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Bracon sp. (Hymenoptera: *Bracon*idae) as parasitoid wasps in biological control

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Abstract
Biological control is an important component of sustainable pest management that reduces reliance on chemical pesticides and promotes environmental safety. Species of the genus *Bracon* (Hymenoptera: *Bracon*idae) are among the most effective parasitoids used against several economically important insect pests. This review summarizes current knowledge on the taxonomy, biology, ecology, host range, parasitism mechanisms, mass-rearing techniques, and biological control applications of *Bracon* species. Particular emphasis is given to *Bracon hebetor*, *B. brevicornis*, and *B. nigricans*, which are widely used against lepidopteran pests such as *Spodoptera* spp., *Helicoverpa armigera*, *Tuta absoluta*, and stored-product moths. Their high reproductive potential, efficient host-searching ability, adaptability, and compatibility with Integrated Pest Management (IPM) programs make them valuable biocontrol agents. Recent advances in molecular tools and climate-related studies have improved understanding of their biology and field performance. Despite challenges related to mass production, storage, and commercialization, *Bracon* parasitoids remain promising agents for sustainable and eco-friendly pest management.

Keywords: *Bracon hebetor*, biological control, parasitoid, integrated pest management, mass rearing, sustainable agriculture

Introduction

Biological control is an important component of Integrated Pest Management (IPM) and is considered an eco-friendly and sustainable approach for managing insect pests (Cock *et al*., 2016; Lacey *et al*., 2015) [8, 20]. It reduces dependence on chemical pesticides through the use of natural enemies such as predators and parasitoids, thereby minimizing environmental damage and suppressing pest populations effectively. Parasitoids develop on or within a host insect and the developing larvae ultimately kill the host before emerging as adults to search for new hosts.

Among the important parasitoids used in biological control are species of the family *Bracon*idae, particularly the genus *Bracon*. This family is considered one of largest and most ecologically important, comprising over 40,000 described species worldwide (Salim *et al*., 2016) [26]. *Bracon* spp. are effective parasitoid wasps widely utilized for the management of several agricultural pests particularly lepidopteran and coleopteran larvae that damage crops and stored products due to their high parasitization ability, adaptability and suitability for mass rearing in IPM programs (Antolin *et al*., 1995) [4]. *Bracon* species are primarily larval ectoparasitoids or endoparasitoids that attack a wide range of holometabolous insects. The most extensively studied species, *Bracon hebetor* Say (often referred to as *HabroBracon hebetor* in older literature), has been recognized as an efficient biological control agent of lepidopteran pests for over a century (Agasyeva, 2021) [1]. Other species such as *B. brevicornis* and *B. nigricans* have also demonstrated significant biocontrol potential against major agricultural pests including *Spodoptera* spp. and *Tuta absoluta* (Ghosh *et al*., 202). By stinging the host larva, the parasitoid wasp injects a venom and paralyzes the host larva, which stops feeding and moving immediately (Abbas, 1980) [6]. Afterwards, eggs are laid on the outside of the host larva, which remains paralyzed. After hatching, the wasp larvae feed on their host and finally kill it.

These natural enemies offer several advantages: they are host-specific or oligophagous, can be mass-reared on factitious hosts, exhibit high searching efficiency and can be integrated into IPM programs (Mbata *et al*., 2019) [22]. However, successful implementation of *Bracon-based* biological control requires a comprehensive understanding of their taxonomy, biology, ecology and interactions with hosts and the environment.

This review synthesizes current knowledge on *Bracon* parasitoids from both classical and recent research (primarily 2011-2026), addressing 18 key thematic areas essential for their effective utilization in biological control. The review emphasizes studies with clear experimental evidence, field evaluations and applied relevance to agro-ecosystems, providing a foundation for future research and commercial development of *Bracon* based biocontrol products.

Taxonomy and Systematics

The genus *Bracon* belongs to the subfamily *Bracon*inae of the family *Bracon*idae, one of the largest families of parasitoid Hymenoptera. Members of this family are important biological control agents and are characterized by reduced wing venation and distinct metasomal features (Rakhshani *et al*., 2021) [24]. Taxonomic identification of *Bracon* species is mainly based on morphological characters such as body size, coloration, antennal segments, wing venation, mandible structure and metasomal tergites. However, considerable morphological variation and the presence of cryptic species complexes make species identification difficult (Salim *et al*., 2016) [26].

Bracon hebetor, one of the most important species used in biological control, is characterized by a small body size (3-4 mm), dark brown to black colouration, yellowish legs and distinct forewing venation patterns. The species previously placed under *HabroBracon* is now considered a synonym of *Bracon* (Mbata *et al*., 2019) [22]. In mass-rearing programs,

morphometric parameters such as body length, wing length, ovipositor length and antennal segments are used for quality assessment and detection of genetic deterioration in laboratory colonies (Veiga *et al*., 2013) [28]. Nevertheless, accurate identification remains challenging because closely related species often show similar morphology and life-cycle characteristics (Alam *et al.,* 2015) [3].

The genus *Bracon* shows high species diversity and includes several hundred described species distributed across different zoogeographic regions. The subfamily *Bracon*inae contains nearly 2,800 described species worldwide, with *Bracon* being one of its largest genera (Salim *et al*., 2016) [26]. Species diversity is generally higher in tropical regions compared to temperate areas. Distinct *Bracon* faunas occur in the Palearctic, Nearctic, Neotropical, Afrotropical, Oriental and Australasian regions, although some species have cosmopolitan distributions due to human-mediated spread through agricultural trade (Mbata *et al*., 2019) [22].

Several species of *Bracon* are widely used in biological control programs. *Bracon hebetor* is one of the most important species, originally native to the Palearctic region but now distributed worldwide for the control of stored-product pests and lepidopteran larvae (Mbata *et al*., 2019; Agasyeva, 2021) [1, 22]. *Bracon brevicornis* has gained importance in Asia for managing *Spodoptera* species, including the invasive fall armyworm *Spodoptera frugiperda*, due to its high parasitization efficiency (Ghosh *et al*., 2021; Moustafa *et al*., 2023) [14, 23]. Similarly, *Bracon nigricans* and *Bracon didemie* have shown promising potential against the tomato leaf miner *Tuta absoluta*, particularly in Mediterranean and nearby regions (Karut *et al*., 2023) [19].

Biology and Ecology

The life cycle of *Bracon* species follows complete metamorphosis, consisting of egg, larval, prepupal, pupal and adult stages. Development from egg to adult generally requires 10-30 days depending on species, host quality, temperature and humidity (Gould *et al*., 2011; Dabhi, 2013; Souna, 2018) [10, 15, 27]. The egg stage lasts about 1-3 days, followed by three larval instars developing over 5-15 days. In many species, the early larval instars develop internally within the host, while the final instar feeds externally, a phenomenon known as endo-ectoparasitism (Dabhi, 2013; Souna, 2018) [10, 27]. After completing feeding, the mature larva enters the prepupal stage and forms a silken cocoon for pupation. The pupal period usually lasts 5–15 days under favorable conditions (Dabhi, 2013; Gould *et al*., 2011) [10, 15].

Adult *Bracon* wasps are small parasitoids, usually measuring 2-6 mm in length, with coloration varying from dark brown or black to yellowish or reddish markings. Females are generally larger than males and possess a longer metasoma with a short ovipositor adapted for parasitizing host larvae, whereas males have comparatively more antennal segments associated with pheromone detection (Dabhi, 2010; Veiga *et al*., 2013; Saadat *et al*., 2016) [9, 25, 28].

Fecundity and longevity in *Bracon* species are greatly influenced by host quality, environmental conditions and food availability. Females of *Bracon hebetor* can produce 50–300 offspring during their lifetime, making them highly effective biological control agents (Aswini *et al*., 2024) [5]. *Bracon* species generally exhibit arrhenotokous reproduction, where males develop from unfertilized eggs and females from fertilized eggs, a characteristic feature of Hymenoptera (Saadat *et al*., 2016) [25].

The distribution of *Bracon* species is influenced by host availability and climatic conditions. Many species are polyphagous and parasitize larvae of several lepidopteran families, enabling their establishment in diverse agricultural ecosystems (Maeto, 2018) [21].

Climate change can significantly influence the effectiveness of *Bracon* parasitoids in biological control by altering temperature, rainfall patterns and host–parasitoid interactions. Rising temperatures may expand the distribution of some *Bracon* species and improve control of invasive pests, but extreme climatic conditions can disrupt host synchronization, reduce parasitoid survival and affect biological control efficiency (Gesraha *et al*., 2022) [13]. Therefore, understanding thermal tolerance, population dynamics and adaptive responses of parasitoids is important for developing climate-resilient biological control strategies.

Bracon hebetor is widely recognized as an important parasitoid in pest management and can complete 8–12 generations annually under favorable conditions, supporting its effectiveness in biological control programs (Mbata *et al*., 2019) [22].

Parasitism Strategy and Host Preference

Bracon species exhibit parasitism strategies ranging from ectoparasitism to endo-ectoparasitism. *Bracon hebetor* is a gregarious ectoparasitoid that lays multiple eggs on paralyzed host larvae, while some species develop internally during early larval stages before feeding externally (Ghosh *et al*., 2021; Souna, 2018) [14, 27]. Most *Bracon* species are idiobiont parasitoids that stop further host development after parasitism, which supports efficient mass rearing (Maeto, 2018) [21].

Bracon species mainly parasitize larval stages of lepidopteran hosts, with *B. hebetor* showing preference for late-instar larvae due to their higher nutritional suitability (Aswini *et al*., 2024) [5]. Host stage and quality significantly influence parasitoid development, survival and reproductive potential (Souna, 2018) [27].

Host Range and Pest Targets

Bracon species exhibit diverse parasitism strategies ranging from ectoparasitism to endo-ectoparasitism. Among them, *Bracon hebetor* is a well-known gregarious ectoparasitoid that lays multiple eggs on or near paralyzed host larvae and is known to parasitize over 60 lepidopteran species across multiple families such as Pyralidae, Noctuidae, Gelechiidae, Crambidae and Tortricidae (Mbata *et al.,* 2019; Agasyeva, 2021) [1, 22]. This broad host range enhances its importance in biological control programs by allowing survival on alternative hosts and use against multiple pest species. However, the polyphagous nature of some *Bracon* species may also pose risks to non-target and beneficial lepidopteran insects, particularly in classical biological control programs, highlighting the need for careful host-specificity assessment before large-scale release (Maeto, 2018) [21].

Aswini *et al*. (2024) [5] evaluated *B. hebetor* performance on five lepidopteran hosts (*Corcyra cephalonica*, *Galleria mellonella*, *Spodoptera litura*, *Helicoverpa armigera* and *Pericallia ricini*), documenting significant variation in all fitness parameters. *C. cephalonica* and *G. mellonella* supported superior parasitoid development and reproduction

compared to other hosts, explaining their widespread use as factitious hosts in mass rearing. Ghosh *et al*. (2021) [14] compared *B. brevicornis* performance on two *Spodoptera* species (*S. litura* and *S. frugiperda*), finding that while both hosts were suitable, parasitoid development was faster and survival higher on *S. litura*. This differential suitability has implications for biological control of the invasive fall armyworm *S. frugiperda*, suggesting that *B. brevicornis* may require adaptation or selection for improved performance on this novel host.

Host preference may differ from host suitability, with parasitoids sometimes preferring hosts that do not maximize their fitness. Behavioral assays are necessary to distinguish innate host preferences from learned responses based on prior experience. Understanding both preference and suitability is critical for predicting parasitoid efficacy against target pests in complex agricultural environments (Aswini *et al*., 2024) [5].

Host–parasitoid interactions have also driven the evolution of defense and counter-defense mechanisms, with *Bracon* species developing effective venoms and parasitization strategies to overcome host immune responses. The venom of *Bracon brevicornis* effectively suppresses immune responses in both *S. litura* and *S. frugiperda*, including the invasive fall armyworm, indicating that the venom targets conserved immune mechanisms present in lepidopteran hosts (Ghosh *et al*., 2021) [14].

Host developmental stage and size greatly influence parasitism success and parasitoid fitness in *Bracon* species. Most species prefer mid- to late-instar larvae, which provide sufficient nutrition for offspring development, although very large hosts may exhibit stronger defense responses (Aswini *et al*., 2024) [5]. Host age also affects parasitoid development, fecundity and survival, thereby influencing biological control efficiency (Souna, 2018) [27].

In agricultural ecosystems, *Bracon* parasitoids often encounter multiple host species and can switch to alternative hosts when necessary. This ability enhances parasitoid survival and biological control potential against invasive pests such as *S. frugiperda* and *Tuta absoluta* (Ghosh *et al*., 2021) [14]

Mechanism of Parasitism

Bracon species parasitize mainly the larval stages of lepidopteran insects through a series of behavioural and physiological mechanisms. Female parasitoids first locate suitable hosts using chemical and physical cues emitted by host insects and infested plants. After locating the host, the female injects venom through its ovipositor, causing paralysis and suppressing host immune responses. In ectoparasitoid species such as *Bracon hebetor*, the venom induces permanent paralysis, preventing host movement and further development while keeping host tissues fresh for larval feeding (Mbata *et al*., 2019) [22].

Following paralysis, the female lays eggs on or near the host body. The emerging larvae feed on host tissues and complete development through several larval instars. In some species, early larval stages develop internally before feeding externally, a strategy known as endo-ectoparasitism (Souna, 2018) [27]. Venom composition varies among species and contains enzymes, peptides, proteases, phosphatases and other bioactive compounds that aid in host paralysis, immune suppression and successful parasitoid development (Souna, 2018) [27]. Venom suppresses host immune responses by reducing haemocyte activity and inhibiting encapsulation (surrounding parasitoid eggs or larvae with haemocyte) and melanization (surrounding parasitoid eggs or larvae with haemocyte) processes, thereby enabling parasitoid larvae to survive and develop successfully within the host (Ghosh *et al*., 2021) [14].

Paralysis and Host Regulation

In ectoparasitoid *Bracon* species such as *Bracon hebetor*, venom-induced paralysis is essential for preventing host movement and maintaining host tissues suitable for larval feeding. The paralysis is generally permanent, keeping the host alive but immobile and suppressing further development and immune responses (Mbata *et al*., 2019) [22]. This paralysis is mainly caused by neurotoxic venom components that disrupt normal neuromuscular signaling in the host (Ghosh *et al.*, 2021) [14]. The diversity of venom composition in *Bracon* species reflects their adaptation to different hosts and parasitism strategies. Comparative studies of venom components can help explain host specialization and improve the effectiveness of biological control programs. Souna (2018) [27] developed PCR primers for detection of *T. javanus* based on venom gland-expressed genes, demonstrating the applied utility of venom research for molecular diagnostics.

Mass Rearing Techniques

Successful mass rearing of *Bracon* parasitoids requires selection of suitable factitious hosts, *i.e.,* alternative hosts that are easily reared in large numbers and support high-quality parasitoid production. The most widely used factitious hosts are *Galleria mellonella* (greater wax moth) and *Corcyra cephalonica* (rice moth), both of which are easily reared on artificial diets and support excellent parasitoid development (Alam *et al.,* 2015; Hasan *et al*., 2019). Aswini *et al.* (2024) [3, 5, 16] compared *B. hebetor* performance on five lepidopteran hosts, documenting that *C. cephalonica* and *G. mellonella* supported superior development, survival and fecundity compared to other hosts. These species have become standard factitious hosts for the commercial production of *B. hebetor* worldwide.

Recent innovations include use of gamma-irradiated hosts for parasitoid production. Hasan *et al*. (2019) [16] demonstrated that irradiated *G. mellonella* and *Plodia interpunctella* larvae could be used for mass rearing *H. hebetor*, with irradiation preventing host development and emergence while maintaining suitability for parasitoid development. Similarly, Moustafa *et al.* (2023) [23] showed that gamma-irradiated hosts enhanced *B. brevicornis* production, potentially reducing costs and improving efficiency of mass rearing programs.

Parasitoid and host density significantly affect mass rearing efficiency, influencing parasitism rates, offspring quality and production costs. At very low host densities, parasitoids may fail to locate hosts efficiently, reducing parasitism rates. At very high densities, hosts may interfere with each other or deplete resources, reducing host quality and parasitoid fitness. Optimal host densities typically range from 50-100 larvae per rearing container, depending on container size and host species (Alam *et al*., 2015) [3].

Maintaining optimal environmental conditions is critical for efficient mass rearing. Temperature is typically maintained at 25-28 °C for *B. hebetor*, balancing rapid development with high survival and fecundity. Relative humidity is

maintained at 60-75% RH to prevent desiccation while minimizing fungal growth. Photoperiod is typically set at 14:10 or 16:8 (L:D) to promote continuous reproduction without diapause induction (Gould *et al*., 2011; Alam *et al.*, 2015) [3, 15].

Provision of adult nutrition is essential for maintaining fecundity and longevity in mass-reared parasitoids. Honey or sugar water (10-50% solutions) are commonly provided on cotton wicks or as droplets on rearing container surfaces. Some protocols also provide pollen or protein supplements to enhance egg production, though the benefits vary among species (Hasan *et al*., 2019) [16].

Host Searching and Foraging Behaviour

Bracon parasitoids employ efficient host-searching and foraging strategies that contribute significantly to their effectiveness as biological control agents. Females locate hosts using chemical cues released from host-infested plants, damaged plant tissues and host frass. These herbivore-induced plant volatiles help parasitoids identify habitats containing suitable hosts (Souna, 2018) [27]. After locating potential hosts, females use antennal and tarsal sensilla to recognize host species, developmental stage and host suitability before oviposition.

Host acceptance behaviour is influenced by host quality, host density and previous parasitism status. *Bracon* females generally prefer healthy and unparasitized larvae, avoiding superparasitism whenever possible (Mbata *et al*., 2019) [22]. Gregarious species such as *Bracon hebetor* can also adjust clutch size according to host size, depositing more eggs on larger hosts to maximize reproductive success (Aswini *et al*., 2024) [5]. In addition, *Bracon* parasitoids exhibit behavioural plasticity and associative learning, enabling them to improve foraging efficiency through experience. Such adaptive host-searching behaviour enhances their performance in both field crops and stored-product ecosystems.

Role in Biological Control Programs

Bracon species have shown considerable effectiveness against major lepidopteran pests in various agricultural crops. *Bracon brevicornis* has demonstrated high parasitism rates against the invasive fall armyworm *Spodoptera frugiperda*, indicating its potential for integration into IPM programs (Ghosh *et al*., 2021) [14]. Similarly, *Bracon nigricans* and *Bracon didemie* have proven effective against the tomato leaf miner *Tuta absoluta*, significantly reducing pest populations and crop damage under greenhouse and field conditions (Karut *et al*., 2023) [19]. Field studies on *Bracon hebetor* have also reported successful suppression of important pests such as *Helicoverpa armigera* and *Ostrinia nubilalis*, particularly when combined with other biological control agents in integrated pest management systems (Agasyeva *et al*., 2023) [2].

Although *Bracon* species mainly parasitize lepidopteran pests, some *Bracon*id parasitoids are also effective against coleopteran pests, particularly wood-boring beetles. Species such as *Spathius agrili* and *Spathius galinae* have shown successful establishment and suppression of the invasive emerald ash borer *Agrilus planipennis*, contributing to classical biological control programs (Gould *et al.*, 2011 [15]; Duan *et al*., n.d.). Similarly, *Ontsira mellipes* has been studied for the management of the Asian longhorned beetle *Anoplophora glabripennis* through mass-rearing approaches (Wang *et al*., n.d.).

Bracon hebetor is also widely utilized in stored-product pest management because of its ability to locate concealed hosts and tolerate storage conditions. It has been effectively used against important storage pests such as *Plodia interpunctella*, *Ephestia kuehniella* and *Sitotroga cerealella*, with field studies reporting significant reductions in pest populations and grain damage (Mbata *et al*., 2019) [22]. Natural parasitism by *B. hebetor* has also been observed in vegetable ecosystems, highlighting its importance in conservation and augmentative biological control programs (José *et al.*, 2025) [18].

The field efficacy of *Bracon* parasitoids is influenced by several factors, including release rate, release timing, environmental conditions, habitat complexity and pest density. Appropriate parasitoid release rates and synchronization with susceptible host stages are important for achieving effective pest suppression (Karut *et al*., 2023) [19]. Temperature, humidity and weather conditions also affect parasitoid survival, dispersal and parasitism efficiency (Gesraha *et al*., 2022) [13]. In addition, crop architecture and habitat diversity influence host-searching behavior, while very high pest populations may reduce the effectiveness of parasitoids if not integrated with other pest management strategies (José *et al.*, 2025; Ghosh *et al.*, 2021) [14, 18].

Role in Integrated Pest Management

Bracon parasitoids play an important role in IPM by providing long-term suppression of insect pests with minimal non-target effects (Jha *et al*., n.d.). *Bracon* species are utilized in classical, augmentative and conservation biological control programs. Augmentative releases of mass-reared parasitoids such as *Bracon hebetor* are widely used in stored products and field crops, while conservation biological control focuses on preserving natural parasitoid populations through habitat management and reduced pesticide use (Mbata *et al.*, 2019; José *et al*., 2025) [18, 22].

Cultural practices can further enhance parasitoid efficiency in IPM systems. Crop rotation, adjustment of planting dates, sanitation and maintenance of non-crop vegetation such as flower strips and hedgerows provide alternative hosts, nectar sources and overwintering sites for parasitoids, thereby improving their survival and persistence in agricultural ecosystems (Salim *et al*., 2016) [26].

Bracon parasitoids can be effectively integrated with physical, mechanical and monitoring-based pest management practices in IPM programs. Methods such as pheromone traps help reduce pest populations and assist in determining optimal timing for parasitoid releases, while exclusion barriers like nets and screens can limit pest entry without affecting parasitoid activity (Agasyeva *et al.*, 2023; Karut *et al*., 2023) [2, 19]. In stored-product systems, temperature management combined with parasitoid releases has shown improved pest suppression (Mbata *et al*., 2019) [22].

Decision support systems based on pest monitoring, parasitism assessment, weather conditions and economic thresholds are important for improving the efficiency of *Bracon*-based biological control. Several IPM case studies have demonstrated that combining *Bracon* parasitoids with pheromone traps, selective insecticides, sanitation and entomopathogenic agents provides better pest suppression

and reduces dependence on chemical pesticides (Agasyeva *et al*., 2023; Mbata *et al*., 2019) [2, 22].

Compatibility with Chemical and Biological Pesticides

Bracon parasitoids can be effectively integrated with selective chemical and biological pesticides in Integrated Pest Management programs. Compatibility depends on pesticide toxicity, application timing and exposure level. Selective pesticides such as insect growth regulators, microbial insecticides and some botanical products generally show lower toxicity to parasitoids compared to broad-spectrum insecticides (Mbata *et al*., 2019) [22]. Microbial agents such as *Bacillus thuringiensis*, *Beauveria bassiana* and *Metarhizium anisopliae* are often compatible with *Bracon* species when applied properly (Agasyeva *et al*., 2023) [2].

Pesticide applications can be optimized through ecological and temporal selectivity, including spot treatments, reduced-risk formulations and application before parasitoid release to minimize parasitoid mortality (Vreysen *et al*., 2011) [29]. Integration of parasitoids with selective pesticides also supports pesticide resistance management by reducing excessive chemical use and enhancing sustainable pest suppression. Proper monitoring of pest and parasitoid populations is essential for successful integration in IPM programs (Karut *et al*., 2023) [19].

Interactions with Other Natural Enemies

Bracon parasitoids are affected by interactions with predators, hyperparasitoids and other parasitoid species. Predators such as spiders, ants and lacewings may feed on parasitized hosts or adult parasitoids, reducing biological control efficiency (Rakhshani *et al*., 2021) [24]. Hyperparasitoids from families like Pteromalidae and Eulophidae can also decrease parasitoid effectiveness.

Competition among parasitoid species may occur when they attack the same host, while positive interactions with other natural enemies, such as *Trichogramma* spp., can improve pest suppression (Maeto, 2018; Agasyeva *et al*., 2023) [2, 21]. Habitat management and conservation biological control help maintain stable and effective natural enemy communities in agricultural ecosystems (José *et al*., 2025) [18].

Advantages of *Bracon* spp. in Pest Management

Bracon species are important biological control agents due to their high parasitism efficiency, wide host range and adaptability to different agroecosystems. They effectively parasitize several economically important lepidopteran pests, reducing pest populations and crop damage in both field and stored-product systems (Mbata *et al*., 2019) [22].

One major advantage of *Bracon* parasitoids is their eco-friendly nature. They reduce dependence on chemical pesticides, minimize pesticide residues and help conserve environmental and human health. Most species are host-specific or selective, thereby lowering harmful effects on non-target organisms and beneficial insects compared to broad-spectrum insecticides (Maeto, 2018) [21].

Bracon species also possess high reproductive potential, short generation time and ease of mass rearing on factitious hosts such as *Corcyra cephalonica* and *Galleria mellonella*. These characteristics make them suitable for augmentative biological control programs and commercial production (Alam *et al*., 2015) [3]. In addition, their compatibility with Integrated Pest Management (IPM) practices and selective pesticides enhances their effectiveness in sustainable agriculture.

Another important advantage is their ability to adapt to diverse environmental conditions and attack multiple pest species. Some species, such as *Bracon hebetor* and *Bracon brevicornis*, exhibit strong host-searching behavior and venom-induced host paralysis, improving parasitism success and biological control efficiency (Ghosh *et al.,* 2021) [14].

Constraints and Challenges

- High production costs for labor, rearing facilities and consumables limit large-scale commercialization of *Bracon* parasitoids (Alam *et al.,* 2015) [3].
- Maintaining parasitoid quality over successive generations requires strict quality control and genetic management (Veiga *et al*., 2013) [28].
- Limited shelf life and storage potential complicate transport and field distribution (Mbata *et al*., 2019) [22].
- Environmental conditions such as temperature, humidity and weather strongly affect parasitoid survival and efficacy (Gesraha *et al*., 2022) [13].
- Limited dispersal ability and mismatch between parasitoid activity and susceptible host stages can reduce biological control success (Canale *et al*., 2012) [7].
- Registration and biosecurity regulations for biological control agents are often lengthy and expensive (Vreysen *et al*., 2011) [29].
- Accurate species identification remains difficult because of cryptic diversity and morphological similarities (Souna, 2018) [27].
- Limited farmer awareness, infrastructure requirements and dependence on chemical pesticides restrict wider adoption of parasitoid-based IPM programs (Jha *et al*., n.d.).

Advances in Molecular and Climate-Related Studies

Recent advances in molecular and genomic studies have improved the identification and understanding of *Bracon* parasitoids. Techniques such as DNA barcoding, molecular diagnostics, transcriptomics and population genomics help in species identification, venom analysis and assessment of genetic diversity (Souna, 2018) [27]. These approaches also support quality control and improvement of biological control efficiency.

Climate change studies have highlighted the influence of temperature and environmental changes on parasitoid distribution, phenology and host interactions. Understanding thermal tolerance and adaptive responses is important for developing climate-resilient biological control strategies (Gesraha *et al*., 2022) [13].19. Future Prospects for Commercialization and Sustainable Agriculture

Future Prospects

Recent advances in molecular tools, mass production technology and precision agriculture have improved the potential use of *Bracon* parasitoids in sustainable pest management. Growing demand for pesticide-free food, improved rearing techniques, selective breeding and integration with precision agriculture are expected to enhance the commercial application of *Bracon* species in biological control programs (Jha *et al*., n.d.; Mbata *et al*., 2019) [22].

Conclusion

The genus *Bracon* encompasses diverse parasitoid wasp species with significant potential for biological control of lepidopteran and coleopteran pests in agricultural and stored product systems. This comprehensive review has synthesized current knowledge across 18 key thematic areas, from taxonomy and systematics through field efficacy and prospects for commercialization. Several *Bracon* species, particularly B. hebetor, B. brevicornis and B. nigricans , have demonstrated substantial efficacy against major agricultural pests including Spodoptera spp., Tuta absoluta , stored product moths and wood-boring beetles. These parasitoids exhibit favorable biological characteristics for biocontrol including broad host ranges within target pest groups, amenability to mass rearing on factitious hosts, effective host-finding and parasitism behaviors and potent venom-mediated immune suppression mechanisms that ensure high parasitism success. Recent advances in molecular diagnostics, transcriptomics and genomics have provided new tools for species identification, quality control and understanding of parasitoid biology at the molecular level. Venom transcriptome studies have revealed the complex molecular arsenal that *Bracon* species employ to suppress host immunity and regulate host physiology, opening avenues for enhancing parasitoid efficacy through selective breeding or biotechnology. Climate change research has highlighted the importance of understanding parasitoid thermal biology and phenological responses to predict and adapt to changing environmental conditions. However, significant challenges remain for widespread implementation of *Bracon* -based biological control. Production costs, quality maintenance in mass-reared colonies, limited shelf life, environmental sensitivity and regulatory constraints all present obstacles to commercialization. Addressing these challenges requires continued research on mass rearing optimization, storage and formulation technology, selective breeding for enhanced performance and development of decision support systems for IPM integration. The future of *Bracon* parasitoids in sustainable agriculture is promising, driven by growing market demand for biological control, regulatory restrictions on synthetic pesticides and advances in production and application technology. Integration with precision agriculture, development of improved strains through selective breeding and supportive policies and institutions will be critical for realizing the full potential of these natural enemies. As components of diversified IPM programs, *Bracon* parasitoids can contribute to the transition toward sustainable agricultural systems that minimize environmental impacts while maintaining productivity and profitability. Continued interdisciplinary research integrating taxonomy, ecology, physiology, molecular biology and applied entomology will be essential for advancing *Bracon* based biological control. Collaboration among researchers, industry, extension specialists and farmers will ensure that scientific advances are translated into practical applications that benefit agricultural sustainability and food security.

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