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Innovations in Artificial Rearing and Mass Production of Beneficial Insects for Biocontrol: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

The mass production and artificial rearing of beneficial insects have emerged as essential strategies in biological control, offering sustainable alternatives to chemical pesticides in integrated pest management (IPM). The recent innovations in insect mass rearing, focusing on advancements in artificial diet formulations, genetic improvements, automation, and precision agriculture technologies. Traditional rearing methods have faced challenges related to high costs, genetic variability, pathogen contamination, and reduced field performance of artificially reared insects. Cutting-edge biotechnological tools such as CRISPR-Cas9, RNA interference (RNAi), and microbiome engineering have enhanced insect adaptability, resistance to environmental stress, and reproductive efficiency. The implementation of artificial intelligence (AI) and robotics in mass-rearing facilities has optimized environmental conditions, reduced labour costs, and improved quality control. Climate-controlled rearing chambers and sustainable diet formulations incorporating nanotechnology and microencapsulation have significantly enhanced insect fitness, longevity, and field efficacy. The integration of mass-reared beneficial insects with precision agriculture techniques, including drone-assisted releases and GIS-based monitoring, has further increased efficiency and target-specific pest suppression. Despite these advancements, challenges remain, particularly concerning economic viability, regulatory constraints, and ethical considerations associated with large-scale insect production and field release. To address these issues, future research should focus on refining artificial rearing techniques, developing cost-effective rearing systems, and improving genetic diversity in captive insect populations. Strengthening international regulatory frameworks and adopting sustainable mass production practices will be key to the long-term success of biocontrol programs. The potential of artificial rearing technologies to revolutionize pest management, reduce reliance on chemical pesticides, and promote ecological conservation, reinforcing the role of biological control as a cornerstone of modern sustainable agriculture.

Keywords: Biological control; mass rearing; artificial diets; genetic engineering.

1. INTRODUCTION

1.1 Biological Control and its Importance in Sustainable Agriculture

Biological control is a vital strategy in integrated pest management (IPM) that involves the use of natural enemies, such as predators, parasitoids, and pathogens, to suppress pest populations (Akter et al., 2018). This approach provides an environmentally sustainable alternative to chemical pesticides, reducing risks to human health, non-target organisms, and ecosystem integrity. The foundation of biological control lies in ecological interactions, where natural enemies regulate pest species under specific environmental conditions. There are three primary types of biological control: classical, augmentative, and conservation. Classical biological control involves the introduction of exotic natural enemies to regulate invasive pest species, whereas augmentative biological control entails the mass production and periodic release of beneficial insects. Conservation biological control focuses on modifying the environment to enhance the survival and efficacy of native natural enemies (Begg et al., 2017). Sustainable agriculture relies on biological control as a key component for reducing pesticide dependence and maintaining long-term soil and plant health. The excessive use of chemical pesticides has led to several issues, including pesticide resistance, non-target effects, and biodiversity loss. In contrast, biological control fosters a more balanced agroecosystem where natural enemy populations can persist and contribute to long-term pest suppression. Therefore, continued innovations in biological control practices, including artificial rearing and mass production of beneficial insects, are essential for achieving sustainable pest management (Bale et al., 2008).

1.2 Role of Beneficial Insects in Pest Management and Crop Protection

Beneficial insects play a significant role in biological control by preying on or parasitizing pest species, ultimately reducing their population

Table 1. Role of beneficial insects in pest management and crop protection

Beneficial Insect	Scientific Name	Role in Pest Management	Target Pest	Crops Benefited
Ladybird Beetles	*Coccinellidae*	Predation of aphids, scales, and whiteflies	Aphids, Mealybugs, Whiteflies	Vegetables, Fruits, Cereals
Lacewings	*Chrysopidae*	Larvae feed on soft-bodied insect pests	Aphids, Thrips, Mites	Cotton, Wheat, Horticultural Crops
Hoverflies	*Syrphidae*	Larvae consume aphids and other small insects	Aphids, Leafhoppers	Flowers, Fruits, Oilseeds
Parasitic Wasps	*Braconidae, Ichneumonidae*	Parasitism of insect pests	Caterpillars, Whiteflies, Aphids	Vegetables, Ornamentals, Field Crops
Predatory Mites	*Phytoseiidae*	Consume harmful mites and insect eggs	Spider Mites, Thrips	Orchard Crops, Vineyards, Greenhouses
Ground Beetles	*Carabidae*	Predation of soil-dwelling insect larvae	Cutworms, Armyworms, Slugs	Maize, Wheat, Rice, Root Crops
Tachinid Flies	*Tachinidae*	Parasitism of caterpillars and beetle larvae	Cutworms, Borers, Leaf Beetles	Sugarcane, Corn, Forestry Crops
Dragonflies	*Odonata*	Predation of flying insects	Mosquitoes, Midges, Small Moths	Paddy Fields, Wetland Areas, Gardens
Bees	*Apidae*	Pollination, indirectly reducing pest impact	Various indirect pest reductions	Fruits, Vegetables, Legumes
Ants	*Formicidae*	Predation and disrupting pest populations	Termites, Aphids, Caterpillars	Agroforestry, Orchards, Plantation Crops

(Sources: Hajek et al., 2018, Assefa et al., 2008)

densities in agricultural systems (Table 1). Predatory insects such as lady beetles (*Coccinellidae*), lacewings (*Chrysopidae*), and predatory mites (*Phytoseiidae*) actively hunt and consume various agricultural pests, including aphids, whiteflies, and spider mites. Parasitoids, such as *Trichogramma* spp. and *Aphidius* spp., lay their eggs inside or on pest hosts, leading to their eventual death. These natural enemies offer an effective means of pest suppression with minimal ecological disruption (Hajek et al., 2018). Studies have demonstrated that biological control can significantly reduce pest populations in major crops such as cotton, maize, and horticultural plants. The introduction of *Cotesia flavipes* in sugarcane fields successfully controlled *Diatraea saccharalis* populations in several countries (Assefa et al., 2008). Augmentative releases of *Trichogramma* parasitoids have been widely adopted for managing lepidopteran pests in cereals, vegetables, and orchards. Beneficial insects not only improve pest control efficiency but also support biodiversity conservation and ecosystem services, making them indispensable for modern agricultural practices. Despite their advantages, the effectiveness of biological control agents depends on environmental factors, prey availability, and conservation strategies. Therefore, ensuring a steady supply of high-quality beneficial insects through artificial rearing and mass production is critical for successful implementation in large-scale agriculture.

1.3 Need for Artificial Rearing and Mass Production of Beneficial Insects

Artificial rearing and mass production of beneficial insects are crucial for expanding the application of biological control in commercial agriculture. While natural enemy populations can regulate pests under favourable conditions, their numbers often decline due to habitat destruction, pesticide exposure, and climate change (Thomson et al., 2010). Mass rearing and release programs can supplement natural enemy populations, ensuring timely and effective pest suppression. One of the primary challenges in biological control is the inconsistent availability of natural enemies in agricultural landscapes. Artificial rearing facilities address this issue by producing large quantities of beneficial insects under controlled conditions, allowing for strategic augmentation and inundative releases. For example, mass production of *Trichogramma* parasitoids has been widely implemented for controlling lepidopteran pests in maize, rice, and vegetable crops. Commercial production of predatory mites has proven effective in greenhouse pest management (Gerson et al., 2007). Artificial diets and optimized rearing protocols play a crucial role in sustaining high reproduction rates and survival of beneficial insects. Advances in biotechnology, microencapsulation, and automation have further improved the cost-effectiveness and efficiency of mass rearing programs. Challenges such as genetic deterioration, adaptation to artificial environments, and high production costs must be addressed to enhance the scalability of these systems (Carroll et al., 2014), (Ravensberg et al., 2011).

1.4 Scope and Objectives of the Review

This review aims to explore recent innovations in artificial rearing and mass production of beneficial insects for biological control. It will discuss advancements in rearing techniques, artificial diet formulations, and mass production strategies, with a focus on enhancing the efficiency and cost-effectiveness of biological control programs. The review will also examine the challenges associated with mass rearing, including genetic bottlenecks, insect quality maintenance, and adaptation issues. Emerging technologies such as artificial intelligence, automation, and genetic modifications in insect rearing will be analysed for their potential contributions to sustainable pest management. By synthesizing recent research and developments in biological control, this review will provide valuable insights into optimizing artificial rearing and mass production techniques. The ultimate goal is to enhance the large-scale implementation of beneficial insects in integrated pest management, reducing reliance on chemical pesticides and promoting sustainable agricultural practices (Pretty et al., 2015).

2. BENEFICIAL INSECTS IN BIOCONTROL: IMPORTANCE AND APPLICATIONS

2.1 Categories of Beneficial Insects: Predators, Parasitoids and Pollinators

Beneficial insects play a critical role in integrated pest management (IPM) by regulating pest populations through predation, parasitism, and pollination. These insects are broadly classified into three categories: predators, parasitoids, and pollinators. Predatory insects directly consume pests at different life stages, thereby reducing their populations in agricultural landscapes. Examples of predatory insects include lady beetles (*Coccinellidae*), lacewings (*Chrysopidae*), and predatory mites (*Phytoseiidae*), which feed on aphids, whiteflies, and spider mites, respectively. Parasitoids, on the other hand, lay their eggs inside or on pest hosts, leading to the eventual death of the host upon the larval emergence. The most commonly used parasitoids in biological control include *Trichogramma* spp., *Aphidius* spp., and *Encarsia* spp., which target lepidopteran pests and aphids. Pollinators, though not directly involved in pest suppression, are essential for crop production and ecosystem balance (Kremen et al., 2007). The activity of pollinators such as bees (*Apis mellifera*) and hoverflies (*Syrphidae*) enhances plant health, indirectly supporting biological control by promoting biodiversity.

2.2 Key Species Used in Biocontrol Programs

Biological control programs have successfully utilized various species of beneficial insects for pest management across different cropping systems. Predatory beetles, such as *Harmonia axyridis* and *Coccinella septempunctata*, are widely used against aphid infestations in cereal crops and orchards. Green lacewings (*Chrysoperla carnea*) have been deployed in vegetable and horticultural crops to target soft-bodied insects like aphids and whiteflies. Predatory mites (*Phytoseiulus persimilis*) are commonly mass-reared for the control of *Tetranychus urticae* in greenhouses (Momen et al., 2020). Among parasitoids, *Trichogramma* spp. are extensively used for controlling lepidopteran pests in maize, cotton, and sugarcane. Braconid wasps such as *Cotesia flavipes* have been effective in managing sugarcane borers in tropical regions. For greenhouse pest control, *Encarsia formosa* has been successfully deployed against whiteflies (*Bemisiatabaci*) in protected environments. The selection of species for biocontrol programs depends on factors such as host specificity, environmental adaptability, and reproductive efficiency.

2.3 Mechanisms of Pest Suppression by Beneficial Insects

The effectiveness of beneficial insects in biocontrol is largely determined by their feeding behaviours, reproductive strategies, and interactions with prey or hosts (Mills et al., 2008). Predatory insects employ different foraging strategies, including active hunting, ambush predation, and trap building, to locate and consume their prey. Predatory beetles and true bugs use their mandibles and proboscis to subdue prey, while lacewing larvae use specialized mouthparts to pierce and digest aphids externally. Parasitoids, in contrast, rely on host-seeking behaviour, often guided by chemical cues emitted by host insects or host plants under attack. Once located, parasitoids deposit their eggs inside or on the host, triggering physiological disruptions that eventually lead to host mortality (Hance et al., 2007). For example, *Aphidius colemani* targets aphids by injecting a single egg into the host's hemocoel, where the larva consumes internal tissues before pupating. Pollinators contribute to biocontrol through indirect mechanisms by enhancing plant resistance and resilience to pest damage. The increased fruit and seed set facilitated by pollinators improves plant vigour, reducing the likelihood of pest infestations (Gagic et al., 2016). Beneficial insects can interact synergistically with microbial control agents, such as entomopathogenic fungi and bacteria, further enhancing pest suppression in IPM programs.

2.4 Economic and Ecological Benefits of Biocontrol

Biological control offers substantial economic and ecological advantages over conventional chemical pesticides (Bale et al., 2008). One of the primary benefits is the long-term cost-effectiveness of biocontrol, as natural enemies can establish self-sustaining populations that reduce the need for repeated pesticide applications. In some cases, successful biocontrol programs have led to annual savings of millions of dollars in pest management costs. The introduction of *Rodolia cardinalis* against cottony cushion scale (*Iceryapurchasi*) in citrus groves resulted in significant cost reductions for growers in California. Ecologically, biocontrol minimizes environmental contamination and preserves biodiversity by reducing chemical pesticide dependency. Unlike broad-spectrum insecticides, which can disrupt non-target organisms, biocontrol agents selectively target pests, maintaining the balance of natural ecosystems. This approach also mitigates the risk of pesticide resistance, a growing concern in modern agriculture. Biocontrol enhances soil health and pollinator conservation, contributing to overall agricultural sustainability (Holland et al., 2017). The integration of biological control into agroecosystems aligns with global sustainability goals, promoting environmentally friendly pest management practices. Ongoing research and technological advancements in mass rearing, genetic improvement, and habitat conservation will further enhance the efficacy and adoption of biocontrol strategies in the future.

3. ARTIFICIAL REARING TECHNIQUES FOR BENEFICIAL INSECTS

3.1 Principles of Mass Rearing: Nutritional, Environmental and Genetic Considerations

Mass rearing of beneficial insects involves optimizing nutritional, environmental, and genetic factors to ensure high reproduction rates, survival, and efficacy in biological control programs (Table 2) (Jensen et al., 2017). Nutritional considerations include the provision of appropriate diets that mimic natural food sources, ensuring the insects' development and longevity. Many beneficial insects require complex diets, which may include live prey, artificial diets, or a combination of both. Environmental factors such as temperature, humidity, photoperiod, and air circulation play crucial roles in influencing insect behaviour, reproductive success, and metabolic processes. Genetic considerations are essential to maintaining the fitness of mass-reared populations, as prolonged laboratory rearing can lead to genetic bottlenecks and inbreeding depression (Leung et al., 2025). Careful selection and periodic introduction of wild strains can help maintain genetic diversity and ensure robust performance in field conditions.

3.2 Rearing of Predatory Insects (e.g., Lady Beetles, Lacewings, Syrphid Flies, Predatory Mites)

Predatory insects, such as lady beetles (*Coccinellidae*), lacewings (*Chrysopidae*), syrphid flies (*Syrphidae*), and predatory mites (*Phytoseiidae*), are commonly used in biocontrol due to their voracious appetite for agricultural pests (Hagen et al., 1976). Rearing techniques for lady beetles involve maintaining colonies on aphids or alternative artificial diets supplemented with essential nutrients to ensure proper development and high fecundity. Lacewings, particularly *Chrysoperla carnea*, are mass-reared using factitious hosts such as *Sitotroga cerealella* eggs or artificial diets enriched with proteins and carbohydrates. Syrphid flies, which primarily target aphids, require careful rearing with flowering plants for adult nectar feeding and host aphids for larval sustenance. Predatory mites, like *Phytoseiulus persimilis*, are reared on spider mites or pollen-based diets in controlled environments with optimal temperature and humidity to maximize reproduction and dispersal capabilities.

3.3 Rearing of Parasitoids (e.g., Trichogramma, Aphidius, Encarsia, Braconid Wasps)

Parasitoids such as *Trichogramma*, *Aphidius*, *Encarsia*, and braconid wasps are crucial in biological control programs targeting various pest species (Colmenaraz et al., 2018). *Trichogramma* spp. are mass-reared on artificial or factitious hosts, typically *Sitotroga cerealella* eggs, with temperature and humidity conditions optimized for rapid multiplication. *Aphidius colemani* and *Encarsia formosa* are reared on their respective aphid and whitefly hosts in greenhouses, where they undergo parasitism under controlled conditions to produce high-quality progeny. Braconid wasps, such as *Cotesia flavipes*, require live hosts for successful development, necessitating intricate rearing protocols that involve synchronized host-parasitoid interactions. Advances in artificial diets and host substitutions have improved mass rearing efficiency, reducing dependency on live hosts and lowering production costs.

3.4 Rearing of Pollinators for Agricultural Benefits

Pollinators such as honeybees (*Apis mellifera*), bumblebees (*Bombus* spp.), and solitary bees play a vital role in enhancing crop productivity. Mass rearing of honeybees is well established, involving managed hives with regulated foraging areas and supplemental feeding during periods of floral scarcity. Bumblebee colonies are reared in laboratory conditions by providing pollen, nectar substitutes, and controlled nesting environments (Rowe et al., 2023). The rearing of solitary bees, including mason bees (*Osmia* spp.), involves the provision of nesting substrates and floral resources to promote reproduction. Research on artificial diets and microbiome management has further enhanced the efficiency of pollinator rearing, improving their resilience to environmental stressors.

Table 2. Artificial rearing techniques for beneficial insects in agriculture (Leung et al., 2025, Colmenaraz et al., 2018)

Beneficial Insect	Rearing Medium	Feeding Requirements	Environmental Conditions	Mass production feasibility
Ladybird beetles	Controlled cages	Aphids, artificial diets	25-30°C, 60-70% RH, ample light	High
Lacewings	Rearing chambers	Ephestia eggs, artificial diets	22-28°C, 60-75% RH	High
Hoverflies	Greenhouse conditions	Aphids, sugar-based solutions	20-25°C, moderate humidity	Moderate
Parasitic Wasps	Host insect culture	Host larvae for parasitism	22-30°C, 70% RH	High
Predatory Mites	Controlled microhabitats	Pollen, small arthropods	20-25°C, 65-80% RH	High
Ground Beetles	Soil-based containers	Larvae of insect pests	18-28°C, 50-70% RH	Moderate
Tachinid Flies	Host-rearing systems	Host caterpillars, nutrient-rich artificial diet	22-30°C, high humidity	Moderate
Dragonflies	Aquatic larval rearing	Small aquatic insects, plankton	18-26°C, aquatic setups	Low
Bees	Hive boxes	Nectar, pollen, sugar syrup	20-35°C, moderate humidity	High
Ants	Artificial nests	Small insects, honey, protein-rich diet	22-30°C, stable humidity	Moderate

3.5 Development of Artificial Diets for Sustained Rearing

Artificial diet formulation is a critical aspect of mass rearing programs, allowing for year-round production and cost-effective scaling of beneficial insects (Hendrichs et al., 2015). These diets must provide essential macronutrients (proteins, lipids, carbohydrates) and micronutrients (vitamins, minerals) to support optimal growth and reproduction. Advances in diet development include microencapsulation techniques to enhance nutrient stability and bioavailability. Factitious host substitution, such as using *Ephestia kuehniella* eggs for *Trichogramma* spp. instead of natural lepidopteran eggs, has improved mass production efficiency. Recent studies have explored symbiotic microbial supplementation to enhance insect fitness and longevity in artificial rearing conditions (Rull et al., 2015).

4. INNOVATIONS IN ARTIFICIAL DIET FORMULATION FOR MASS REARING

4.1 Nutritional Requirements of Predators and Parasitoids

The nutritional needs of predators and parasitoids vary based on their developmental stages and feeding behaviours. Predators require a diet rich in proteins and lipids to support their growth, metabolism, and reproductive capabilities (Kumar et al., 2018). Essential amino acids, fatty acids, vitamins, and sterols are critical for their survival and efficacy in biocontrol. Parasitoids, on the other hand, rely on their host for necessary nutrients during larval development, but adult females require carbohydrate-rich diets to enhance longevity and oviposition rates. The absence of specific nutrients can lead to reduced survival, deformities, and suboptimal predation or parasitization rates.

4.2 Artificial Diets vs. Natural Prey/Hosts

Natural prey and hosts provide the most suitable nutritional profile for rearing beneficial insects, but their availability and cost remain significant challenges. Artificial diets have been developed to replace or supplement natural food sources, improving cost-effectiveness and scalability in mass rearing. Artificial diets must replicate essential nutrients, feeding stimulants, and microbial symbionts found in natural hosts to ensure the quality and performance of reared insects. Studies have demonstrated that while artificial diets can sustain insects, they often result in longer development times, lower fecundity, and reduced field efficacy compared to natural diets.

4.3 Advances in Semi-Synthetic and Synthetic Diets

Recent innovations in semi-synthetic and synthetic diets have improved the efficiency of artificial rearing programs. Semi-synthetic diets incorporate natural ingredients, such as insect hemolymph extracts or plant-based proteins, combined with synthetic additives to enhance digestibility and nutritional balance (Majeed et al., 2023). Fully synthetic diets, formulated with chemically defined nutrients, eliminate the need for natural components, reducing contamination risks and improving reproducibility. Advances in encapsulation technology and nanonutrient delivery have further optimized nutrient uptake and utilization in artificially reared insects.

4.4 Impact of Diet Formulation on Growth, Longevity, and Reproduction

The formulation of artificial diets significantly affects the growth rate, longevity, and reproductive success of mass-reared insects. Protein-rich diets have been linked to enhanced larval growth and higher survival rates in predatory insects, whereas carbohydrate supplementation is crucial for adult parasitoid longevity. Imbalanced diets may lead to reduced predation efficiency, lower fecundity, and shorter lifespan. Optimizing macronutrient and micronutrient compositions has been a key focus in improving the viability and cost-effectiveness of artificial diets (Sniatala et al., 2023), (Borrelli et al., 2017).

5. MASS PRODUCTION STRATEGIES FOR LARGE-SCALE BIOCONTROL PROGRAMS

5.1 Traditional Rearing Methods vs. Modern Innovations

Traditional rearing methods for beneficial insects primarily relied on labour-intensive and small-scale production systems, often using natural prey or host insects as food sources. These conventional approaches, while effective in controlled environments, posed challenges related to scalability, cost, and quality consistency. Modern innovations have revolutionized mass rearing by incorporating automation, artificial diets, and genetic improvements to enhance productivity and efficiency. The development of artificial rearing media has enabled the substitution of natural hosts, reducing dependency on wild insect populations and minimizing the risks of disease transmission and contamination. The introduction of semi-synthetic and synthetic diets has improved rearing efficiency, resulting in better insect fitness and longevity (Ahmed et al., 2023). Advanced biotechnological approaches, such as selective breeding and microbiome engineering, have further contributed to the optimization of mass production strategies for biological control agents.

5.2 Automation and Mechanization in Insect Production Facilities

Automation and mechanization have played a crucial role in enhancing the scalability and efficiency of mass rearing programs for beneficial insects. Mechanized systems have been introduced to automate key processes such as egg collection, larval feeding, and pupation, significantly reducing labour costs and improving output consistency. Automated feeding systems ensure the precise delivery of artificial diets, optimizing nutrition and minimizing waste. High-throughput rearing systems have been developed for commercially important parasitoids such as *Trichogramma* and predatory mites, allowing for the continuous production of high-quality insects. The integration of robotics and machine learning in insect rearing facilities has further enhanced monitoring capabilities, allowing for real-time adjustments to rearing conditions and early detection of abnormalities (Nawoya et al., 2024). These technological advancements have enabled large-scale insect production to meet the growing demand for biological control solutions in commercial agriculture.

5.3 Role of Climate-Controlled Rearing Chambers

Maintaining optimal environmental conditions is critical for the success of mass rearing programs, as fluctuations in temperature, humidity, and photoperiod can significantly impact insect development and reproductive performance. Climate-controlled rearing chambers provide precise environmental regulation, ensuring consistent quality and survival rates across production cycles. Temperature-controlled rearing has been widely adopted for the mass production of *Phytoseiulus persimilis*, a key predatory mite used in greenhouse pest control. Advanced climate control systems incorporate automated sensors and real-time data analysis to adjust conditions dynamically, optimizing rearing efficiency and reducing production losses (Hassan et al., 2023). The use of bio secure chambers minimizes contamination risks, preventing pathogen outbreaks that can compromise insect quality. Future innovations in climate control technology, including artificial intelligence-driven climate modelling, will further enhance mass rearing capabilities and support the expansion of biological control programs worldwide.

5.4 Sustainable and Cost-Effective Production Systems

The sustainability of large-scale insect rearing operations depends on cost-effective and resource-efficient production systems. The transition to artificial diets and alternative protein sources has significantly reduced the cost of insect production while maintaining or improving quality. Sustainable rearing systems incorporate circular economy principles, such as the recycling of waste materials and the utilization of byproducts for feed production (Abbasi et al., 2024). For example, agricultural waste and plant-based substrates have been successfully used to rear beneficial insects, reducing reliance on expensive and unsustainable inputs. Mass-rearing facilities are increasingly adopting renewable energy sources and water-saving technologies to minimize their environmental footprint. Sustainable rearing practices not only contribute to economic viability but also enhance the adoption of biological control in integrated pest management programs by providing affordable and effective biocontrol agents.

5.5 Standardization and Quality Control Measures in Mass Rearing

Ensuring consistency and efficacy in mass-reared insects requires rigorous standardization and quality control measures (Parker et al., 2021). Key parameters such as survival rate, reproductive success, and field performance must be continuously monitored to maintain product reliability. Standardized protocols have been developed for the mass production of *Trichogramma* species, ensuring uniformity in parasitoid quality across different rearing facilities. Genetic quality control is also essential, as prolonged laboratory rearing can lead to inbreeding depression and reduced field efficacy. Regular genetic assessments and the introduction of wild-type individuals help maintain genetic diversity and adaptive potential. Certification and regulatory frameworks have been established in several countries to ensure that mass-produced insects meet industry and environmental safety standards. These measures contribute to the reliability and effectiveness of biological control programs, supporting the continued expansion of sustainable pest management solutions.

6. STORAGE AND TRANSPORT OF MASS-REARED INSECTS

6.1 Cold Storage Techniques and Cryopreservation

Cold storage and cryopreservation techniques are critical for maintaining the viability of mass-reared beneficial insects before their release in biocontrol programs (Van lenteren et al., 1996). Cold storage involves maintaining insects at low temperatures to slow down their metabolism and prolong their shelf life without compromising their biological effectiveness. Parasitoids such as *Trichogramma* spp. can be stored at temperatures ranging from 4°C to 10°C for weeks while retaining high emergence rates and host-seeking behaviours. Predatory mites such as *Phytoseiulus persimilis* and *Neoseiulus californicus* can be stored at near-freezing temperatures for short durations without losing their efficacy in pest suppression. Cryopreservation, on the other hand, involves ultra-low temperatures (usually -196°C in liquid nitrogen) to preserve insect eggs, embryos, or spermatozoa for extended periods. This method has been successfully applied to *Chrysoperla carnea* eggs, ensuring long-term viability and reducing the need for continuous mass rearing. Challenges such as ice crystal formation and cellular damage must be addressed through cryoprotectants and controlled freezing techniques to improve survival rates. These storage strategies significantly enhance the logistical efficiency of insect mass production, facilitating better planning for field releases.

6.2 Packaging Methods for Improved Survival During Transport

The transportation of mass-reared beneficial insects requires specialized packaging techniques to minimize mortality and ensure their fitness upon arrival at the release sites (Reynolds et al., 2012). Key considerations in insect packaging include temperature regulation, humidity control, oxygen availability, and physical protection from mechanical damage. Different insect species require customized packaging approaches; for example, parasitoids such as *Encarsia formosa* are often transported as pupae in perforated containers to allow aeration and prevent suffocation. Gel-based formulations and biopolymeric coatings have been explored for protecting and sustaining insects during transport. Refrigerated transport methods have been employed for sensitive species like *Aphidius colemani*, ensuring that the insects remain in diapause or reduced metabolic states during transit. Vibration and mechanical shocks can severely impact insect quality; therefore, cushioning materials such as paper-based inserts and foam padding have been incorporated in packaging designs (Akelah et al., 2013). Advancements in smart packaging technology, including microclimate sensors and real-time tracking systems, are improving the monitoring of transport conditions to ensure that insects arrive in optimal health. Standardizing these packaging methods is crucial for maintaining consistency in biological control programs, preventing losses during transportation, and ensuring effective pest control upon release.

6.3 Release Strategies: Augmentative, Inoculative, and Classical Biocontrol Approaches

The success of biocontrol programs depends on the effective release of mass-reared insects using different strategies, including augmentative, inoculative, and classical biocontrol approaches. Augmentative biocontrol involves periodic releases of beneficial insects to suppress pest populations, often in greenhouses and high-value crop systems. This method has been widely used for *Trichogramma* spp. against lepidopteran pests and *Oriusinsidiosus* for thrips management. Inoculative biocontrol entails the introduction of natural enemies at the beginning of the growing season, allowing them to establish and provide long-term pest control (Hajek et al., 2018). This strategy has been effectively applied in fruit orchards with *Aphidius colemani* and *Neoseiuluscucumeris*, which persist over multiple generations to regulate aphid and mite populations. Classical biocontrol, also known as importation biocontrol, involves the introduction of exotic natural enemies to control invasive pests. A historical example includes the introduction of *Rodolia cardinalis* for controlling *Iceryapurchasi* in citrus groves, which led to the successful long-term suppression of this pest. The selection of the appropriate release strategy depends on factors such as target pest biology, environmental conditions, and economic feasibility.

6.4 Post-Release Monitoring and Field Establishment Success

Post-release monitoring is essential for evaluating the effectiveness of biocontrol programs and ensuring that released insects establish sustainable populations in the field. Monitoring techniques include direct observation, sampling of pest and natural enemy populations, and molecular tools such as DNA barcoding to confirm insect establishment (Chua et al., 2023). Population dynamics studies have shown that successful field establishment depends on environmental conditions, competition with native species, and pesticide exposure. Studies on *Cotesia flavipes* have demonstrated that its establishment and efficacy in sugarcane fields are influenced by habitat conditions and host availability. The integration of GIS (Geographic Information Systems) and remote sensing technologies has enhanced the spatial tracking of released insects, providing insights into their dispersal patterns and interactions with pest populations. Additionally, adaptive management strategies, such as supplemental releases and habitat modifications, can be employed to improve establishment success in challenging environments.

7. CHALLENGES AND LIMITATIONS IN ARTIFICIAL REARING AND MASS PRODUCTION

7.1 High Production Costs and Economic Viability

One of the primary challenges in artificial rearing and mass production of beneficial insects is the high operational costs associated with maintaining insect colonies, developing specialized diets, and ensuring appropriate environmental conditions (Ortiz et al., 2016). The expenses related to labour, infrastructure, and continuous supply of high-quality artificial diets make large-scale production financially burdensome. Despite efforts to develop cost-effective rearing protocols, many commercial insectaries struggle to maintain profitability due to fluctuating market demands and competition from chemical pest control alternatives. In addition, the mass production of insects for biocontrol requires significant initial investments in controlled environment facilities, climate regulation systems, and quality control mechanisms, further adding to the financial constraints. Research on alternative cost-reduction strategies, such as optimizing artificial diets and using automation in rearing processes, has shown promise in improving economic feasibility. The scalability of these approaches remains limited, particularly for small-scale producers and emerging markets where financial resources are constrained. The integration of sustainable production methods, including the utilization of agricultural byproducts as diet components, could help mitigate some of the cost-related challenges in large-scale insect rearing (Sharma et al., 2022).

7.2 Genetic Variability and Inbreeding Depression in Captive Populations

Maintaining genetic diversity is essential for ensuring the fitness and performance of mass-reared insect populations, yet prolonged laboratory rearing often results in inbreeding depression and genetic bottlenecks. Reduced genetic variability can lead to lower reproductive success, increased susceptibility to diseases, and diminished adaptability to field conditions. Many biocontrol programs have reported declines in the efficacy of mass-reared insects due to genetic drift and artificial selection pressures favouring traits suited for laboratory environments rather than field survival. Efforts to mitigate genetic deterioration include periodic introduction of wild genetic material into breeding programs and the use of selective breeding to enhance desirable traits. Cryopreservation and genetic banking have also been explored as potential solutions to preserve genetic diversity and restore population variability when necessary. These methods require advanced infrastructure and expertise, limiting their accessibility to many commercial insectaries (Guissou et al., 2022).

7.3 Insect Adaptation to Artificial Conditions vs. Field Performance

Mass-reared insects often undergo physiological and behavioural modifications that can hinder their effectiveness in natural environments. Adaptation to artificial rearing conditions may result in changes in mating behaviour, host-seeking efficiency, and foraging strategies, ultimately reducing the field efficacy of released individuals. Parasitoids such as *Trichogramma* spp. reared on unnatural hosts may exhibit reduced host-finding capabilities when released into agricultural fields. Laboratory-reared predators may display reduced predatory efficiency due to prolonged exposure to artificial diets that differ from their natural prey. To counteract these challenges, research has focused on conditioning techniques that expose insects to semi-natural conditions before field release, improving their ability to adapt and perform in real-world agricultural ecosystems. Field trials and adaptive rearing strategies are necessary to bridge the gap between artificial environments and natural habitats to optimize biocontrol effectiveness (Lirakis et al., 2019).

7.4 Risk of Pathogen Contamination and Disease Outbreaks in Rearing Units

The high-density rearing conditions used in insect production facilities create an environment conducive to pathogen proliferation and disease outbreaks. Bacterial, fungal, and viral infections can rapidly spread through colonies, leading to significant mortality and production losses. For example, *Nosema* spp. infections have been a major issue in the rearing of pollinators such as bumblebees, resulting in reduced colony health and productivity. Sanitation protocols, biosecurity measures, and regular health monitoring are critical components of disease management in mass rearing facilities. Researchers have explored the use of probiotic supplements and immune-boosting dietary additives to enhance the disease resistance of reared insects. The development of cost-effective and scalable disease prevention strategies remains a major challenge for large-scale production.

7.5 Regulatory and Ethical Considerations in Mass Production and Release

The large-scale rearing and release of beneficial insects for biocontrol are subject to various regulatory and ethical considerations that influence industry practices. Governments and international organizations have established guidelines to ensure that mass-reared insects do not pose ecological risks, such as disrupting non-target species populations or competing with native natural enemies. Regulatory approvals often require extensive risk assessments, which can delay the implementation of biocontrol programs and increase operational costs (Barratt et al., 2021). Ethical concerns also arise regarding the unintended consequences of introducing non-native biological control agents into new ecosystems. Cases of invasive biocontrol organisms negatively impacting native species have led to increased scrutiny and stricter release protocols. The welfare of mass-reared insects has become a topic of discussion, particularly regarding rearing conditions and handling practices that minimize stress and mortality before release.

8. EMERGING TECHNOLOGIES

8.1 Application of Biotechnology and Genetic Engineering in Biocontrol

Biotechnology and genetic engineering have revolutionized biological control by enhancing the effectiveness, adaptability, and efficiency of mass-reared beneficial insects. Advances in gene editing techniques, such as CRISPR-Cas9, have allowed for targeted modifications that improve pest resistance, reproductive success, and host specificity in parasitoids and predators. Genetic improvements in insects, such as sterilization techniques and transgenic enhancements, have been explored to enhance their performance in integrated pest management (IPM) programs (Scolari et al., 2011). For example, gene editing has been employed to develop temperature-resistant strains of *Trichogramma* parasitoids, increasing their field survival and efficacy in varying climatic conditions. RNA interference (RNAi)-based approaches have been utilized to improve the adaptability and biocontrol efficiency of predatory beetles and mites. Future applications of biotechnology in mass rearing include the development of genetically optimized artificial diets, increased resistance to diseases, and improved dispersal behaviours of released insects.

8.2 Use of Artificial Intelligence and Automation in Insect Rearing

Artificial Intelligence (AI) and automation are transforming the mass production of beneficial insects by optimizing rearing processes, improving monitoring capabilities, and reducing production costs. AI-driven image recognition and machine learning algorithms enable real-time tracking of insect development, health, and behaviour, facilitating early detection of anomalies. Automated rearing systems equipped with robotics and smart feeding mechanisms have significantly increased production efficiency and scalability in commercial insectaries (Bouyer et al., 2020). The use of sensor-based climate control and automated nutrient delivery has improved consistency in rearing conditions, minimizing mortality rates and enhancing the overall quality of mass-produced insects. AI-driven models have been used to predict the best timing for insect releases, ensuring optimal synchronization with pest populations for maximum biocontrol impact. The continuous advancement of AI and automation technologies will play a crucial role in streamlining the mass rearing of beneficial insects, making large-scale biocontrol programs more cost-effective and efficient.

8.3 Role of Microbial Symbionts in Enhancing Rearing Success

Microbial symbionts have emerged as a key component in improving the health, longevity, and performance of mass-reared beneficial insects. Many insects, including parasitoids and predatory insects, rely on gut microbiota to digest artificial diets, enhance immunity, and promote reproductive success (Engel et al., 2013). The introduction of beneficial bacteria and fungi into artificial diets has been shown to improve nutrient assimilation and reduce developmental time in biocontrol agents such as *Chrysoperla carnea* and *Trichogramma* species. Studies have demonstrated that symbiotic bacteria such as *Wolbachia* can be harnessed to manipulate insect reproduction and enhance biocontrol efficiency. The use of probiotics in rearing media has also led to increased survival rates and resilience against pathogens in commercially produced insects. Future research in this area will likely focus on genetic modifications of symbionts to optimize their interactions with host insects, leading to enhanced performance in field conditions.

8.4 Integration of Artificial Rearing with Precision Agriculture Techniques

Precision agriculture involves the application of advanced technologies such as remote sensing, GIS mapping, and data analytics to optimize agricultural practices, including pest control. The integration of mass-reared beneficial insects with precision agriculture techniques allows for targeted releases based on real-time pest monitoring and predictive modelling (Nawaz et al., 2015). Drones and automated dispersal systems have been successfully employed for the precise release of parasitoids and predators in large-scale cropping systems. GPS-based tracking of insect movement post-release has further enhanced the effectiveness of biocontrol programs by identifying dispersal patterns and optimizing release densities. The combination of insect mass production with site-specific pest control strategies significantly improves resource efficiency and reduces reliance on chemical pesticides.

8.5 Potential of Nanotechnology and Microencapsulation in Diet Development

Nanotechnology and microencapsulation have introduced innovative solutions for improving artificial diets and enhancing the viability of mass-reared insects (Qadri et al., 2020). The application of nanomaterials in insect nutrition has improved the stability, bioavailability, and delivery of essential nutrients required for optimal growth and reproduction. Microencapsulation techniques have been developed to protect sensitive bioactive compounds in artificial diets, ensuring prolonged shelf life and better nutrient absorption by beneficial insects. For example, encapsulated essential fatty acids and sterols have been incorporated into artificial diets for *Chrysoperla carnea* and *Trichogramma* parasitoids, resulting in improved survival rates and reproductive performance. Nanocarrier-based delivery of pheromones and attractants has facilitated the development of novel insect release strategies, improving dispersal efficiency and establishment success in field conditions (Ali et al., 2023).

9. CONCLUSION

The advancements in artificial rearing and mass production of beneficial insects have significantly contributed to the development of sustainable pest management strategies. Despite challenges such as high production costs, genetic variability, adaptation issues, and disease outbreaks, emerging technologies including biotechnology, artificial intelligence, microbial symbionts, precision agriculture, and nanotechnology are enhancing efficiency and scalability. The integration of genetic engineering, automated monitoring, and optimized diet formulations has improved the viability and effectiveness of mass-reared insects, addressing limitations associated with traditional methods. Moreover, sustainable rearing practices and regulatory frameworks play a crucial role in ensuring the long-term success of biological control programs. Future research should focus on refining mass production techniques, improving field performance, and minimizing environmental risks to maximize the potential of biocontrol agents in integrated pest management. The continued innovation in this field will strengthen global efforts toward sustainable agriculture and ecological conservation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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