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COMMERCIALIZATION OF LADYBIRD BEETLES AND FUTURE PERSPECTIVES IN BIOCONTROL

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ABSTRACT

Ladybird beetles (Coleoptera: Coccinellidae) are among the most effective and commercially important predatory insects employed in global biological control programs. Their ability to suppress economically significant pests such as aphids, mealybugs, whiteflies, scale insects, psyllids, and spider mites has made them indispensable components of Integrated Pest Management and sustainable agriculture. Increasing concerns regarding pesticide resistance, biodiversity conservation, eco-degradation, and consumer demand for pesticide-free agricultural produce have accelerated the commercialization and global marketing of ladybird beetles. Today, several specialist and generalist species, such as *Cryptolaemus montrouzieri*, *Hippodamia convergens*, *Adalia bipunctata*, *Coccinella septempunctata*, *Delphastus catalinae*, and *Stethorus punctillum*, are mass-produced and marketed by commercial insectaries for greenhouse crops, orchards, protected cultivation, and field agriculture. Recent advances in artificial diets, automated insect-rearing systems, molecular genetics, digital marketing, and e-commerce have significantly improved the efficiency of mass production and expanded market opportunities for these beneficial insects. Nevertheless, commercialization is constrained by challenges such as production costs, transportation logistics, and ecological concerns associated with the release of exotic species, particularly, ladybirds. This review synthesizes current knowledge on the biological attributes supporting commercialization, global market trends, and emerging innovations in the marketing of ladybird beetles. Furthermore, it highlights future opportunities for integrating AI-driven production systems, and climate-resilient rearing technologies to strengthen the global biological control industry. Recent developments in genetics, artificial diets, and industrial-scale rearing are expected to further enhance their commercial value in sustainable crop protection.

Keywords: Coccinellidae; biological control; commercialization; Integrated Pest Management; mass rearing; sustainable agriculture.

INTRODUCTION

Today's agriculture faces the challenge of increasing food production while minimizing adverse environmental impacts. The widespread and often indiscriminate use of synthetic insecticides has resulted in insecticide resistance, pollution, contamination of food products, destruction of natural enemy complexes, and declines in biodiversity. Consequently, sustainable pest management strategies that reduce reliance on chemical pesticides have become central to global agricultural policies and research programs (Heimpel & Mills, 2017; van Lenteren et al., 2018). Among the numerous natural enemies used in biological control, predatory ladybird beetles (Coleoptera: Coccinellidae) occupy a unique position because of their remarkable predatory efficiency, broad prey range, high reproductive capacity, adaptability to diverse agroecosystems, and compatibility with Integrated Pest Management (IPM). Ladybird beetles constitute one of the most economically important groups of predatory insects employed in biological control (Hodek et al., 2012; Omkar and Pervez, 2016). The family comprises more than 6,500 described species distributed across approximately 360 genera, inhabiting nearly every terrestrial ecosystem except the extreme polar regions (Hodek et al., 2012; Escalona et al., 2017). Although popularly recognized for their role as aphid predators, members of the family exhibit remarkable ecological diversity, including predaceous, phytophagous, fungivorous, and coccidophagous feeding habits. Predatory species dominate agricultural ecosystems and have become indispensable agents in Integrated Pest Management because of their capacity to regulate populations of economically important arthropod pests (Roy et al., 2016; Seago et al., 2011).

Historically, these ladybird beetles are associated with a pioneer and most successful example of classical biological control. The introduction of vedalia beetle, *Rodolia cardinalis* against the heavy infestations of cottony cushion scale, *Icerya purchasi* in California citrus orchards during 1888-89 demonstrated the enormous potential of predatory insects in suppressing invasive pests. This landmark success laid the foundation for the commercialization of beneficial insects and remains a classic example of environmentally sustainable pest management (Obrycki & Kring, 1998; Hodek et al., 2012). Over the past four decades, commercialization of biocontrol agents has evolved into a rapidly expanding global industry. Commercial insectaries now mass-produce numerous predatory insects and parasitoids for augmentative biocontrol. Ladybird beetles constitute one of the most valuable groups in this sector because of their high predation rates, ease of handling, and applicability across greenhouse, horticultural, ornamental, and field cropping systems. Reviews indicate that at least 35 ladybird species have been commercially reared for augmentative biocontrol, however only a limited number dominate international markets owing to their better performance and production efficiency (Montanari et al., 2021; Rondoni et al., 2021).

The global demand for commercially produced ladybird beetles has increased substantially due to several converging factors. First, consumer awareness regarding pesticide residues has stimulated the growth of organic agriculture and residue-free food production. Second, increasing incidences of pesticide resistance among aphids, whiteflies, and mealybugs have reduced the efficacy of conventional insecticides. Third, stricter pesticide regulations in many countries have encouraged growers to adopt biological alternatives. Finally, advances in protected cultivation, greenhouse production, and precision agriculture have created favourable environments for augmentative releases of predatory insects. Together, these factors have transformed ladybird beetles from naturally occurring beneficial insects into valuable commercial biological control products. Commercially important ladybird beetles include *Cryptolaemus montrouzieri* (mealybug destroyer), *Hippodamia convergens* (convergent lady beetle), *Adalia bipunctata* (two-spotted ladybird), *Coccinella septempunctata* (seven-spotted ladybird), *Delphastus catalinae* (whitefly predator), and *Stethorus punctillum* (spider mite predator). Each species has specialized ecological characteristics that make it particularly suitable for suppressing specific pest groups under greenhouse or open-field conditions. Commercial insectaries rear these predators under carefully controlled environmental conditions and distribute them through agricultural supply networks, e-commerce platforms, and integrated crop management programs.

Recent technological innovations have further transformed the commercialization landscape. Artificial diets, automated climate-controlled rearing systems, machine vision for quality control, molecular tools for strain improvement, and AI-assisted production management are improving the efficiency and consistency of mass production. Likewise, digital marketing, online advisory platforms, and direct-to-farmer e-commerce have expanded access to biocontrol agents, particularly in developing countries where awareness of sustainable pest management is increasing. Recent researches identify genetics-guided breeding and optimized artificial diets as future directions to advance commercialization of ladybird beetles (Cheng et al., 2022; Zeng et al., 2025). Despite these advances, commercialization is not without challenges. Large-scale production requires reliable and economical prey or artificial diets, maintenance of genetic diversity, standardized quality-control protocols, and efficient packaging and transportation systems. Furthermore, releases of non-native species must be evaluated carefully because some commercially important ladybirds have become invasive in certain regions, raising concerns about intraguild predation and impacts on native biodiversity. Consequently, commercialization strategies increasingly emphasize risk assessment, regulatory compliance, and the preference for indigenous or regionally adapted biological control agents.

In India, the commercialization of ladybird beetles is gaining momentum with the expansion of organic farming and government-supported IPM initiatives (Ghosh, 2022). Research institutions under the Indian Council of Agricultural Research, State Agricultural Universities, and private biocontrol companies are developing mass-rearing protocols for indigenous predators such as *C. septempunctata*, *Cheilomenes sexmaculata*, and *C. montrouzieri*. Nevertheless, the domestic market remains relatively underdeveloped compared with those in Europe and North America, indicating considerable opportunities for entrepreneurship, startup development, and public–private partnerships. Given the growing global emphasis on environmentally sustainable agriculture, the commercial importance of ladybird beetles is expected to increase substantially during the coming decades. Their integration with artificial intelligence and precision agriculture is likely to reshape the biocontrol industry and strengthen sustainable crop protection. Hence, we reviewed the existing information on ladybird beetles to find out how the integration of ladybird beetles as biocontrol agents can be augmented and used at the industry level for their

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commercialization leading to an advanced version of insect biocontrol.

Biology of Ladybird Beetles Supporting Commercialization

Taxonomy, Diversity and Global Distribution

Historically, the taxonomy of ladybird beetles was based primarily on external morphological characteristics such as elytral coloration, body shape, antennal segmentation, tarsal formula, and genital morphology. However, the extraordinary variation in colour polymorphism and mimicry among species often complicated species identification. Recent advances in molecular phylogenetics, particularly multilocus DNA sequencing, mitochondrial genome analyses, and phylogenomic approaches, have significantly improved our understanding of coccinellid evolution and taxonomy (Che et al., 2021; Pang & Li, 2025). Molecular evidence has confirmed several previously controversial tribal relationships and facilitated the revision of numerous genera of commercial importance. Commercial biological control largely relies on predatory species belonging to the subfamilies Coccinellinae, Scymninae, and Chilocorinae, which include many of the most effective natural enemies of aphids, mealybugs, scale insects, whiteflies, spider mites, and psyllids (Hodek et al., 2012). Among these, *C. montrouzieri*, *Hippodamia convergens*, *Adalia bipunctata*, *C. septempunctata*, *C. sexmaculata*, *Harmonia axyridis*, *D. catalinae*, and *S. punctillum* are the principal species mass-produced for augmentative biological control programs worldwide (van Lenteren et al., 2018) (Table-1).

The evolutionary history of ladybird beetles suggests that predatory feeding evolved early within the family and subsequently diversified alongside the radiation of Hemipteran insects, particularly aphids and scale insects (Pang & Li, 2025). Co-evolution with prey insects has resulted in specialized adaptations such as highly developed chemosensory systems, rapid locomotion, cryptic egg-laying behaviour, and exceptional searching efficiency that enhance predatory performance (Hodek et al., 2012). The successful ladybirds are usually cosmopolitan occurring from tropical rainforests to temperate grasslands and alpine ecosystems. Tropical regions, particularly Southeast Asia, Central America, and the Amazon Basin, possess exceptionally high species richness owing to year-round availability of prey and favourable climatic conditions (Roy et al., 2016). Temperate species such as *C. septempunctata* and *H. convergens* dominate biocontrol programmes in Europe and North America, whereas tropical species including *C. sexmaculata*, and *C. montrouzieri* are widely utilized throughout Asia, Africa, and Australia (Omkar and Pervez, 2016).

India represents one of the world's biodiversity hotspots for ladybirds with more than 400 species have been reported from diverse agroecological regions, including the Himalayan foothills, Indo-Gangetic plains, Deccan Plateau, Western Ghats, and northeastern hill ecosystems (Poorani, 2002; Omkar and Pervez, 2004). Species such as *C. sexmaculata*, *C. septempunctata*, *C. montrouzieri, Propylea dissecta* and *Coccinella transversalis* are largely recognized for their biocontrol potential and pest suppression. Their adaptation to local climatic conditions makes them promising candidates for indigenous commercialization programmes. Commercialization has traditionally focused on species exhibiting broad prey ranges, rapid reproductive rates, high survival during transportation, and compatibility with greenhouse environments. Among these, *C. montrouzieri* remains the world's most successful commercially produced mealybug predator, whereas *D. catalinae* dominates the whitefly biological control market due to its exceptional feeding capacity and ability to establish under protected cultivation (van Lenteren et al., 2018). The increasing availability of DNA barcoding databases also facilitates quality assurance in commercial insectaries by enabling accurate species identification and preventing accidental contamination of breeding colonies. Molecular diagnostics have therefore become an important component of commercial biological control programmes, particularly where morphologically similar species coexist (Che et al., 2021). Collectively, taxonomic advances, molecular phylogenetics, and genomic technologies are transforming both the scientific understanding and commercial utilization of ladybird beetles.

Packaging, Storage and Transportation of Commercially Produced Ladybird Beetles

Packaging, storage, and transportation are among the most critical components of the commercialization chain for ladybird beetles. The success of augmentative biocontrol depends not only on efficient mass production but also on the ability to deliver healthy, vigorous, and highly predatory insects to growers with minimal mortality and maximum field performance.

Table 1. Commercially Important Ladybird Beetles Used in Biological Control

Species	Principal prey	Major crops	Commercial importance	Distribution
Cryptolaemus montrouzieri	Mealybugs	Grapes, citrus, ornamentals	Very High	Worldwide
Hippodamia convergens	Aphids	Vegetables, cereals	Very High	North America, Europe
Coccinella septempunctata	Aphids	Wheat, mustard, vegetables	High	Europe, Asia
Adalia bipunctata	Aphids	Greenhouse vegetables	High	Europe
Cheilomenes sexmaculata	Aphids, whiteflies	Cotton, vegetables	High	Asia
Delphastus catalinae	Whiteflies	Greenhouse vegetables	Very High	Worldwide
Stethorus punctillum	Spider mites	Fruit crops	High	Europe, North America
Micraspis discolor	Aphids	Rice, cereals	Moderate	South Asia
Brumoides suturalis	Aphids	Pulses, vegetables	Moderate	India
Harmonia axyridis	Aphids	Multiple crops	Restricted (due to invasiveness)	Worldwide

Unlike chemical pesticides, ladybird beetles are living organisms whose survival and biological efficacy can be adversely affected by inappropriate packaging materials, prolonged storage, mechanical injury, temperature fluctuations, dehydration, oxygen deficiency, and handling stress. Consequently, modern insectaries devote considerable attention to designing packaging systems and cold-chain logistics that preserve insect quality from the production facility to the point of release (van Lenteren et al., 2018; Riddick, 2017). Commercial packaging aims to maintain adequate ventilation, regulate humidity, minimize physical injury, prevent cannibalism, and ensure ease of handling during transportation. Packaging systems differ according to the developmental stage being marketed (eggs, larvae, pupae, or adults), the target crop, shipping distance, and climatic conditions. While adult beetles remain the most commonly marketed stage because of their immediate predatory activity and ease of release, eggs and larvae are increasingly supplied for greenhouse crops where longer establishment and localized pest suppression are desired (Hodek et al., 2012).

An effective packaging system should satisfy several biological and commercial requirements, which are: (1) maintain insect survival above 90–95%, (2) provide sufficient aeration while preventing escape, (3) protect insects from mechanical injury during transit, (3) minimize dehydration and condensation, (4) reduce metabolic activity without inducing physiological stress, (5) prevent excessive aggregation and cannibalism, (6) facilitate convenient field release, and (6) be lightweight, inexpensive, recyclable, and environmentally sustainable. The packaging design should also comply with national and international phytosanitary regulations governing the movement of live biological control agents.

Packaging Materials

Commercial insectaries employ a wide range of packaging materials depending on the species and shipment duration.

(i) Ventilated Plastic Containers

Rigid polypropylene containers fitted with fine mesh ventilation windows are among the most widely used packaging systems. These containers provide excellent mechanical protection while maintaining adequate gas exchange. Their transparent walls also permit rapid quality inspection during shipping.

(ii) Paperboard Cartons

Corrugated paperboard cartons lined with breathable paper are commonly used for large commercial consignments. These cartons reduce temperature fluctuations, absorb excess moisture, and provide insulation against mechanical shocks.

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(iii) Mesh Bags
Fine nylon or polyester mesh bags are increasingly used for greenhouse releases because they permit gradual emergence of adult beetles after placement among crop canopies.

(iv) Biodegradable Release Tubes
Several European biological control companies have introduced biodegradable paper tubes that allow growers to distribute predators directly into crops without opening multiple containers, thereby reducing handling time.

(v) Release Sachets
Release sachets are particularly suitable for larvae and eggs. These sachets slowly release predators over several days, providing sustained pest suppression in greenhouse crops.

Packaging According to Developmental Stage
Different developmental stages require specialized packaging systems (Table-2).

Adult Beetles
Adults are generally packaged at moderate densities (typically 200–2,000 individuals per container depending on species and container size). Excessive crowding leads to overheating, oxygen depletion, dehydration, mechanical injury, stress-induced mortality and cannibalism. Ventilated containers containing paper shreds provide additional climbing surfaces that reduce insect aggregation.

Eggs

Eggs are highly sensitive to mechanical vibration and excessive moisture. Commercial producers usually attach egg masses to paper strips or artificial oviposition cards before packaging them inside ventilated containers with humidity-buffering materials.

Larvae
Larvae exhibit strong cannibalistic tendencies; therefore, they are often packaged individually or in small groups with sufficient prey or artificial diet.

Pupae
Pupae are relatively resistant to transportation stress and can be attached to cardboard strips or foam sheets before shipment. They are widely marketed because of their high survival during transport and predictable adult emergence.

Table 2. Recommended Packaging Systems for Different Developmental Stages

Developmental stage	Packaging method	Advantages	Limitations
Eggs	Oviposition cards	High hatchability	Sensitive to vibration
Larvae	Individual compartments	Reduced cannibalism	Higher packaging cost
Pupae	Cardboard strips	Excellent transport survival	Delayed field activity
Adults	Ventilated plastic containers	Immediate pest control	Higher metabolic activity

Storage Conditions

Cold storage represents one of the most important technological advances in commercial biocontrol because it enables synchronization of production with market demand while reducing transportation costs. Low temperatures reduce metabolic rate, conserve energy reserves, and prolong shelf life without significantly affecting predatory performance if storage duration remains within species-specific limits (Table-3).

Table 3. Recommended Storage Conditions for Commercial Ladybird Beetles

Species	Temperature (°C)	Relative humidity (%)	Maximum storage period
C. montrouzieri	10–12	65–70	7–10 days
C. septempunctata	8–10	65–75	14–21 days
C. sexmaculata	10–12	60–70	7–10 days
Propylea dissecta	10-12	65-75	7-15 days
Hippodamia convergens	5–8	65–75	30–60 days (diapause)
Delphastus catalinae	10–12	65–70	7–10 days

Storage temperatures below species-specific thresholds may cause chilling injury, whereas prolonged storage may reduce fecundity, longevity, flight activity, and predation efficiency. Consequently, commercial insectaries continuously monitor temperature and humidity using automated environmental sensors. Transportation stress activates physiological responses including, such as, increased respiration, depletion of lipid reserves, oxidative stress, dehydration, reduced reproductive capacity, and impaired flight ability. The transportation exceeding 48–72 hours under suboptimal conditions significantly reduces field establishment and prey consumption (Riddick, 2017). Consequently, commercial producers increasingly use overnight courier services, temperature-controlled vehicles, and insulated shipping containers to minimize transit time. Every commercial shipment should undergo quality evaluation before release. The recommended parameters include, Survival (%), flight ability, walking activity, predation rate, female fecundity, adult weight, colour development, genetic purity, and absence of pathogens and parasitoids. The International Organization for Biological Control (IOBC) recommends standardized quality-control protocols to ensure consistency among commercial producers (van Lenteren et al., 2020).

Sustainable Packaging

Growing environmental awareness has encouraged insectaries to replace petroleum-based plastics with biodegradable materials. Recent innovations include, biodegradable cellulose containers, moulded paper pulp trays, compostable bioplastic tubes, recycled cardboard packaging, starch-based cushioning materials, mushroom mycelium packaging, and reusable shipping containers. Such sustainable packaging reduces environmental impact while improving consumer acceptance of biological control products.

Comparative Analysis of four companies

The four leading companies share several common principles in the handling of live biological control agents, although the specific packaging formats differ according to product design and marketing strategy (Table-4; Figure-1). The details of the four major companies are mentioned below:

Koppert Biological Systems, established in 1967 in the Netherlands, is amongst the world's leading companies in biological crop protection (Kapular, 2019). It emphasizes precision field deployment, using paper bags, cardboard release boxes (Dibox), and biodegradable carriers that can be placed directly in crop canopies. Products are distributed through an extensive cold-chain network, with storage recommendations typically limited to one or two days after delivery to preserve predator quality. This company supplies beneficial insects, including ladybird beetles, to more than 100 countries and has pioneered the commercialization of numerous natural enemies for greenhouse and field crops. Among its ladybird beetle products, Aphidalia® (*Adalia bipunctata*) is specifically developed for aphid management in orchards and woody crops (Rojht et al., 2009). Koppert emphasizes protective yet environmentally sustainable packaging. Aphidalia® is supplied in paper bags containing 100 larvae with buckwheat hulls as an inert carrier, which cushions the larvae during transport, maintains aeration, and facilitates gradual field release (Andrišić, 2019). The paper bag is designed to be hung directly on infested trees using wire or nails, thereby minimizing handling and reducing stress on the insects. This packaging system also promotes localized establishment because larvae emerge close to aphid colonies, where food is immediately available. To preserve insect quality, Koppert recommends that products be applied immediately after receipt or stored for no longer than 1–2 days at 8–10°C in darkness. The company relies on rapid distribution networks and insulated transport systems to maintain product quality throughout the supply chain. An additional innovation is the integration of its products into the Koppert One digital decision-support platform, which assists growers in selecting compatible biocontrol strategies and evaluating pesticide side effects on beneficial insects.

However, recently, Joubert (2026) criticised insects should not be confined to the lens of 'pest management' or 'pest lens' only. He further stated that without purpose-specific policy and regulation, this insect culture and industry will be susceptible to trade barriers due to legal uncertainty. Furthermore, Gómez et al. (2018) further commented that the augmentation of biocontrol agent commercialization will be driven by changes in the policies and regulatory focusing on eco-safety. However, these biocontrol products have concerns for human-safety, lack of residuality, safety with environment, *etc*.

Biobest Group NV, in Belgium, is another global leader in biocontrol and pollination technologies (Mathieu and Bernard, 2008). It has focused strongly on environmental sustainability by replacing conventional plastic packaging with biodegradable cardboard containers and honeycomb paper. The honeycomb structure cushions insects during transport while simultaneously acting as a convenient release substrate in the field. This approach reduces packaging waste and allows several release points from a single container (Čajkulić and Bažok, 2023). The company recently introduced Propylea-System®, based on the fourteen-spotted ladybird (*Propylea quatuordecimpunctata*), as a biological solution for aphid management in greenhouse vegetables and ornamentals (Ban et al., 2012). One of Biobest's major innovations is its 100% biodegradable packaging system. The predators are supplied in a cardboard cup containing approximately 250 adults, with honeycomb paper serving both as a cushioning material during transportation and as a release substrate in the crop. A water-containing gel formulation is incorporated to maintain humidity and reduce dehydration during shipping, ensuring that beetles arrive in excellent physiological condition. Unlike conventional plastic containers, the entire packaging including the cup, lid, and honeycomb insert can be placed directly in the crop after arrival, creating multiple release points while reducing plastic waste. This innovative approach simplifies field application, minimizes disturbance to the insects, and aligns with sustainable agriculture practices. Biobest emphasizes compatibility of Propylea-System® with parasitoids and other predators within integrated pest management programmes, allowing growers to combine several biological control agents effectively.

BioBee Biological Systems, founded in Kibbutz Sde Eliyahu, Israel, are also important producers of beneficial insects, including ladybird beetles (Lotan, 2011; Vacante, 2012; Veldkamp et al., 2022). The company markets ladybird beetles under products such as BioAdalia® (*Adalia bipunctata*) and BioCryptolaemus® (*Cryptolaemus montrouzieri*) for insect pest management. BioBee employs ventilated plastic bottles designed to ensure adequate air exchange while preventing escape and mechanical injury. It combines cold-chain transportation with nutritional support by placing honey-soaked paper inside ventilated containers. The honey provides a temporary carbohydrate source that helps maintain adult vigour during shipment. It recommends releasing beetles within 24 hours of receipt and transporting products in cooled, insulated shipping boxes to minimize heat stress. Its production system also operates under ISO 9001 quality management and follows IOBC quality standards for mass-produced beneficial insects. The containers may include honey-treated paper or similar nutritional substrates that provide a temporary carbohydrate source during transportation, helping maintain adult vigour and reducing starvation stress. Products are shipped in insulated, chilled boxes, and customers are advised to keep the packaging intact until the insects are placed in the crop. If immediate release is not possible, the beetles should be stored in their original containers in a cool, dark environment at 8–10°C, with protection from direct sunlight. BioBee recommends releasing predators during the early morning or late afternoon to avoid thermal stress and maximize establishment. The company also emphasizes comprehensive quality assurance through standardized production protocols and international quality management systems, contributing to consistent product performance in commercial agriculture.

Applied Bio-nomics Ltd., based in British Columbia, Canada, specializes in the commercial production of beneficial insects, and predatory mites for crop production (Shipp et al., 2007; Mader and Adamson, 2009). Although the company markets a broad portfolio of natural enemies, its handling procedures for ladybird beetles are representative of its overall emphasis on preserving biological quality during transport and field deployment. Applied Bio-nomics places particular emphasis on rapid delivery and technical support. Although specific packaging configurations vary among products, the company relies on ventilated containers, insulated shipping, refrigerated storage, and expedited transport to maintain the biological quality of living natural enemies until field release. Applied Bio-nomics uses ventilated vials, bottles, and release containers depending on the product and target market. Packaging generally incorporates inert carrier materials such as shredded paper or vermiculite to reduce mechanical injury during shipment. Refrigerated storage and overnight or expedited courier services are employed to minimize transit time and physiological stress, thereby ensuring that predators retain high mobility and predatory capacity upon arrival. Technical support accompanies product distribution, providing growers with guidance on storage, release timing, and integration with broader IPM programs. Unlike companies focusing primarily on packaging innovation, Applied Bio-nomics places particular emphasis on rapid logistics, customer support, and live-arrival quality assurance. This strategy has been especially successful in supplying greenhouse producers in North America, where timely delivery is essential because of the short shelf life of living biological control agents.

Table 4. Comparative Packaging and Transportation Protocols Used by Major Commercial Insectaries for Ladybird Beetles.

Company	Ladybird product(s)	Packaging format	Internal packing material	Storage recommendation	Transportation protocol	Release method	Notable innovations
Koppert Biological Systems, Netherlands	*Adalia bipunctata* (Aphidalia®)	Paper bags, cardboard release boxes (Dibox), bottles depending on product	Buckwheat hulls or inert carrier; breathable paper packaging	Refrigerated (typically **8–10°C**); apply as soon as possible, generally within 1–2 days after receipt	Temperature-controlled shipping; insulated cartons; rapid distribution through professional dealer network	Bags or release boxes are attached directly to plants or near infestation hotspots	Extensive use of biodegradable packaging, hotspot release systems (Dibox), sustainability-oriented packaging redesign
Biobest (Belgium)	*Propylea quatuordecimpunctata* (Propylea-System®)	Cardboard cups, biodegradable release containers	Honeycomb paper that cushions insects and serves as release substrate	Short-term cool storage; immediate field use recommended	Environmentally friendly packaging designed to minimize mechanical injury during transport	Honeycomb paper, lid, and cup can each be placed in the crop to create multiple release points	Fully biodegradable packaging, sustainable materials, multiple release-point design, reduced plastic use
BioBee (Israel)	*Cryptolaemus montrouzieri* (BioCryptolaemus®)	Ventilated plastic containers containing adults	Honey-soaked paper for temporary nourishment	Store cool; avoid sunlight; release within **24 hours** after arrival	Cooled insulated shipping boxes; cold-chain logistics; minimize exposure during unloading	Open container beside infestation or gently tap beetles onto plants during cool hours of the day	Integrated quality assurance (ISO 9001 and IOBC standards), insulated transport, nutritional support during shipping
Applied Bio-nomics Ltd. (Canada)	Other Ladybird beetles	Vials, ventilated bottles, release containers (product dependent)	Inert carrier materials, shredded paper or vermiculite (product dependent)	Refrigerated storage before release; avoid prolonged storage	Overnight or expedited shipping with insulated packaging and temperature protection	Manual distribution at pest hotspots following technical guidelines	Strong emphasis on live-arrival quality assurance, regional production, technical support, and rapid shipping to preserve insect vigor

Common Best Practices Adopted by Commercial Insectaries

Despite differences among companies, several best management practices are consistently followed:

1. Maintenance of an uninterrupted cold chain (generally 8–10°C for adult ladybird beetles).
2. Use of breathable containers to provide adequate ventilation while preventing escape.
3. Inclusion of cushioning materials (paper strips, buckwheat hulls, honeycomb paper, or inert carriers) to reduce mechanical injury.
4. Minimization of storage duration, with recommendations for release within 24–48 hours whenever possible.
5. Distribution through insulated shipping boxes with rapid courier services.
6. Preference for biodegradable and recyclable packaging materials to improve environmental sustainability.
7. Compliance with IOBC quality-control standards and national phytosanitary regulations for the transport of biological control organisms.

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Figure-1: Comparative Packaging and Transport Systems used by major commercial industries.

Emerging technologies are expected to further improve packaging and transportation. Future developments include, smart packaging with embedded IoT sensors for continuous monitoring of temperature, humidity, vibration, and oxygen. RFID and QR-code traceability systems for real-time shipment tracking. AI-based logistics platforms that optimize delivery routes and predict stress-related mortality. Nano-enabled moisture regulators and oxygen-scavenging materials to stabilize the transport environment. Drone-assisted last-mile delivery for protected cultivation and remote farming regions. Customized release devices that combine transport and field release in a single biodegradable package. These innovations will improve insect quality, reduce losses during transit, and strengthen the commercialization of ladybird beetles in both domestic and international markets.

Conclusion

We conclude that certain ladybird beetles possess immense potential to be used as biocontrol agents. The four companies discussed in this review are instrumental in propagating them at the industrial level. The growing awareness towards sustainable agriculture, environmental protection and biological control will inspire many more companies to come forward for the industrial mass-multiplication of ladybird beetles. The government regulatory bodies should also intervene in such programmes for the propagation of sustainable ecofriendly agriculture and food security.

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