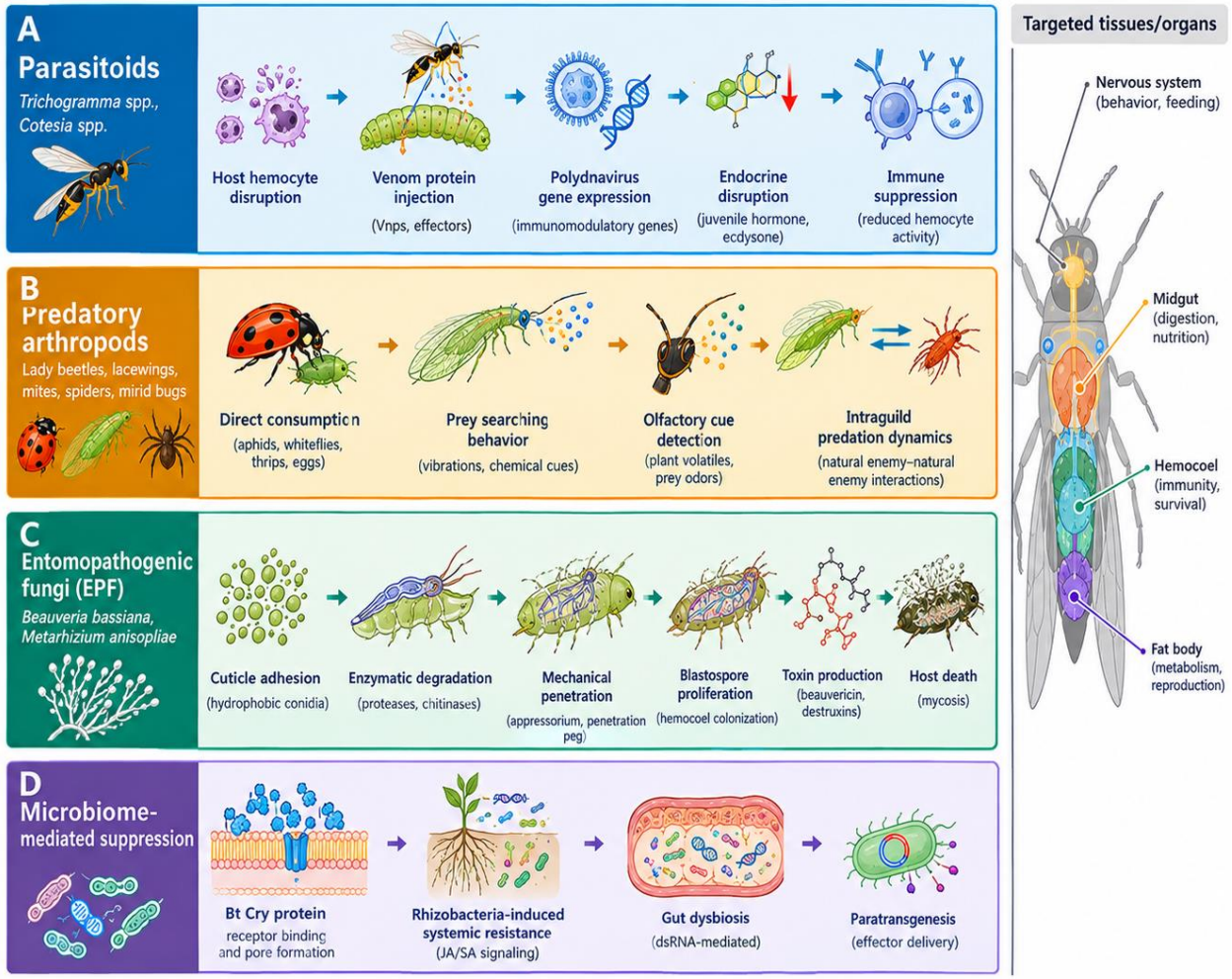


Fig. 2 Molecular and ecological mechanisms of pest suppression by major biological control agent categories. A Parasitoid immune suppression via venom proteins and polydnaviruses; B Predatory arthropod foraging and consumption dynamics; C Entomopathogenic fungal infection cascade including enzymatic penetration and mycotoxin production; D Microbiome-mediated mechanisms (Bt Cry protein pore formation, rhizobacteria-induced systemic resistance, dsRNA-mediated gut dysbiosis, paratransgenesis). Shared host insect silhouette (right) indicates target tissues: nervous system, midgut, hemocoel, and fat body.

6. Integration of Biological Control into IPM Systems

Integrated Pest Management represents the dominant paradigm for sustainable crop protection, combining biological, cultural, physical, and chemical control methods within a framework guided by economic thresholds and ecological monitoring [58]. Biological control agents are most effective when deployed within IPM systems that minimize disruptive pesticide applications, provide habitat for natural enemies, and maintain diverse agricultural landscapes that support year-round natural enemy populations. The design of effective biocontrol-centered IPM programs requires a thorough understanding of the ecological interactions among crops, pests, natural enemies, and the physical and chemical environment [59].

A bibliometric analysis of conservation biological control and IPM research published between 2000 and 2025 documented a sustained increase in publications integrating multiple natural

enemy groups and habitat management strategies, reflecting growing recognition of the complementarity among different biocontrol agents and tactics [60]. The simultaneous use of multiple biocontrol agents introduces the risk of intraguild predation, the consumption of one natural enemy by another, which can reduce overall biocontrol efficacy if not carefully managed. Evidence suggests that intraguild predation is most likely to reduce biocontrol efficacy when all natural enemies target the same pest developmental stage and when prey density is low [61].

The development of selective insecticides with minimal impact on natural enemies has been a significant advance in enabling the integration of chemical and biological control within IPM programs. Insect growth regulators, diamides, spinosyns, and some neonicotinoids applied as seed treatments rather than foliar sprays are among the insecticide classes with the most favorable selectivity profiles relative to most biocontrol agents [62]. Pest resistance management, which requires maintaining susceptible insect populations through refuge strategies, also creates opportunities for biological control agents to suppress pest populations in refuge areas, potentially slowing resistance evolution [63].

Economic considerations are central to the adoption of biological control by farmers, who must weigh the costs of biocontrol agent procurement, application infrastructure, and monitoring against the economic benefits of pest suppression, reduced insecticide expenditure, and avoided resistance development [64]. Life cycle assessment studies have consistently demonstrated the superior environmental performance of biocontrol-based IPM systems relative to conventional insecticide-based management, but translating these environmental benefits into economic signals that reach individual farmers remains a challenge. Policy instruments including payments for ecosystem services, differential pesticide taxes, and preferential regulatory pathways for biopesticides have been proposed as means of correcting market failures that currently undervalue biological control [65].

Farmer extension services and knowledge transfer represent critical but frequently underinvested links in the adoption of biological control within IPM programs. Many growers, particularly in smallholder farming systems in developing countries, lack access to reliable information on the identification of natural enemies, monitoring protocols for biological control efficacy assessment, and the agronomic conditions that favor or constrain biocontrol agent performance [66]. Digital extension platforms, including smartphone-based pest identification tools, decision support applications, and online advisory services, are emerging as scalable channels for delivering IPM knowledge to underserved farming communities, and their integration with local extension networks offers a promising model for accelerating biological control adoption at scale.

The landscape context of individual farms profoundly influences the effectiveness of on-farm biological control interventions. Farms embedded within diverse, heterogeneous landscapes that contain abundant semi-natural habitat tend to support higher populations of natural enemies and exhibit stronger biological control of pest species than farms in simplified, homogeneous agricultural landscapes. This landscape effect means that the benefits of on-farm conservation biological control measures, such as field margin establishment and reduced pesticide use, are amplified when implemented collectively across networks of neighboring farms rather than in isolation on individual holdings. Area-wide IPM programs that coordinate pest management across entire farming districts therefore have the potential to generate biological control outcomes substantially exceeding what any individual farmer could achieve alone [67].

Table 2. Selected case studies of successful biological control programs integrated within IPM systems: pest identity, crop, region, agent(s) deployed, strategy type, suppression outcomes.

Pest Species	Crop	Region	Biocontrol Agent(s)	Strategy Type	Suppression Outcome
Icerya purchasi **(cottony cushion scale)**	Citrus	California, USA	*Rodolia cardinalis* (vedalia beetle)	Classical	>95% suppression; successful establishment and long-term control
Chilo partellus **(spotted stem borer)**	Maize, sorghum	East Africa	*Cotesia flavipes*	Classical	30–60% reduction in stem borer damage; established across multiple countries
Phenacoccus manihoti **(cassava mealybug)**	Cassava	Sub-Saharan Africa	*Anagyrus lopezi*	Classical	80–90% suppression; saved an estimated USD 1–2 billion in crop losses
Plutella xylostella **(diamondback moth)**	Vegetables (cabbage, broccoli)	Southeast Asia, Australia	*Cotesia plutellae*, *Diadegma semiclausum*, *Trichogramma* spp.	Augmentative + Conservation	40–70% reduction in larval density; reduced insecticide applications by 30–50%
Bemisia tabaci **(whitefly)**	Tomato, pepper, cucumber	Mediterranean region, greenhouse	*Nesidiocoris tenuis*, *Macrolophus pygmaeus*, *Amblyseius swirskii*, *Beauveria bassiana*	Augmentative + Conservation	70–90% whitefly suppression; comparable to chemical control in greenhouse trials
Spodoptera frugiperda **(fall armyworm)**	Maize	Africa, Asia	*Trichogramma* spp., *Cotesia* spp., *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*	Augmentative + Microbial	30–60% reduction in larval damage; variable across agroecological zones
Helicoverpa armigera **(cotton bollworm)**	Cotton, chickpea, tomato	India, Australia, China	*Trichogramma chilonis*, *Habrobracon hebetor*, *Helicoverpa armigera* NPV, *Bt* transgenic crops	Augmentative + Microbial + Transgenic	50–80% reduction in boll damage; Bt cotton reduced insecticide sprays by 50–70%
Cydia pomonella **(codling moth)**	Apple, pear, walnut	Europe, North America	*Cydia pomonella* granulovirus (CpGV), *Tricho*	Augmentative + Microbial	60–90% fruit damage reduction; CpGV effective in organic orchards

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			gramma spp., *Beauveria bassiana*		
Costelytra zealandica **(grass grub)**	Pasture	New Zealand	*Serratia entomophila*	Augmentative (microbial)	50–80% larval mortality; established in soil populations
Frankliniella occidentalis **(western flower thrips)**	Sweet pepper, cucumber, ornamental crops	Global (greenhouse)	*Amblyseius swirskii*, *Neoseiulus cucumeris*, *Beauveria bassiana*, *Metarhizium anisopliae*	Augmentative + Microbial	60–85% thrips suppression; combined predator + EPF treatments outperform single agents
Aphis gossypii **(cotton aphid)**	Cotton, vegetables	China, USA, Brazil	*Harmonia axyridis*, *Chrysoperla* spp., *Aphidius colemani*, *Beauveria bassiana*	Augmentative + Conservation	40–75% aphid suppression; conservation strips increased predator abundance 2–3 fold
Tuta absoluta **(tomato leafminer)**	Tomato	South America, Europe, Africa	*Nesidiocoris tenuis*, *Trichogramma achaeae*, *Bacillus thuringiensis*, *Beauveria bassiana*	Augmentative + Microbial	50–80% reduction in leaf damage; IPM programs reduced insecticide use by 40–60%

Note: EPF = entomopathogenic fungi; Bt = *Bacillus thuringiensis*; NPV = nucleopolyhedrovirus; CpGV = *Cydia pomonella* granulovirus; IPM = Integrated Pest Management. Suppression percentages are reported from published field trials or program reviews and represent typical ranges observed across multiple studies; actual outcomes vary with local conditions, pest pressure, and implementation quality.

7. Challenges and Limitations of Biological Control

Despite compelling evidence for the efficacy of biological control agents under favorable conditions, achieving consistent and reliable pest suppression under the variable environmental conditions typical of agricultural production remains a persistent challenge. The performance of biological control agents is sensitive to temperature, humidity, crop architecture, pest density, and the composition of the surrounding agricultural landscape, all of which vary across space and time in ways that are difficult to predict and control [68]. The gap between laboratory bioassay efficacy and field performance is a recurring concern with EPF and microbial biocontrol agents, which may be highly effective under optimal controlled conditions but significantly less so under field conditions where abiotic stress, competing microorganisms, and UV degradation reduce their viability [69].

Regulatory frameworks for the registration and commercialization of biological control agents vary substantially among countries and regions, creating significant barriers to market development and international trade in biocontrol products [70]. In many jurisdictions, biological control agents are regulated under frameworks designed primarily for synthetic chemicals, requiring data packages and risk

assessments that are inappropriate for living organisms and do not reflect their fundamentally different risk profiles. Streamlined, science-based regulatory pathways that recognize the biological specificity and environmental safety of well-characterized biocontrol agents would significantly accelerate the commercial development of this sector.

Climate change poses multifaceted challenges for the deployment of biological control. Warming temperatures are expected to accelerate the development and reproduction of many insect pests, potentially shortening the window during which biocontrol agents can suppress pest populations below damaging thresholds [71]. Changes in the phenological synchrony between pests and their natural enemies, driven by differential responses to temperature and photoperiod, may disrupt the tritrophic interactions on which effective biocontrol depends. Screening biocontrol agent populations and strains for thermotolerance, and selecting or evolving strains with enhanced performance at elevated temperatures, will be important priorities for maintaining the effectiveness of biological control under future climate scenarios [72].

The durability of resistance to biological control agents is generally considered superior to that of synthetic insecticides, but it is not unlimited. Resistance to Bt toxins has evolved in field populations of several lepidopteran pests including Plutella xylostella, Spodoptera frugiperda, and Helicoverpa zea, driven primarily by selection pressure from Bt transgenic crops rather than spray applications [73]. Proactive resistance management strategies for biological control agents, analogous to the insecticide resistance management frameworks already in place for conventional pesticides, are needed to preserve the long-term utility of key biocontrol tools. Pyramiding of multiple Bt toxins with different receptor specificities, rotation among biocontrol agent types, and integration with non-toxin-based control methods are among the resistance management tactics currently being evaluated.

Non-target effects of introduced biological control agents on native species remain an important ecological concern, particularly for classical biocontrol programs that introduce exotic natural enemies with the intention of permanent establishment. Historical cases, including the negative impacts of introduced parasitoids on non-target Lepidoptera in Hawaii and the spread of the multicolored Asian lady beetle (Harmonia axyridis) beyond its intended range, have established the importance of rigorous pre-release risk assessment [74]. Modern classical biocontrol programs apply substantially more rigorous host specificity testing than was practiced in earlier decades, and the risk of unintended ecological consequences has been substantially reduced as a consequence, though it can never be entirely eliminated for any self-sustaining introduced organism.

8. Future Research Directions and Emerging Frontiers

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, are transforming the discovery and characterization of biological control agents and the mechanisms underlying their interactions with target pests [68]. Comparative genomics of EPF species has revealed the genetic basis of host range, virulence, and environmental stress tolerance, enabling informed selection of candidate strains for biocontrol agent development. Transcriptomic studies of parasitoid-host interactions have elucidated the sophisticated mechanisms by which parasitoids suppress host immunity, opening possibilities for biotechnological enhancement of parasitoid performance.

Nanotechnology offers exciting possibilities for enhancing the delivery, stability, and efficacy of microbial biocontrol agents in the field. Encapsulation of EPF conidia or Bt spore-crystal complexes in nanoparticle matrices can substantially improve UV stability, moisture retention, and target adhesion, potentially overcoming some of the major limitations of current formulation technologies [75].

Nanoparticle-mediated delivery of dsRNA for RNAi-based pest control is an area of particularly rapid development, with polymer and lipid nanoparticles demonstrating enhanced dsRNA stability and insect uptake in laboratory assays. However, the environmental fate and ecotoxicological implications of agricultural nanotechnologies require thorough evaluation before widespread deployment.

Artificial intelligence and precision agriculture technologies are creating new opportunities for the targeted and timely deployment of biological control agents. Machine learning algorithms trained on satellite imagery, weather data, and historical pest monitoring records can predict pest outbreak risk with increasing accuracy, enabling proactive rather than reactive biocontrol agent deployment [76]. Autonomous robotic platforms capable of identifying and targeting individual pest insects or releasing biocontrol agents at precise locations within fields are transitioning from research tools to commercial products, and may fundamentally transform the economics of augmentative biocontrol by reducing application costs.

Synthetic biology approaches offer the prospect of engineering microorganisms with enhanced or novel biocontrol properties beyond what is achievable through conventional strain selection. Expression of novel insecticidal proteins in EPF, engineering of Bt strains with broadened toxin spectra or improved gut receptor binding, and the construction of synthetic microbial consortia with complementary and synergistic biocontrol functions are among the avenues being actively explored [77]. Rigorous environmental risk assessment and public engagement will be essential prerequisites for the responsible development and deployment of engineered biocontrol agents in agricultural systems.

The integration of biological control with digital agriculture infrastructure, including sensor networks, drone-based monitoring platforms, and farm management software, represents a near-term opportunity to substantially improve the precision and cost-effectiveness of augmentative biocontrol programs. Real-time pest density monitoring using automated traps equipped with image recognition software can trigger precision biocontrol agent releases at optimal timing, reducing the cost of unnecessary applications while ensuring that releases occur when conditions for establishment and pest suppression are most favorable. Connecting these digital pest monitoring systems with supply chains for commercially produced natural enemies, enabling rapid delivery of augmentative releases in response to automated outbreak alerts, is a practical integration that is within reach of current technology [78].

9. Conclusion

Biological control is no longer an aspirational alternative to chemical pest management but an indispensable component of sustainable agriculture systems that are under mounting pressure from insecticide resistance, regulatory attrition of chemical tools, and the ecological imperative to reduce pesticide use. The four categories of biological control agents reviewed here, parasitoids, predatory arthropods, entomopathogenic fungi, and microbiome-based agents, each contribute unique and complementary mechanisms of pest suppression that, when strategically integrated within IPM frameworks, can provide robust and durable pest management outcomes.

Realizing the full potential of biological control in global agriculture will require sustained investment in fundamental research to elucidate the ecological and molecular mechanisms underlying natural enemy effectiveness; applied research to develop and optimize biocontrol agent formulations, mass rearing systems, and deployment strategies; and policy innovation to create market conditions and regulatory frameworks that enable biological control to compete on equitable terms with synthetic insecticides. The convergence of omics technologies, nanotechnology, artificial intelligence, and precision agriculture with classical biological control principles creates an unusually rich opportunity landscape for the

transformation of pest management in the twenty-first century.

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