



Harnessing Tachinid Parasitoids for Sustainable Pest Management in Agriculture

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Abstract: *Tachinid parasitoids (Diptera: Tachinidae) represent one of the most diverse and ecologically significant groups of flies, functioning as natural biological control agents in various ecosystems. They parasitize a wide range of insect hosts, primarily Lepidoptera and Coleoptera, contributing to the regulation of pest populations and ecological balance. This review highlights their taxonomy, host range, ecological significance, and the role they play in Integrated Pest Management (IPM). It also explores the physiological and behavioral mechanisms underlying parasitism, including host location cues, hormonal manipulation, and host parasitoid coevolution. Furthermore, the paper discusses environmental and ecological factors influencing their field success, such as habitat diversity, pesticide use, and climate change. Emerging biotechnological tools including genomics, bioinformatics, CRISPR-based genetic engineering, and microbial consortia offer new prospects for enhancing Tachinid efficacy in sustainable pest management. Despite challenges like habitat loss, operational failures, and incomplete knowledge of host selection behavior, ongoing research and ecological innovations promise to strengthen their integration into modern IPM systems and advance eco-friendly agriculture.*

Keywords: *Tachinid parasitoids, Host selection cues, Oviposition behavior, Ecological interactions, Habitat management, biological control, Integrated Pest Management (IPM), Biocontrol agent (BCA) establishment, Compatibility (with control methods), Molecular techniques*

1. Introduction

Tachinid parasitoids belong to the family *Tachinidae* in the order *Diptera* and are a vast group of flies that maintain a parasitic relationship with host insects (Panda et al., 2025). These parasitoids are particularly important from an ecological perspective due to their contribution to limiting pest populations and preying mainly upon Lepidoptera, Heteroptera, and other insect groups (Stireman et al., 2006; Yeh et al., 2025). The classification of *Tachinidae* has altered substantially over time and has been impacted by many contributions aimed at identifying the family taxonomy (O'Hara, 2013; Cerretti et al., 2017).

Historically, this classification has shifted in the direction of the superfamily Oestroidea, which now generally adopts the scheme with a common agreement regarding the various subfamilies and tribes (O'Hara, 2013; Stireman et al., 2006). *Tachinidae* is considered monophyletic and closely related to Sarcophagidae, with supportive systematic positioning within the *Diptera* order (Stireman et al., 2019; Cerretti et al., 2017). Tachinid flies use a large number of cues for subsequent location and selection when identifying a host, which may rely on a developed visual

orientation system, especially host motion, or environmental cues such as chemical volatiles from damaged host plants (Stireman, 2002; Yeh et al., 2025).

Tachinids exhibit a wide range of host selection strategies and ovipositions and may have host selection flexibility that allows them to use a wide variety of hosts, a characteristic often noted in comparison to parasitic wasps (Belshaw, 1994). In terms of evolutionary adaptations, some *Tachinidae* display developed sensory adaptations that might include tympanal hearing organs to better locate hosts, although not all of the tachinid flies exhibit it (Cerretti et al., 2017; Lakes-Harlan et al., 2000).

Tachinid flies (family name *Tachinidae*) are crucial natural enemies of agroecosystems because these insects help in controlling pest insects (Quicke et al., 2025; Barrett et al., 2025; Stireman et al., 2006). The flies are known as parasitoids (and sometimes hyperparasitoids), because their development occurs in the body or on another part of the host insect's body, which eventually kills the host (Stireman et al., 2006; Falcon-Brindis et al., 2024; Gaviria et al., 2024). Parasitism in Tachinids is directed on lepidopteran and coleopteran pests that affect different parts of forests, crops, and fruit trees, thus making Tachinid flies important in the biotic control of pests (Quicke et al., 2025; Barrett et al., 2025; Dios et al., 2024).

Moreover, Tachinid flies play an essential role in the biotic control of pests as an independent aspect (Quicke et al., 2025; Barrett et al., 2025; Stireman et al., 2006). Their population in agroecosystems contributes to various ecological services that support sustainable agriculture (Yeh et al., 2025; Stireman et al., 2006). According to various ecological studies, the number and diversity of Tachinid flies can be positively related to the presence of semi-wild perennials or diverse flowering plants found in agricultural fields, which provide necessary habitats and adult food sources (Ellis & Bradley, 1996; Stireman et al., 2006).

This means that a diverse habitat provides resources for these flies, which, in turn, offer effective biotic control services in cultivated areas (Ellis & Bradley, 1996). This service plays an intermediate role where the flies have to breed, since their food source, the pest insects, are found in trained fields (Quicke et al., 2025; Barrett et al., 2025). Moreover, in relation to natural pest controllers, Tachinid flies are important components of applied biological control programs which are widely adopted across the globe (Dios et al., 2024).

These programs employ inoculative, augmentative, or inundative strategies to release Tachinid flies into the field, possibly to suppress pests' population on a broader scale (Quicke et al., 2025; Barrett et al., 2025; Stireman et al., 2006). The rate of success using biological control means may depend on several factors including species-specific interactions between the Tachinid flies and the targeted pest, ecological monitoring, and habitat management (Dios et al., 2024;). In general, Tachinid flies provide a critical service in the management of pests for agroecosystems' sustainability, and in so doing, they help strengthen the stability in production and biodiversity of the agricultural landscape (Ellis & Bradley, 1996). Conclusively, this therefore emphasizes the necessity of agricultural conservation to realize continued benefits from these important natural life forms (Panda et al., 2025)

Figure1.1 Tachinid parasitoids (*Diptera Tachinidae*)



2. Tachinid Parasitoids: Diversity, Host Range, and Ecological Significance

Tachinid parasitoids, a highly diverse family in the *Diptera* order, are ecologically significant taxa due to their broad host range and ecological impact (Stireman et al., 2006; O'Hara, 2013). These flies are larval parasitoids of Lepidoptera (moths and butterflies) and represent vital natural enemies in multiple terrestrial ecosystems (Heraty et al., 2017; Inclán Luna et al., 2015; Dios et al., 2014; Falcon-Brindis et al., 2024; Gaviria et al., 2024).

The worldwide diversity of tachinid parasitoids encompasses a wide range of host specificity, which varies dramatically among species, ranging from extremely specialized taxa to those with broad host ranges that parasitize specimens across multiple taxa (Stireman et al., 2006; Cerretti et al., 2017). The diversity in ecology and inherent relationship make tachinids an ideal system for

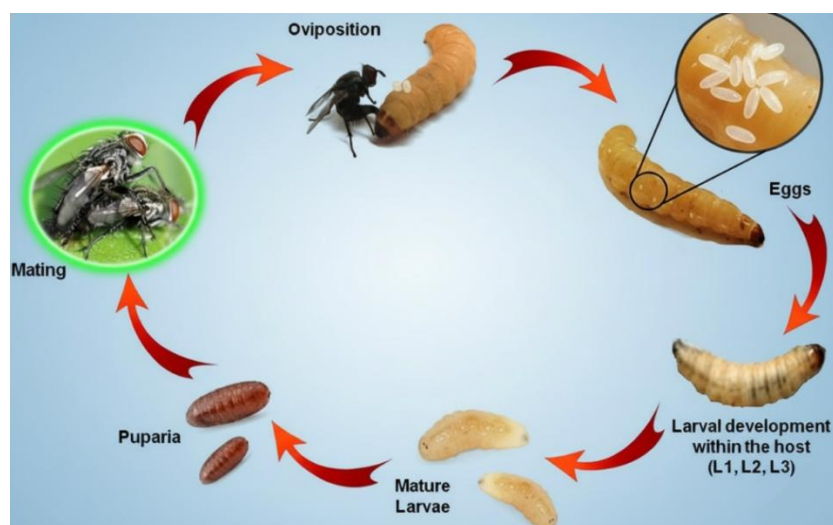
examining the dynamics of host association and the ecological and historical processes that underlie these patterns (Heraty et al., 2017; Inclán Luna et al., 2015; Dios et al., 2014; Wood, 1987). Phylogenetic groupings within *Tachinidae* have been demonstrated to impact the host range, as have the modes of reproduction (Wood, 1987).

However, specific ecological determinants, such as host abundance, gregariousness, food plant type, and host morphology, are more important influences on host choice (Stireman et al., 2006; Wood, 1987). Notably, the phylogenetic associations between the tachinid species and their hosts are less predictive of actual usage, indicating that ecological conditions likely have a stronger impact (Stireman et al., 2006). Many tachinids use different modalities to locate and choose their hosts (Falcon-Brindis et al., 2024; Gaviria et al., 2024).

For example, the generalist *Exorista mella* relies on actual host movement, as well as volatiles from the decaying host food, rather than chemical cues directly from the hosts themselves (Stireman, 2002). Work has revealed that some economically relevant tachinid species presumed to be polyphagous (having a broad host range) are instead cryptic groups composed of host-specific species (Stireman et al., 2019; Cerretti et al., 2017). Use of DNA barcoding has also revealed that the global species richness of *Tachinidae* is likely underestimated due to the occurrence of cryptic diversity, complicating taxonomy (O'Hara, 2013).

In other words, the ecological importance of tachinid parasitoids also includes their effect on parasitism rates, which in turn contributes to the maintenance of ecological balance due to an increased community within the number of parasitoids (Falcon-Brindis et al., 2024; Gaviria et al., 2024). Nevertheless, this trend may depend on the type of habitat and human factors (such as agricultural practices), which implies that the interplay between tachinid hosts and parasitoids is even more complicated than it seems and sensitive to environmental changes (Quicke et al., 2025; Barrett et al., 2025; Ellis & Bradley, 1996). At the same time, conviction of the additionality of detailed information on the full range of interactions between tachinids and their hosts is contained, which is a boost for the introduction of new methods to study these complicated ecological networks, such as DNA metabarcoding (Stireman et al., 2019). First and foremost, the species of the *Exorista* genus are tachinid parasitoids, which means they differ from other insect parasitoids in terms of locating and parasitizing their hosts (Letourneau et al., 2015; Burington et al., 2020; Gaviria et al., 2024; Chen et al., 2020; Weber et al., 2020).

Figure2.1 Life cycle of Tachinid parasitoids (*Diptera Tachinidae*)



3. Role in Integrated Pest Management (IPM)

The tachinid parasitoids have contributed significantly to Integrated Pest Management (IPM) through adding an environmentally friendly and sustainable way to control insect pests (Stireman et al., 2006; Quicke et al., 2025; Barrett et al., 2025). Based on the *Tachinidae* family, these parasitoids have provided an effective biological control agent within the IPM discipline through parasitism (Falcon-Brindis et al., 2024; Gaviria et al., 2024). The parasitoid's ability to reduce the populations of insect pests naturally by their parasitic behavior to specific insect hosts has been one of the important contributions to IPM (Panda et al., 2025).

The ability of Tachinid parasitoids to be employed in various biological control strategies makes them highly valuable. For instance, this has been successfully adhered to in the Nearctic and Neotropical areas, leading to considerable success in biological control (Quicke et al., 2025;

Barrett et al., 2025; Wood, 1987). They have been useful when pests are targeted using inoculatory, augmentative, or inundative releasing strategies (Quicke et al., 2025; Barrett et al., 2025). Evidence of success in pest suppression can be deduced from the release of tachinids against the gypsy moth (*Lymantria dispar*). This involved an augmentation releasing strategy that was successful in North America (Stireman et al., 2006; Quicke et al., 2025; Barrett et al., 2025). Therefore, specific species such as *Gonia kimorum* (now *Palpexorista kimorum*) have been useful in the use of biological control alongside select bioinsecticides, which do not have the negative non-target effects of chemical pesticides (Chen et al., 2020). When used simultaneously, these two approaches have resulted in greater control of pests. Therefore, this is in line with the extensive use of insect parasitoids in the IPM's ecologically sound pest management approach (Yeh et al., 2025)

4. Mechanisms of Parasitism and Host Interaction

Tachinid flies, well known for their role as parasitoids of a diverse range of insect pests, utilize some combination of physiological and behavioral mechanisms to suppress their hosts (Falcon-Brindis et al., 2024; Gaviria et al., 2024). Tachinid flies present a wide range of different oviposition strategies necessary for the success of parasitization (Falcon-Brindis et al., 2024; Gaviria et al., 2024; Wood, 1987). Some tachinid flies species such as *Exorista larvarum* and *Exorista japonica* lay eggs directly on the host cuticle (Cerretti et al., 2017). This oviposition method is required because it allows the newly hatched larva to penetrate the host, develop within it, and suppress the host by parasitization (Falcon-Brindis et al., 2024; Gaviria et al., 2024). Tachinids use a plethora of sensory cues to locate and accept hosts. Such cues are needed for increased host finding and parasitization rates to parasitize a higher number of hosts (Letourneau et al., 2015; Burington et al., 2020; Gaviria et al., 2024; Chen et al., 2020; Weber et al., 2020; Stireman, 2002). For instance, in the case of *Exorista japonica* parasitizing the silkworm *Bombyx mori*, the host's physiology changes are accompanied by hormonal changes, among others (Tanaka et al., 2022). After parasitoid infestation, the juvenile hormone titer decreases, and the 20-hydroxyecdysone titer increases abnormally, leading to the synthesis of abnormal developmental stages and, in turn, lower emergence rates of parasitized hosts (Tanaka et al., 2022; Falcon-Brindis et al., 2024; Gaviria et al., 2024). Parasitized caterpillars have been documented to alter their feeding patterns based on the ability of the host plants to provide better survival outcomes for both

the host and parasitoid fly larvae (Stireman et al., 2006; Falcon-Brindis et al., 2024; Gaviria et al., 2024). This altered behavior may also increase the parasitoid infection rate.

Host-parasitoid coevolution significantly influences the effectiveness of pest control, and the process vitally influences the biological control systems' dynamics (Falcon-Brindis et al., 2024; Gaviria et al., 2024). Host-parasitoid interactions contain considerable added factors of variability depending on the mutual adaptations necessary to either maximize or downregulate the overall rate of pest control (Jeffs & Lewis, 2013). Another determinant is the coevolution of host resistance and parasitoid virulence. To combat parasitoid attacks, hosts have developed several defense mechanisms, including the formation of cellular capsules (encapsulation) around the parasitoid egg or larva (Jeffs & Lewis, 2013). In response, parasitoids have evolved counteradaptations to these defenses, such as venom or immunosuppressive factors. This evolutionary process results in a coevolutionary arms race (Falcon-Brindis et al., 2024;).

Moreover, some pests have defensive symbionts, such as aphids with *Hamiltonella defensa*, thereby significantly challenging biological control efforts (Oliver et al., 2003). This indicates that in such cases, biological control efficiency is a function of the outcome of interactions mediated by parasitoid drought-tolerant genotypes that can overcome the symbiont-conferred resistances and not directly based on the parasitoid reproductive mode (Gaviria et al., 2024). Fecundity also contributes to control efficiency. Generally, high fecundity accounts for better suppression, although variations in control patterns exist. For example, some parasitoid taxa, particularly with evolutionary traits and ecological dynamics, have a low fecundity-to-search efficiency ratio (Jeffs & Lewis, 2013). Tolerance influences host physiology and parasite development. For example, some parasitoids affect host biochemistry by inducing nitric oxide and enhance their own growth and defense suppression, which may be beneficial for biological control (Politano & Lewis, 2010). Finally, there are environmental variables, such as climate change. Changes in climate will affect population dynamics, including distribution and phenology and adaptations among hosts and parasitoids (Jeffs & Lewis, 2013). Thus, the success of biological control might be affected by various adaptations and species interdependence changes in ecosystems (Politano & Lewis, 2010; Jeffs & Lewis, 2013). Moreover, the ecological context described factors, like host refuges, can affect the stability and success of host-parasitoid dynamics within pest control, thus undermining its potential (Gaviria et al., 2024). A refuge predisposes enclosures where the larger part of the

pest population would remain untreated, ultimately challenging pest extinction efforts to factor in control approaches.

Table 4.1 Mechanisms of Parasitism and Host Interaction

Mechanism	Description	Citation(s)
Oviposition Strategies	Lay eggs on host cuticle (e.g., <i>E. larvarum</i> , <i>E. japonica</i>); Allows larval penetration and host suppression.	(Dindo & Nakamura, 2018; Tachi & Shima, 2010)
Host Location and Selection Cues	Use sensory cues for efficient finding and parasitization; Increases host encounter rates.	(Stireman, 2002; Stireman et al., 2006)
Hormonal Manipulation	Induce changes in juvenile hormone and 20-hydroxyecdysone; Leads to abnormal development and lower host emergence.	(Dai et al., 2022; Dai et al., 2024)
Host Plant Choice Influence	Parasitized hosts alter feeding for better survival; May increase parasitoid infection rates.	(Karban & English-Loeb, 1997)
Coevolution: Host Resistance and Parasitoid Virulence	Arms race with host defenses (e.g., cellular capsules) and parasitoid counteradaptations; Affects control efficiency.	(Kraaijeveld et al., 1998; Käch et al., 2017)
Defensive Symbionts in Hosts	Symbionts like <i>Hamiltonella defensa</i> confer resistance; Parasitoids evolve to overcome for effective control.	(Rossbacher & Vorburger, 2020)
Fecundity and Search Efficiency	High fecundity aids suppression; Low ratios in some taxa with evolutionary traits.	(Lane et al., 1999; Umbanhowar et al., 2003)
Physiological Effects (e.g., Nitric Oxide)	Induce host nitric oxide for growth and defense suppression; Beneficial for biocontrol.	(Dai et al., 2024)

Environmental Factors	Alter dynamics, distribution, phenology; (Jeffs & Lewis, 2013)
(Climate Change)	Impact adaptations and interdependence.
Ecological Context	Refuges stabilize dynamics but challenge
(Host Refuges)	complete pest control.

5. Factors Influencing Effectiveness

Overall, the field success of Tachinid parasitoids largely depends on environmental and ecological factors (Stireman et al., 2006; Quicke et al., 2025; Barrett et al., 2025). Perhaps the most important of these is the availability of semi-wild perennial vegetation, serving as a suitable habitat and a source of resources (e.g., nectar) for the adult parasitoids (Ellis & Bradley, 1996). Academic research has found that both the abundance and species richness of Tachinids show a positive correlation with the cover of semi-wild perennial vegetation (Ellis & Bradley, 1996; Letourneau et al., 2015).

What is more, the effective number of Tachinid species is positively associated with the cover of perennial vegetation and, conversely, negatively with the cover of annual crops (Letourneau et al., 2015). Therefore, preserving semi-wild fragments can help increase biological diversity and promote ecosystem services in agricultural landscapes (Ellis & Bradley, 1996). With respect to environmental modifications, global warming is another factor shaping host-parasitoid relations (Jeffs & Lewis, 2013). Phenological shifts, alterations in the geographical distribution of Tachinids, and response strategies such as phenotypic plasticity and evolutionary changes are all consequences of rising temperatures (Politano & Lewis, 2010; Jeffs & Lewis, 2013). The effect of global warming is closely intertwined with other environmental factors, including high levels of carbon dioxide and nitrogen, which complicate Tachinid relationships with their hosts (Jeffs & Lewis, 2013).

Pesticides and other agronomic operations have also had an impact on Tachinids' ability to establish stable populations (Quicke et al., 2025). Mechanical cultivation, harvesting, and frequent disturbances due to insecticides all detract from the stability of natural enemy communities (Ellis & Bradley, 1996). Additionally, pesticide residues may have a direct detrimental impact on Tachinids' populations and their viability as biological control agents (Barrett et al., 2025). It is,

therefore, critical to implement more environmentally gentle and sustainable bug control practices. For example, ecological engineering focuses on environmentally friendly actions to bolster natural enemies rather than pesticides (Panda et al., 2025). Therefore, the ecological success of Tachinid parasitoids relies on the availability of habitats and environmental conditions, while mechanization and pesticide overuse have severely undermined their success as biological control agents (Letourneau et al., 2015; Burington et al., 2020; Gaviria et al., 2024; Chen et al., 2020; Weber et al., 2020; Stireman et al., 2006).

6. Biotechnological and Ecological Innovations

Molecular tools and biotechnology can immensely contribute to advancing Tachinid-based biocontrol. Hence, these tools have the potential to make biocontrol more efficacious and sustainable. The capabilities of genomic technologies and omics approaches such as next-generation sequencing and meta-omics tools allow exploring Tachinid flies' genetic and biochemical profiles in more detail (Stireman et al., 2019). Such information about their life cycle, host selectivity, and ecological interactions is essential for on-time optimization of their biocontrol efficiency (Gómez-Lama Cabanás & Mercado-Blanco, 2025; Singh et al., 2024).

The further advancement of bioinformatics is required to manage the growing volume of data generated through the implementation of genomic studies (Tan et al., 2022). Bioinformatics tools could assist with analyzing, visualizing, and predicting results to help better understand Tachinid fly biology and their prey/host species (Stireman et al., 2019). Engineering Tachinid flies with certain characteristics in synthetic labs using CRISPR-Cas9 and other related technologies can produce more efficient biocontrol agents (Singh et al., 2024). This approach can help with developing a biocontrol agent that can solve almost every specific pest challenge due to its ideal golden mean of aggressiveness.

The biotechnology field could help with making biocontrol agents even more effective by combining beneficial microorganisms with Tachinid flies (Minchev et al., 2021). Thus, creating a microbial consortium tailored specifically to Tachinid flies' ecological niche and functional types can lead to successful biocontrol of the highest efficiency (Minchev et al., 2021). Many biotechnological approaches could also result in the creation of new biocontrol agents. Therefore, characterizing such agents molecularly becomes essential for ecological safety and compliance,

and use on the market (Mark et al., 2006). A regulatory risk assessment is necessary to inject new agents into the US or European markets.

Advances in nanotechnology also raised the possibility of using targeted delivery of biocontrol agents or bioactives derived from them. It is possible to apply advanced delivery systems to enhance the efficacy of Tachinid flies in field applications by developing the approach for their optimal releasing and action (Mark et al., 2006). A range of recent innovations implemented in making tachinid parasitoids widely available for use in field implementations includes methods to enhance the biological control aspect and pesticides use reduction. This sector of biocontrol resources supplementation in the form of tachinid parasitoids has recently become of increased interest for biological control operations (Quicke et al., 2025; Barrett et al., 2025). One of the significant innovations was the implementation of molecular methods for tachinid identification and detection (Stireman et al., 2019). The molecular markers, such as fragments of the COI gene for mitochondrial DNA, offer better detection rates compared to traditional rearing methodologies (Stireman et al., 2019). There were estimations showing up to twenty times higher parasitism rates with a more molecular-based approach to identification among tachinids and European corn borer (Inclán Luna et al., 2015). The enriched data available from molecular techniques could allow better evaluation of tachinid populations, making use of their parasitism rate more enhanced.

Another highlighted factor in refining mass rearing processes is understanding tachinids' ovipositional strategy and host selection imprints to mass rearing artifacts (Falcon-Brindis et al., 2024; Gaviria et al., 2024). For example, studies on *Exorista larvarum* and *Exorista japonica* allowed for understanding the stimuli involved in the process and the direct ovipositional impact on the host cuticle (Cerretti et al., 2017). Based on that, it was possible to develop artificial substrates where tachinids could lay eggs, enhancing proclivities of their use for pest control (Quicke et al., 2025; Barrett et al., 2025). Finally, another advantage of organic farming practices lies in the value that they have in tachinid parasitoid diversity at the local and landscape levels (Inclán Luna et al., 2015). Organic farming may boost the number of species of tachinids that are present, increasing ecological control by increasing the number of flies and encouraging more species (Inclán Luna et al., 2015; Ellis & Bradley, 1996). These new developments, which range from utilizing molecular techniques to accurately classify species to capitalizing on the tremendous ecological data on host preferences, could significantly improve the effectiveness of tachinid flies

in biological control programs in future years. These improvements are increasingly critical for augmentative and inoculative launch techniques for integrated pest management systems (Quicke et al., 2025; Barrett et al., 2025).

Table 6.1 Biotechnological and Ecological Innovations

Innovation	Description	Citation(s)
Genomic Technologies and Omics	NGS and meta-omics for genetic/biochemical profiles; Optimize life cycle, host selectivity, and interactions.	(Gómez-Lama Cabanás & Mercado-Blanco, 2025; Singh et al., 2024)
Bioinformatics	Manage data for analysis, visualization, and predictions on Tachinid biology and hosts.	(Tan et al., 2022)
Synthetic Biology/Genetic Engineering	CRISPR-Cas9 to engineer traits for efficient biocontrol; Address specific pest challenges.	(Singh et al., 2024)
Microbial Biotechnology	Consortia with beneficial microbes tailored to Tachinid niches; Enhance biocontrol efficacy.	(Minchev et al., 2021)
Regulatory Assessment	Molecular characterization for safety, compliance, and market entry of new agents.	(Mark et al., 2006)
Nanotechnology	Targeted delivery systems for optimal release and action in fields.	(Singh et al., 2024)
Molecular Identification	COI gene markers for accurate detection; Reveals higher parasitism rates (e.g., in European corn borer).	(Agustí et al., 2005; Pohjoismäki et al., 2016)

Mass Improvements	Rearing	Artificial substrates based on oviposition strategies; Enhance proclivities for pest control.	(Dindo & Nakamura, 2018; Quicke et al., 2025; Barrett et al., 2025)
Organic Practices	Farming	Boost Tachinid diversity at local/landscape levels; Increases ecological control.	

7. Challenges and Future Prospects

In conclusion, the use of Tachinid parasitoids in large-scale pest management is not without its own challenges and research areas for improved efficiency and sustainability in agricultural applications (Stireman et al., 2006; Quicke et al., 2025; Barrett et al., 2025). Several possible and actual challenges of their use based on the reviewed literature include:

Key Challenges

- **Host Selection and Oviposition:** The lack of detailed knowledge of what cues the Tachinid parasitoids use for host selection and oviposition is one of the biological control challenges (Falcon-Brindis et al., 2024; Gaviria et al., 2024). The field is underdeveloped compared to the Hymenopteran parasitoids, and this gap in understanding is a common issue cited in the literature (Stireman et al., 2006).
- **Habitat and Environment:** The parasitoids' effectiveness can be negatively impacted by landscape and habitat changes (Ellis & Bradley, 1996). For example, habitat loss due to agricultural intensification and the removal of semi-wild vegetation decrease Tachinid populations and their effectiveness as biological control agents (BCAs) (Inclán Luna et al., 2015).
- **Operational Failures:** While there are reported examples of successful operations in the field, not all large-scale applications have shown positive results on pest control (Quicke et al., 2025; Barrett et al., 2025). Operational failures are often due to insufficient regard

for ecological interactions and specific release conditions necessary for Tachinid establishment (Falcon-Brindis et al., 2024; Gaviria et al., 2024; Wood, 1987).

- **Compatibility:** In tandem with the previous point, there are also issues regarding the incompatibility of Tachinid parasitoids with bioinsecticides or other control methods' side effects (Quicke et al., 2025; Barrett et al., 2025). For instance, some chemical treatments are directly harmful to the natural control agents by reducing their survival or reproductive efforts (Ellis & Bradley, 1996).

Future Research Directions

Future research on Tachinids' challenges covers the following vital aspects:

- **Behavioral Ecology:** Understanding Tachinids' behavioral ecology is necessary for the exploitation of these parasitoids as BCAs due to its gap in knowledge (Stireman, 2002; Stireman et al., 2006). For example, more well-conducted research on the host search strategies and host selection cues may improve Tachinid mass-rearing efforts (Falcon-Brindis et al., 2024; Gaviria et al., 2024).
- **Landscape Management:** Better understanding of how habitat and landscape can be managed to ensure parasitoid viability is an area of improvement (Ellis & Bradley, 1996). For example, semi-wild perennial habitats can be maintained as refugia to increase control agent effectiveness and biodiversity (Letourneau et al., 2015).
- **Release Strategies:** The development of more successful and ecologically compatible release strategies is among the most vital research areas of the future (Quicke et al., 2025; Barrett et al., 2025). For instance, the conditions may be adjusted for different landscapes (e.g., inundative vs. inoculative approaches) for optimum effectiveness (Wood, 1987).
- **Compatibility:** Further studies on the compatibility of Tachinids' use with bioinsecticides, or the development of safer strategies that do not contradict the Tachinids' use, is an important aspect of further research (Quicke et al., 2025; Barrett et al., 2025).

Conclusion

Tachinid parasitoids are indispensable allies in sustainable agriculture, serving as efficient natural regulators of pest populations. Their ecological adaptability, wide host range, and contribution to biodiversity make them vital for maintaining ecosystem stability. However, the success of Tachinid-based biocontrol depends on environmental conservation, reduced pesticide reliance, and deeper insights into their behavioral ecology and host–parasitoid dynamics. Integrating modern biotechnological approaches such as molecular identification, genomic profiling, and synthetic biology can significantly enhance their application in biological control. Future research should focus on improving mass-rearing methods, habitat management, and compatibility with other IPM tools to ensure more reliable and scalable outcomes. By merging ecological understanding with technological innovation, Tachinid parasitoids can play a pivotal role in transforming pest management into a more sustainable and environmentally responsible practice.

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Geospatial Approache

tal contamination. As climate change intensifies droughts and floods, the reuse of treated wastewater emerges as a critical adaptation strategy. However, realizing the full potential of these technologies requires addressing technical barriers such as data interoperability and model uncertainty and policy challenges, including regulatory harmonization and public acceptance. Moving forward, adopting climate-smart, data-driven wastewater management systems supported by geospatial analytics will be essential for achieving water sustainability, food security, and environmental resilience in the face of global climate change.

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