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Biological Control of Agricultural Insect Pests: Recent Advances, Challenges and Future Perspectives

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Agricultural insect pests remain a major constraint to crop productivity, farm profitability and food security. Intensive reliance on conventional insecticides has contributed to resistance, resurgence, disruption of natural enemies and concerns regarding environmental and human health. Biological control provides an ecologically based alternative by using predators, parasitoids, entomopathogenic microorganisms and other naturally occurring antagonists to suppress pest populations. This review discusses recent advances in classical, conservation and augmentative biological control, with particular emphasis on parasitoids, predators, entomopathogenic fungi, bacteria, viruses and nematodes. Advances in mass rearing, molecular identification, genomics, microbiome research, semiochemicals, precision application and digital monitoring are creating new opportunities to improve the reliability and scalability of biological control. Recent work on parasitoids in India, microbial biopesticides and proactive biological control of invasive pests demonstrates the growing importance of biological approaches within integrated pest management. Major challenges include inconsistent field efficacy, climatic sensitivity, non-target effects, production and quality-control constraints, regulatory requirements, farmer awareness, economics and compatibility with chemical pesticides. Future biological control programs should integrate ecological knowledge with genomics, artificial intelligence, improved formulation, climate-resilient agents and decision-support systems. Strengthening mass production, quality assurance, extension, farmer participation and evidence-based regulation will be essential for translating biological control innovations into durable crop-protection solutions.

Introduction

Insect pests are persistent components of agricultural ecosystems and can cause substantial losses by feeding on crop tissues, transmitting plant pathogens and reducing the quality and marketability of agricultural commodities. Conventional chemical insecticides have provided rapid suppression of many pests, but their repeated and indiscriminate use can select resistant populations, disrupt beneficial organisms and increase environmental risks. Biological control is consequently an important component of integrated pest management (IPM), where the objective is not complete eradication but maintaining pest populations below economically damaging levels. FAO describes IPM as an ecosystem approach that combines management strategies while minimizing pesticide use and recommends making use of beneficial predators, parasites and competitors as part of pest suppression. Biological control broadly involves the use, conservation or manipulation of living organisms and their products to suppress pest populations. The principal categories are classical biological control, conservation biological control and augmentative biological control. Classical control introduces and establishes a suitable natural enemy against an invasive pest; conservation control protects and enhances natural enemies already present in the agroecosystem; and augmentative control increases natural-enemy abundance through periodic or repeated releases. Microbial biopesticides based on bacteria, fungi, viruses and nematodes complement these approaches and can provide relatively target-specific pest suppression. Recent research is moving biological control beyond the traditional release of natural enemies. Genomics, molecular ecology, microbiome studies, automated mass rearing, precision application, improved formulations and digital monitoring are increasingly being used to identify effective agents and optimize their deployment. A 2025 review on genomics of insect natural enemies highlighted the growing availability of genomic resources for identifying genes associated with desirable biological-control traits, although translating these discoveries into field performance remains an important research challenge. The present review summarizes recent advances, major limitations and future perspectives for biological control of agricultural insect pests.

Major Approaches to Biological Control

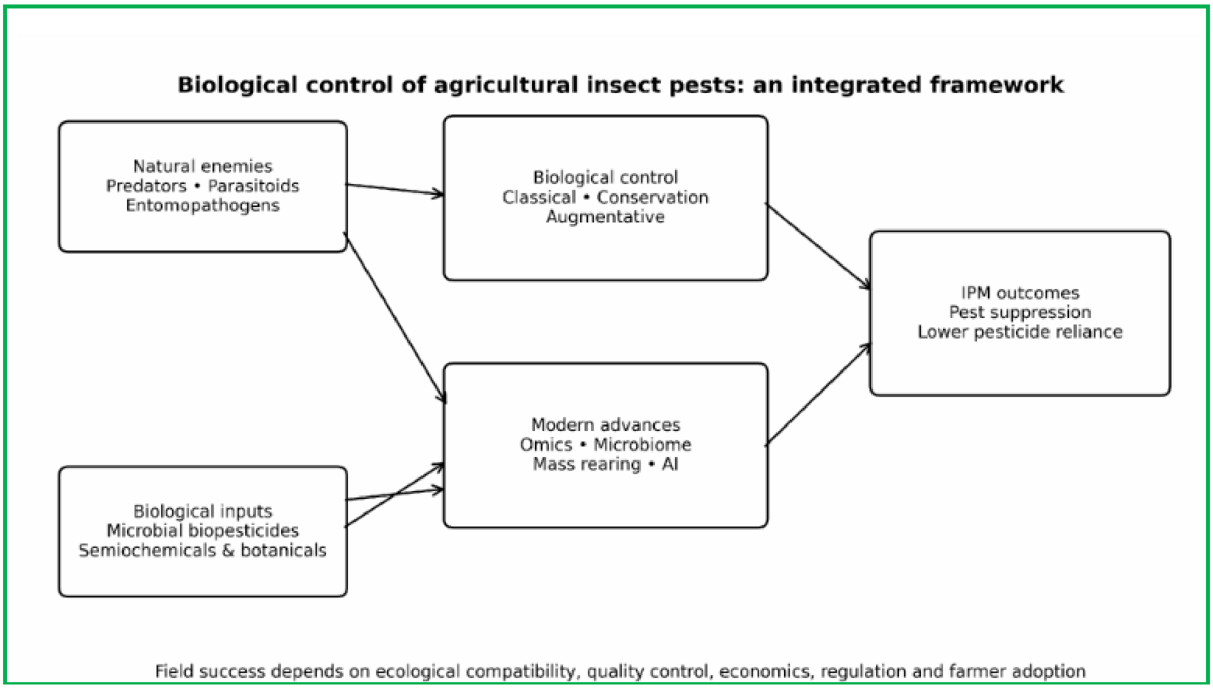

Figure: Conceptual framework showing major biological-control agents, recent technological advances and their integration into sustainable insect pest management

Classical biological control is particularly important for invasive insect pests that arrive in a new region without their co-evolved natural enemies. The approach involves exploration, risk assessment, host-specificity testing, quarantine, release and post-release evaluation. When a natural enemy establishes successfully, it can provide long-term suppression over large areas with relatively limited recurrent inputs. Recent discussions of proactive biological control emphasize that action before an invasive pest becomes widespread may reduce long-term economic and environmental damage, provided that risks and benefits are carefully evaluated. Conservation biological control focuses on protecting natural enemies already present in agricultural landscapes. Habitat diversification, flowering strips, reduced disturbance, selective pesticide use, refuge habitats and provision of alternative food resources can increase predator and parasitoid abundance. This approach is often inexpensive because it works with naturally occurring ecological processes. However, its success depends strongly on crop type, landscape structure, seasonal availability of resources and compatibility with farming practices. Augmentative biological control involves the mass production and periodic release of predators, parasitoids or pathogens. Inoculative releases aim to establish or maintain natural enemies early in the crop season, whereas inundative releases use relatively large numbers to obtain immediate suppression. Commercial production of parasitoids such as Trichogramma species, predatory mites, lacewings and other beneficial organisms has made augmentative control practical in several cropping systems. The success of releases depends on biological quality, synchronization with the pest, release density, weather conditions and crop architecture.

Predators and Parasitoids as Biocontrol Agents

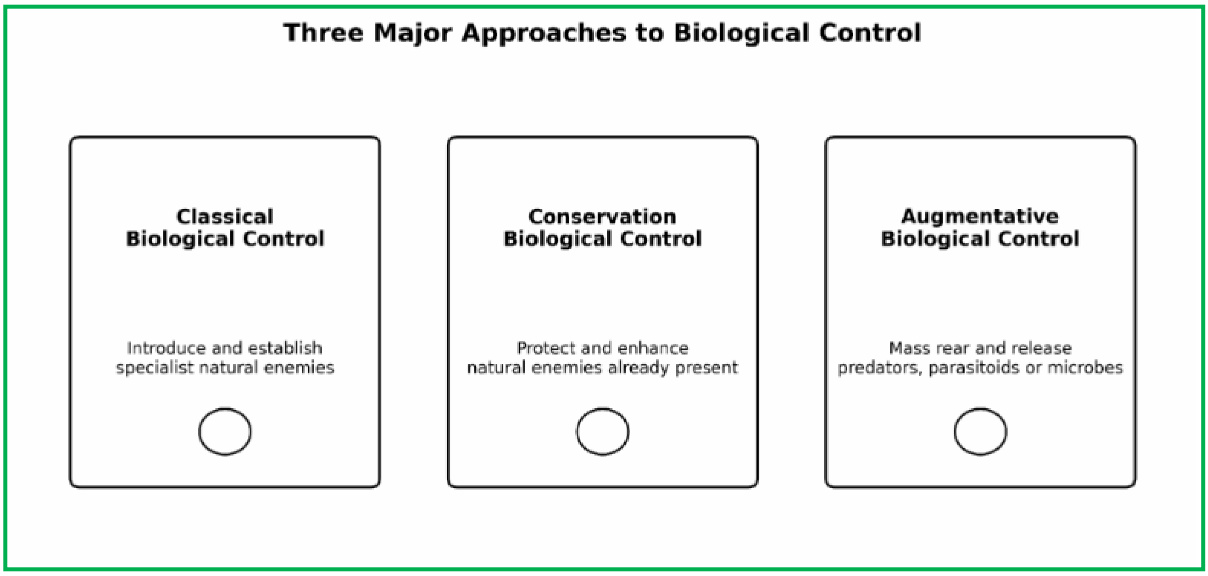

Figure: Three major approaches to biological control: classical, conservation and augmentative strategies

Predatory insects and mites are important natural regulators of agricultural pests. Ladybird beetles, lacewings, predatory bugs, predatory mites and spiders attack multiple pest individuals during their lifetime and can contribute to suppression of aphids, whiteflies, thrips, mites, caterpillars and other pests. Their generalist feeding behaviour can be advantageous in diversified systems because they can persist when one prey species becomes scarce. However, generalism can also reduce effectiveness when alternative prey or non-target organisms divert predator activity. Parasitoids differ from predators because the immature stages develop in or on a host and ultimately kill it. Parasitoid wasps and flies have been central to classical and augmentative biological control programs. Recent reviews of parasitoid-based biocontrol in India emphasize the continuing importance of classical, conservative and augmentative approaches, while also identifying climate adaptability, ecological compatibility, research capacity and policy as important determinants of success. Better understanding of host-finding behaviour, thermal tolerance, reproductive capacity and landscape movement can improve parasitoid deployment. A major recent advance is the use of molecular and genomic tools to characterize natural-enemy populations. DNA barcoding can improve taxonomic identification, particularly for cryptic parasitoid species, while population genomics can reveal genetic variation associated with host use, climatic adaptation, dispersal and reproductive traits. Such information can support the selection of strains or populations better adapted to specific agroecological environments.

Microbial Biological Control and Biopesticides

Microbial control uses pathogenic microorganisms to infect and suppress insect pests. Important groups include entomopathogenic bacteria, fungi, viruses and nematodes. Bacillus thuringiensis is among the best-known bacterial biocontrol agents, with insecticidal proteins that target susceptible insect groups. Baculoviruses are highly specific pathogens of particular insect hosts and are valuable for management of caterpillar pests. Entomopathogenic fungi such as Beauveria bassiana and Metarhizium anisopliae can infect insects through the cuticle and therefore have potential against pests that are difficult to reach through ingestion-based toxins. Recent research on bacterial biopesticides has emphasized microbial diversity, toxin complexes, modes of action and their role in sustainable crop protection. Fungal biocontrol has also received renewed attention because of insecticide resistance and demand for environmentally compatible pest-management tools. A 2025 review specifically examined entomopathogenic fungi under climate change, emphasizing the need to understand fungus–insect interactions under altered temperature and moisture regimes. Formulation technology is a major determinant of microbial biopesticide performance. Ultraviolet radiation, temperature, humidity, desiccation and rainfall can reduce viability after application. Advances in formulation, encapsulation, adjuvants and delivery systems aim to improve shelf life, persistence and field efficacy. Future microbial products are likely to emphasize improved stability, compatibility with IPM and precise application to pest habitats.

Recent Advances in Mass Rearing and Quality Control

The expansion of augmentative biological control depends on the ability to produce large numbers of healthy, effective natural enemies at predictable cost. Mass rearing systems are increasingly using automation, artificial diets, optimized host quality and environmental control. Quality control should include developmental rate, survival, fecundity, longevity, sex ratio, host-searching ability, flight capacity and other traits relevant to field performance. For parasitoids and predators, poor rearing conditions can cause behavioural changes or loss of field performance after many generations. Genetic and microbiome monitoring can help detect deterioration in colony quality. Standardized quality-control protocols are therefore essential for commercial production. Future facilities may combine automated imaging and machine learning to monitor development, detect abnormalities and optimize production conditions.

Genomics, Microbiomes and Molecular Tools

Genomics is creating new opportunities to understand why some natural enemies are more effective than others. Genome sequencing and population genomic analyses can identify candidate genes associated with host recognition, thermal tolerance, reproduction, immunity, dispersal and insecticidal effectors. Such information can support evidence-based selection of biological-control strains. However, genomic association alone does not establish field efficacy; functional validation and ecological testing remain necessary. Microbiome research is another emerging area. Symbiotic microorganisms can influence nutrition, immunity, development, reproduction and pesticide interactions in insects. Understanding the microbiomes of pests and natural enemies may reveal new mechanisms that affect susceptibility to pathogens or performance of parasitoids. Microbial manipulation could eventually contribute to novel biological-control strategies, but ecological safety and reproducibility need careful assessment. Molecular diagnostics can also improve biological-control programs by rapidly confirming pest identity, parasitoid identity and establishment after release. DNA-based methods can distinguish cryptic species that are difficult to separate morphologically, reducing the risk of releasing an ineffective or inappropriate natural enemy.

Semiochemicals and Behaviour-Based Biological Control

Biological control can be strengthened by manipulating insect behaviour. Herbivore-induced plant volatiles, pheromones and other semiochemicals influence host finding by parasitoids and predators. Habitat management that increases availability of suitable volatile cues may improve natural-enemy searching efficiency. Synthetic semiochemicals can also be used in traps or attract-and-kill systems and can be integrated with biological control. Recent approaches increasingly combine biological agents with behavioural manipulation. For example, attractants can concentrate pests or natural enemies in particular areas, while repellents or push–pull systems can reduce pest pressure. Such strategies can decrease the amount of biological or chemical input required and are particularly promising when they are tailored to crop-specific pest behaviour.

Precision Biological Control and Digital Agriculture

Digital agriculture is creating opportunities to make biological control more spatially and temporally precise. Remote sensing, automated traps, imaging, geographic information systems and machine learning can provide information on pest abundance and crop condition. This information can be used to decide where and when natural enemies or microbial biopesticides are most likely to provide economic benefits. Automated monitoring can also improve the timing of releases. Instead of applying a uniform release schedule, pest and natural-enemy observations can be used to synchronize interventions with susceptible pest stages. Such decision-support systems can reduce unnecessary applications and improve the cost-effectiveness of biological control. However, digital tools require reliable field data, connectivity, model validation and farmer-friendly interfaces.

Integration with Chemical and Cultural Pest Management

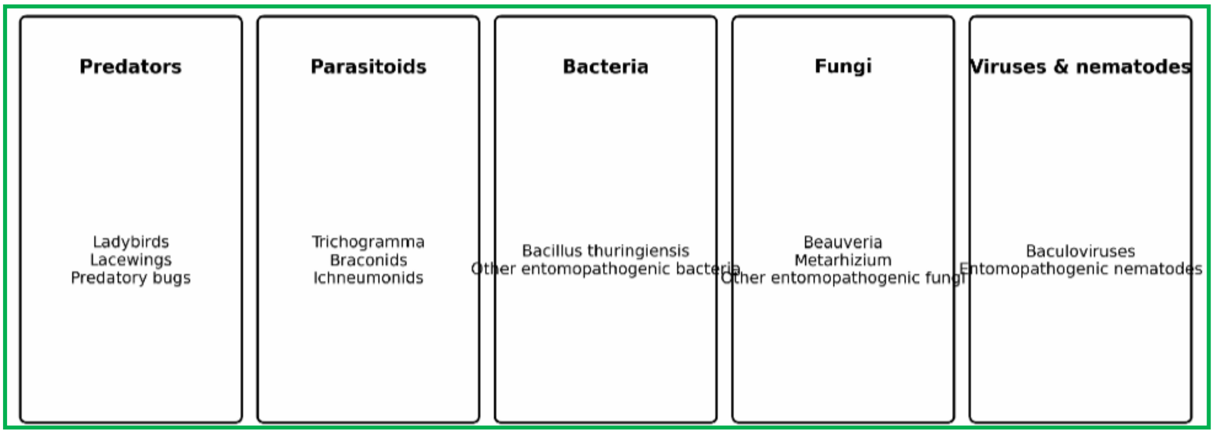

Figure: Principal groups of predators, parasitoids and microbial agents used in agricultural biological control

Biological control should generally be viewed as a core component of IPM rather than as an isolated replacement for every chemical intervention. FAO guidance recommends surveillance, crop diversification, resistant varieties, crop rotation, intercropping, optimized planting dates, sanitation and biological inputs as components of an ecosystem approach. Chemical pesticides may still be necessary when pest populations exceed economic thresholds, but products should be selected and timed to minimize harm to beneficial organisms. Selective insecticides, reduced-risk compounds and compatible application schedules can be integrated with parasitoids, predators and microbial agents. Incompatible pesticide use can rapidly eliminate natural enemies and undermine biological control. Therefore, pesticide compatibility testing should be part of biological-control program design. Extension recommendations should provide practical information on waiting periods, application timing and toxicity to beneficial organisms. Cultural practices can increase the effectiveness of natural enemies. Flowering plants can provide nectar and pollen for adult parasitoids, while field margins and reduced disturbance can provide refuge. Crop rotation and synchronized planting can reduce continuous host availability for pests. These practices demonstrate that biological control is most effective when the whole agroecosystem is managed to favour natural regulation. Regulatory systems can also slow commercialization. Biological control agents may be evaluated under regulatory frameworks designed primarily for conventional chemical pesticides, even though their characteristics and risk profiles can be very different. FAO notes that inappropriate regulatory requirements can impose unnecessary burdens on biological pest control agents. Harmonized, science-based and risk-proportionate regulation could facilitate responsible development while maintaining environmental safeguards. Climate change presents another challenge. Temperature and humidity can alter the survival, reproduction and synchrony of both pests and natural enemies. A biological-control agent effective under current conditions may become less reliable if climate conditions shift. Future programs therefore need climate-resilient strains and predictive models that evaluate pest and natural-enemy responses together.

Economic and Farmer Adoption Considerations

The success of biological control should be measured not only by biological efficacy but also by economic performance. Costs include production, transport, storage, release and monitoring, while benefits include reduced pesticide expenditure, avoided crop losses, improved quality and ecosystem services. Recent economic research emphasizes the importance of incorporating costs and benefits into biological-control program design and evaluation rather than assessing success only through pest mortality. Farmer adoption depends on practical considerations such as availability, ease of use, consistency, technical support and compatibility with existing farming operations. Demonstration plots, farmer field schools and extension programs can improve confidence in biological methods. Participatory approaches are particularly useful because farmers can help identify local constraints and evaluate whether biological-control schedules fit their production practices.

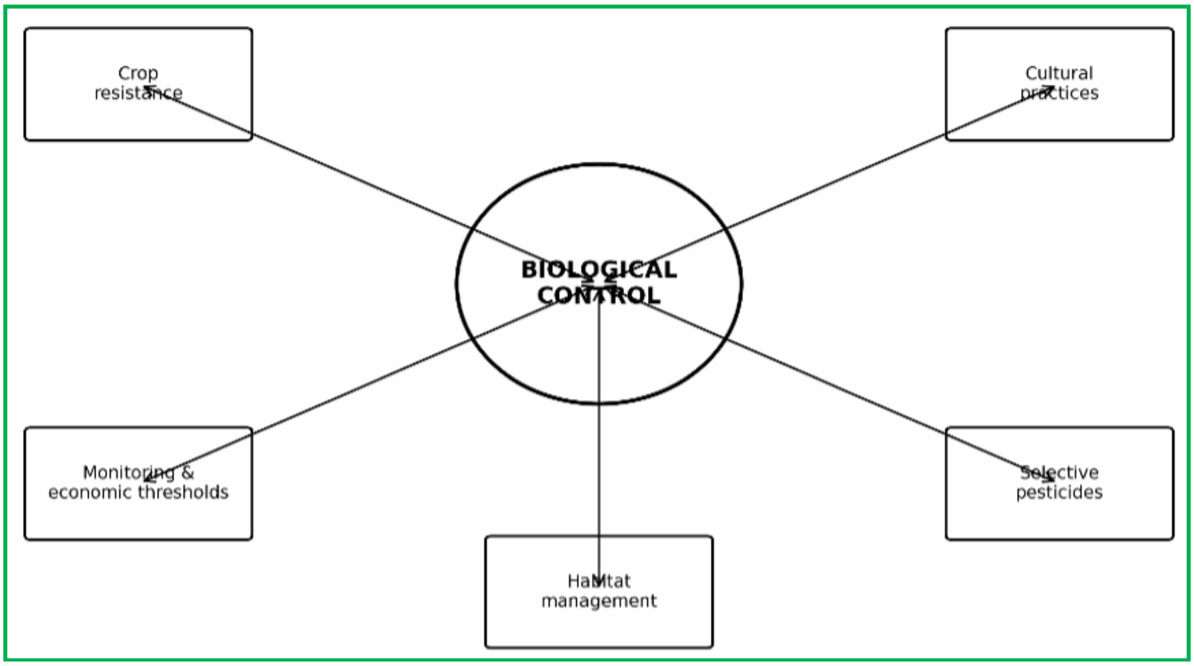

Figure: Integration of biological control with crop resistance, cultural practices, monitoring, habitat management and selective pesticide use within IPM

Future biological control will increasingly combine classical ecological principles with molecular biology, genomics, automation and digital decision support. Genomic information can guide the selection of natural enemies with desirable traits, while climate and landscape models can identify locations where those agents are most likely to establish or perform well. Such approaches should be complemented by rigorous field validation. Proactive biological control is likely to become increasingly important for invasive pests. Early detection, rapid identification, quarantine and pre-emptive assessment of host-specific natural enemies can reduce the time between pest arrival and implementation of sustainable suppression. International collaboration is essential because invasive pests cross political boundaries and biological-control agents may require coordinated research, regulation and monitoring. Climate-smart biological control is another priority. Research should identify natural enemies and microbial agents with broad but appropriate environmental tolerance and develop formulations that remain effective under heat, UV and rainfall stress. Coupling climate forecasts with pest phenology and natural-enemy models could improve release timing and reduce failures. Artificial intelligence and automation offer additional opportunities. Automated insect recognition can support monitoring, while machine-learning models can combine pest counts, weather, crop growth and natural-enemy observations to predict biological-control demand. Automated rearing facilities may use imaging to track development and identify abnormal individuals. These technologies should be designed around farmer needs and validated under diverse field conditions. Finally, the future of biological control depends on stronger links among research institutions, commercial producers, regulators, extension systems and farmers. Investment in local mass-rearing facilities, quality standards, training and affordable delivery systems can improve access. Biological control should be embedded within integrated, climate-resilient crop protection programs rather than promoted as a single universal technology.

Conclusion

Biological control is a cornerstone of sustainable agricultural pest management because it uses natural enemies and biological processes to suppress pests while reducing dependence on conventional insecticides. Classical, conservation and augmentative approaches, together with microbial biopesticides, provide complementary pathways for managing both established and invasive insect pests. Recent advances in genomics, microbiome research, mass rearing, formulation, semiochemicals, precision monitoring and digital agriculture are expanding the possibilities for more reliable and targeted biological control. Nevertheless, successful biological control requires more than identifying an effective organism. Ecological compatibility, climate adaptability, non-target safety, mass-production quality, economics, regulation and farmer adoption all determine field success. Future programs should integrate these dimensions and use evidence-based monitoring to evaluate long-term outcomes. A combination of robust biological agents, supportive farm habitats, compatible IPM practices, digital surveillance and proactive invasive-pest management can strengthen agricultural resilience and contribute to safer and more sustainable crop production.

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