



MINI REVIEW

# Contributions of Dipterans to Pollination Services and Biological Control

Fredrick Ojija<sup>1</sup> | Giovanni Bacaro<sup>2</sup> | Christopher Mzimba<sup>1</sup>

<sup>1</sup>Department of Earth Sciences, Mbeya University of Science and Technology, Mbeya, Tanzania | <sup>2</sup>Department of Life Sciences, University of Trieste, Trieste, Italy

**Correspondence:** Fredrick Ojija ([fredrick.ojija@yahoo.com](mailto:fredrick.ojija@yahoo.com))

**Received:** 20 December 2025 | **Revised:** 13 April 2026 | **Accepted:** 17 April 2026

**Keywords:** agriculture | bioindicators | parasitoids | pollinators | predators | true flies

## ABSTRACT

Diptera form one of the most diverse and functionally important insect groups, yet their ecological contributions to biodiversity maintenance and ecosystem services remain underrecognized and underrepresented in research and conservation planning. This review was undertaken to synthesize current evidence on the functional ecology of Diptera, highlight their roles in pollination services and biological control and identify knowledge gaps that limit their integration into biodiversity conservation and ecosystem management. A systematic search of peer-reviewed articles was conducted by analyzing 83 studies from 114 screened sources. The review reveals that Diptera contribute substantially to pollination and biological control. They visit approximately 72% of the world's major crops and dominate pollination networks in alpine, arctic and shaded habitats where bees are scarce. Several families of Diptera, including Syrphidae, Bombyliidae, Calliphoridae and Muscidae provide pollination services valued in the hundreds of billions of dollars annually. Predatory and parasitoid species in Syrphidae, Tachinidae and Cecidomyiidae deliver natural pest suppression estimated at nearly US\$100 billion annually. Overall, this review demonstrates that Diptera play indispensable roles in sustaining ecosystem processes, agricultural productivity and ecological resilience. However, major gaps persist in quantifying their contributions to pollination and pest regulation, particularly in tropical and developing regions. The review concludes that advancing dipteran research through targeted ecological studies, long-term monitoring and integrative conservation strategies is essential for safeguarding ecosystem functioning and human well-being.

## 1 | Introduction

True flies, belonging to the insect order Diptera, constitute one of the most diverse and ecologically significant groups of animals (Alikhan et al. 2018; Adler and Courtney 2019; Raguso 2020). Diptera include more than 160 000 described species across over 160 families, with potentially millions yet to be discovered (Raguso 2020; de Meyer et al. 2024; Dar et al. 2025). Dipterans inhabit nearly all terrestrial and freshwater ecosystems (Adler and Courtney 2019; Van Der Velden 2024). Both larvae and adult dipterans occupy a wide range of ecological niches, from decaying organic matter and aquatic sediments to animal tissue and floral resources (Adler

and Courtney 2019; Whittington 2019; Cook et al. 2020). According to Adler and Courtney (2019), almost one-third of all true fly species, ca. 46 000 in total, have a life stage that is associated with an aquatic environment. Studies have shown further that many dipteran species are also long-distance migrants, linking ecosystems across vast landscapes (Faiman et al. 2020; Reynolds et al. 2024; Hawkes et al. 2025). Migratory species in families such as Syrphidae and Calliphoridae move seasonally across continents, facilitating gene flow, pollen transfer and nutrient redistribution (Reynolds et al. 2024; Hawkes et al. 2025). These large-scale movements reinforce ecological connectivity between natural and agricultural systems and may buffer ecosystem functions against localized

disturbances (Hawkes et al. 2025). This migratory dynamic positions Diptera as essential players in global ecosystem resilience (Wotton et al. 2019; Hawkes et al. 2024, 2025). For example, Wotton et al. (2019) reported that long-distance migrations of hoverflies redistribute large quantities of essential nutrients, particularly nitrogen (N) and phosphorus (P), while transporting billions of pollen grains between Britain and continental Europe. In addition, locally produced hoverfly populations consume an estimated six trillion aphids annually and make billions of flower visits, highlighting their substantial ecological significance (Wotton et al. 2019).

Moreover, dipterans exert a disproportionately large influence on ecosystem functioning and human well-being (Alikhan et al. 2018; Raguso 2020; Van Der Velden 2024). Their ecological importance underscores their vital role in biodiversity conservation (Moquet et al. 2018) and the maintenance of essential ecosystem services (Adler and Courtney 2019). They form essential links within food webs by contributing to pollination, biological control, decomposition, nutrient cycling and disease transmission (Jandricic et al. 2016; Adler and Courtney 2019; Whittington 2019; Burgio et al. 2025). Diptera biomass collectively contributes significantly to global nutrient and carbon cycles, delivering ecological services comparable to those provided by larger invertebrates and vertebrates (Adler and Courtney 2019). The breakdown of organic matter by dipteran larvae is fundamental to ecosystem functioning. Dipteran larvae of Calliphoridae, Sarcophagidae and Muscidae act as detritivores, consuming decaying organic material, carrion or faeces, thereby accelerating nutrient recycling and enhancing soil fertility (Adler and Courtney 2019; Dar et al. 2025). In aquatic environments, Chironomidae and Simuliidae larvae function as ecosystem engineers by processing detritus and modulating sediment oxygen levels, which helps sustain water quality (Shahidi-Hakak et al. 2022; Kimura and Tuno 2024). In terrestrial systems, adults of Syrphidae, Muscidae and Calliphoridae act as pollinators, scavengers or predators, often participating in several ecological roles simultaneously (Burgio et al. 2025). Such ecological flexibility underscores the evolutionary success and ecological indispensability of Diptera (Kimura and Tuno 2024). Also, their remarkable ecological adaptability and resilience to climatic variability and habitat disturbance makes them key contributors to ecosystem stability.

Globally, insect-mediated pollination services are valued at more than US \$577 billion annually, with Diptera contributing a significant yet often overlooked share (Raguso 2020; Toikkanen et al. 2022). Although bees have traditionally received the most attention in pollination studies (Ojija and Silabi 2024), true flies play critical roles in both wild and agricultural ecosystems (Doyle et al. 2020; Li et al. 2023). Previous studies estimate that flies visit approximately 72% of the world's most important crops, including mango, avocado, cacao and coffee (Doyle et al. 2020; Hawkes et al. 2025; Ríos-Moyano et al. 2025). Hoverflies, bee flies, blowflies and houseflies are considered highly effective pollinators across diverse climatic regions (Raguso 2020). In regions, such as alpine and arctic habitats where bees show low visitation rates, Diptera are especially important. For example, syrphid and muscid flies were reported to dominate floral visitation networks in high-latitude and high-elevation ecosystems,

ensuring seed set and successful reproduction for many wild plant species in these environments (Tiusanen et al. 2016; Raguso 2020).

Also, some Diptera play predatory and parasitic roles in the biological control of agricultural and forest pests (Jandricic et al. 2013; Wojciechowicz-Zytko and Dobin'ska-Graczyk 2025). Larvae of syrphids, tachinids and cecidomyiids feed on aphids, whiteflies, thrips and caterpillars effectively reducing pest populations and minimizing crop damage (Joshi and Ballal 2013; Faheem et al. 2019; Van Oystaeyen et al. 2022; Burgio et al. 2025): it has been reported that a single syrphid larva can consume hundreds of aphids before pupation, indicating its potential for natural pest suppression (Burgio et al. 2025). Worldwide, the economic contribution of insect-mediated pest control, including that provided by Diptera, is estimated at nearly US \$100 billions annually (Losey and Vaughan 2006). This ecosystem service mitigates environmental pollution, safeguards pollinator health and reduces reliance on chemical pesticides. Additionally, owing to their sensitivity to environmental fluctuations, Diptera are valuable bioindicators in ecological assessments (Docile et al. 2015). Variations in their community structure, abundance and diversity often reflect changes in water quality, habitat disturbance or pollution levels (Adler and Courtney 2019; Ulinuha et al. 2025).

Although some studies have highlighted the ecological importance of Diptera (Losey and Vaughan 2006; Whittington 2019), their functional roles, particularly in pollination and pest regulation, remain poorly studied and insufficiently documented. Compared with other insect groups such as bees and beetles, the contributions of true flies to ecosystem functioning have received relatively limited scientific attention. This knowledge gap is especially pronounced in developing regions, where research capacity and funding are often limited, and where most available studies have been conducted in the Global North. As a result, the diversity, distribution and ecological contributions of Diptera in many biodiverse ecosystems remain inadequately understood. The limited availability of region specific studies further constrains the ability to fully appreciate their role in supporting ecosystem services and biodiversity conservation. Consequently, this review seeks to strengthen current understanding by synthesizing available literature on Diptera ecology, highlighting important regional and thematic research gaps, and providing a clearer perspective on their ecological significance. By bringing together existing evidence, the review aims to improve recognition of Diptera contributions to ecosystem functioning across diverse environments.

## 2 | Literature Review Method

As a narrative review, this study followed the Scale for the Assessment of Narrative Review Articles, a structured guideline designed to enhance the quality, rigour and transparency of narrative review processes (Baethge et al. 2019). A systematic, step-wise approach was used to identify literature on the ecological and conservation roles of dipterans, particularly their contributions to pollination, biological control and broader ecosystem functions. Major academic databases including Web of Science, Scopus and Google Scholar were

searched for published peer-reviewed studies. The search strategy combined specific keywords with Boolean operators to ensure comprehensive coverage. Key terms included 'Diptera' OR 'true flies', 'Diptera conservation' OR 'Diptera pollinators', 'Syrphidae' OR 'Bombyliidae' 'Calliphoridae' OR 'Muscidae', 'roles of Diptera' OR 'Diptera as pollinators', OR 'Diptera as biological control', 'Syrphidae' OR 'hoverflies', 'Bombyliidae' OR 'bee flies', combined with 'parasitoid', 'biological control', and 'host-parasite interactions', for example, search strings included combinations such as 'Syrphidae' OR 'hoverflies', 'Bombyliidae' OR 'bee flies', combined with 'parasitoid', 'biological control' and 'host-parasite interactions'. Keywords were grouped with parentheses and combined using 'AND' (e.g., ('Syrphidae' OR 'hoverflies') AND ('parasitoid' OR 'biological control')) to ensure that the retrieved studies were relevant to the focus of this review. Also, the search included studies published between 1990 and 2026 and only considered articles in English. In addition, because the review highlights research gaps between developing regions and the Global North, it was important to include studies from both contexts to synthesize available knowledge and highlight existing gaps in Diptera research, particularly in underrepresented regions. The literature search results from the databases were compiled and exported for screening. Duplicate records identified across databases were removed before further evaluation. The remaining articles were then screened based on their titles, abstracts and, where necessary, full texts to determine their relevance to the objectives of the review. Inclusion criteria focused on studies that addressed the ecological roles, parasitoid behaviour, host associations or biological control potential of Diptera. Studies not directly related to these aspects, as well as non-peer-reviewed materials, conference abstracts and studies lacking sufficient methodological detail, were excluded. This stepwise screening and filtering process substantially reduced the large number of initial search results to a final set of 83 and 114 studies, which were considered most relevant and were therefore included and analyzed in this review.

### 3 | Ecological Roles of Dipterans in Pollination Services

Diptera are among the most important yet least recognized pollinators globally (Borkent and Harder 2007). They remain under-appreciated across a wide range of ecosystems and have historically been overshadowed by bees in pollination research (Cook et al. 2020; Raguso 2020). However, evidence from observational, experimental and meta-analytic studies show that several dipteran groups, including bombyliids, calliphorids, muscids and empidids, frequently visit flowers, effectively transfer pollen and in some ecosystems provide pollination services comparable to or complementary to those of bees (Cook et al. 2020; Doyle et al. 2020; Raguso 2020). The literature on Diptera pollination spans natural ecosystems (alpine, arctic, forest understory, wetlands), agroecosystems (e.g., cacao, carrot, mango and orchard fruits), and diverse human-modified landscapes, highlighting both their ecological breadth and functional importance (Borkent and Harder 2007; Inouye et al. 2015; Tiisanen et al. 2016; Ríos-Moyano et al. 2025). Although pollinator diversity of Diptera varies among ecosystems, several consistent patterns emerge. Syrphid hoverflies dominate temperate

floral-visitor assemblages in many habitats, providing substantial pollination services (Borkent and Harder 2007; Ssymank et al. 2008; Moquet et al. 2018; Martini et al. 2025; Ríos-Moyano et al. 2025). Doyle et al. (2020) stated that hoverflies, which visit at least 72% of the world's food crops, are estimated to contribute about US\$300 billion annually, in addition to pollinating over 70% of animal-pollinated wildflowers. In high-latitude and high-elevation systems where bees may be scarce, muscids and other Diptera families often serve as principal floral visitors (Inouye et al. 2015; Raguso 2020). Tropical systems exhibit a broad taxonomic range of floral-visiting Diptera, for example, blowflies and bee flies are key pollinators in some understories and shaded agroforestry systems, that is, cacao and coffee (Cook et al. 2020; Ríos-Moyano et al. 2025). Agricultural studies have further documented Diptera as frequent or even pivotal pollinators in crops whose floral morphology or phenology favour short-tongued or early-morning visitors (Cook et al. 2020; Toikkanen et al. 2022). Although most dipteran species possess short mouthparts and therefore mainly visit open-corolla flowers, some species exhibit extremely elongated mouthparts, such as *Megistorhynchus longirostris* (Wiedemann) (Vlašánková et al. 2017).

The taxonomic composition of Diptera pollinators depends on climate (Ojija et al. 2025), floral traits, landscape composition and human disturbance (Borkent and Harder 2007; Karimpour 2012). This variability underscores the need to include true flies in both regional pollinator assessments and global pollination service estimates. Starting in November 2026, European legislation mandates that Member States implement monitoring programmes that include not only bees and butterflies but also hoverflies. Diptera pollination is driven by a combination of morphological fit (such as body size and surface structures), foraging behaviour and interactions with floral traits (Ojija et al. 2019). Many flies possess stout, hairy bodies that pick up and deposit pollen effectively on open or shallow flowers (Doyle et al. 2020; Toivonen et al. 2022; Li et al. 2023). Syrphids, for example, often contact anthers and stigmas while probing for nectar, resulting in efficient pollen transfer (Inouye et al. 2015; Doyle et al. 2020). Blowflies and larger muscoids may play key roles in pollinating carrion-scented or large, bowl-shaped flowers that attract generalist visitors (Cook et al. 2020). Temporal niches also contribute to their importance; flies often forage under cooler, wetter, or lower light conditions, that is, early morning, dusk or cloudy weather when bees are less active, thereby extending the window for effective pollination (Inouye et al. 2015; Doyle et al. 2020). Floral traits that favour Diptera pollination include open corollas, accessible nectar, strong odours (including fetid or fermenting scents) and visual cues such as mottling, all of which can promote pollen transfer by a diverse range of dipteran visitors (Borkent and Harder 2007; Raguso 2020).

Quantitative measures of pollen transfer have used single-visit deposition experiments, pollen-load assessments and seed or fruit set following controlled visitation. However, single-visit efficacy varies widely among fly taxa and flower types. Some syrphids approach the per-visit pollen deposition of solitary bees on certain crops, whereas many generalist flies deposit fewer conspecific pollen grains but compensate through high visitation rates (Rader et al. 2009; Rauf et al. 2021). Importantly, the complementarity between flies and bees

across temporal niches, micro-habitats and floral preferences often results in higher overall pollination success than either group provides alone.

Empirical crop studies further document cases where flies substantially increase yields in certain horticultural crops and, in some systems, provide pollination services comparable to bees when visitation frequency is high (Cook et al. 2020; Toikkanen et al. 2022). Meta-analytic evidence also indicates that alternative pollinators, including dipterans, can be as effective as bees for particular crops, although their effectiveness is context-dependent and influenced by floral morphology, visitor behaviour and landscape structure (Rader et al. 2009). Additionally, the dual role of some dipterans, that is, syrphids, whose larvae contribute to pest control (Dunn et al. 2020; Van Oystaeyen et al. 2022; Li et al. 2023; Rehermann et al. 2026), offers agronomic benefits that bees do not provide, reinforcing the importance of conserving diverse pollinator assemblages (Burgio et al. 2025). In general, Diptera represents a diverse and functionally important suite of pollinators that complement bees across ecosystems and environmental conditions (Borkent and Harder 2007). Their contributions to pollination services are context-dependent but often substantial, particularly where bee activity is constrained or where floral traits favour Diptera visitation. Recognizing and quantifying fly contributions will improve pollinator-conservation strategies, ecosystem-service assessments and agricultural resilience (Raguso 2020).

#### 4 | Biological Control and Ecosystem Regulation by Diptera

Dipterans play vital, yet often underappreciated, roles in biological control and broader ecosystem regulation (Bugg et al. 2008; Li et al. 2023; Gaviria et al. 2024). Predatory and parasitoid flies contribute to natural-enemy communities in both agricultural and natural systems (Joshi and Ballal 2013; Jandricic et al. 2016; Faheem et al. 2019; Van Oystaeyen et al. 2022; Cingolani et al. 2025). They act directly on herbivore populations and indirectly influence community dynamics and ecosystem services (Burgio et al. 2025). Key families involved in pest suppression include Syrphidae (hoverflies), Tachinidae (tachinid parasitoids), Cecidomyiidae (gall midges and predatory species), certain Muscidae and Sarcophagidae that prey on or parasitize pest insects (Burgio et al. 2025; Wojciechowicz-Zytko and Dobin'ska-Graczyk 2025). Recent syntheses highlight their long-standing ecological roles and the increasing interest in using dipteran natural enemies in augmentative and conservation biological control. Syrphid larvae are among the best documented dipteran predators. Many species are voracious aphidophages and can substantially reduce aphid populations in crops and ornamentals (Burgio et al. 2025). Adult syrphids, while functioning as pollinators, therefore provide a dual ecosystem service, that is, pollination by adults and pest suppression by larvae (Li et al. 2023; Burgio et al. 2025). Conservation biological control through habitat manipulation to favour natural enemies often seek to increase syrphid populations by providing floral resources and refugia for adults. This support enhances larval recruitment and strengthens aphid suppression in situ. Despite their

importance as the most well-documented dipteran predators, syrphids face several challenges in practical application (Table 1).

Tachinid flies are one of the most important groups of parasitoid dipterans contributing to natural pest regulation in terrestrial ecosystems (Gagnon et al. 2023; Gaviria et al. 2024). They are obligate parasitoids, meaning their larvae develop inside or on host insects, ultimately causing host mortality. This characteristic makes tachinids highly effective biological control agents against a wide range of herbivorous pests (O'Hara 2005; Gaviria et al. 2024; Cingolani et al. 2025). Several species have contributed to the suppression of major pests in both classical and augmentative biological control efforts (Gaviria et al. 2024). Some studies have documented the diversity of tachinid–host interactions, indicating that tachinids target numerous economically significant pests across different orders, including Lepidoptera, Coleoptera, Hemiptera and Orthoptera (Table 1). For instance, *Exorista* spp., *Compsilura concinnata* (Meigen) and *Eucelatoria* spp. are known to parasitize caterpillars of lepidopteran pests, which are responsible for substantial crop damage in cereal, vegetable and fruit production systems (Oberhauser et al. 2007). However, the wider application of tachinids in large-scale augmentative releases is limited by their complex life cycles, strict host specificity and challenges associated with mass rearing. Even so, when applied selectively and with careful assessment of non-target impacts, tachinids have achieved notable pest reductions in several regional programmes (Oberhauser et al. 2007).

The ecological effectiveness of tachinids is enhanced by their high reproductive potential and host-searching behaviour. Females lay hundreds of eggs directly on or near hosts, and in some species, eggs may be deposited on host plants, where larvae subsequently penetrate and develop within the host (Stireman et al. 2006). Such strategies allow tachinid populations to respond rapidly to increases in host abundance, providing density-dependent control of pest populations. Moreover, tachinids have been shown to establish naturally in various agroecosystems, particularly in organic and integrated pest management systems, where they contribute to reducing the reliance on chemical insecticides (Smith et al. 2006). Despite their recognized importance, tachinids remain underutilized in many developing regions, partly due to limited knowledge of their taxonomy, life history and host specificity. Recent reviews suggest that promoting research on tachinid diversity, host associations and mass-rearing techniques can enhance their incorporation into sustainable pest management programmes (Smith et al. 2006; Stireman et al. 2006; Elkinton and Boettner 2012).

Previous empirical case studies have demonstrated tangible benefits of dipteran biological control (Table 1). For instance, one greenhouse study showed that augmentative releases of the hoverfly *Eupeodes corollae* (Fabricius) simultaneously suppressed aphid populations and increased fruit set and yield in multiple vegetable crops, highlighting combined pest suppression and pollination benefits (Li et al. 2023). This study reported meaningful reductions in aphid densities and improved crop performance without insecticides, illustrating practical benefits for sustainable horticulture. Historical

and contemporary records also document tachinid successes (Table 1). Several tachinid species have been implicated in controlling lepidopteran stem borers and other pests in South America and elsewhere, either as naturally occurring enemies enhanced by habitat management or as agents in classical biological control programmes (Gaviria et al. 2024). While results are context dependent, these cases underscore the capacity of dipteran parasitoids to reduce pest pressure in diverse agroecosystems.

Other dipteran groups, that is, predatory Cecidomyiidae (in certain genera) and selected predatory muscids, have also been investigated for augmentative release (Murphy et al. 2012; Topakci 2022; Williams 2025). However, mass rearing and commercialization remains limited compared with hymenopteran parasitoids and predatory beetles (Burgio et al. 2025). Although the diversity of potential dipteran biological-control agents is substantial, effective deployment requires advances in mass-rearing techniques, improved release strategies, and better integration into existing Integrated Pest Management (IPM) frameworks (Bailey et al. 2022).

Syrphid augmentative applications in field and greenhouse settings have achieved high short term aphid suppression. A study reported that a controlled releases of *E. balteatus*, for example, resulted in rapid aphid knockdown in ornamentals and vegetable which demonstrates practical utility under protected

cultivation where environmental conditions are manageable (Jiang et al. 2025). Nevertheless, long term, landscape level effectiveness depends on sustaining populations through habitat management and reducing insecticide impacts. A key characteristic of many dipterans' natural enemies, particularly syrphids, is their multifunctionality, whereby adults act as pollinators while larvae function as effective predators of crop pests. Together, these functions contribute to improvements in both crop yield and quality (Li et al. 2023; Burgio et al. 2025). The strength of these synergies depends on the timing and spatial overlap of adult feeding on floral resources and larval predation in herbivore hotspots. For instance, augmentative adult releases timed to coincide with crop flowering can boost pollination while ensuring egg deposition near pest populations, promoting effective larval biocontrol of aphids. Yet, trade-offs and constraints exist. Adult dietary needs nectar and pollen and larval prey availability may not always coincide spatially or temporally. Some syrphid species forage on flowers that are distant from pest-infested plants, limiting larval recruitment where pests occur. Additionally, landscape simplification and pesticide regimes that destroy nectar sources or kill immature stages can decouple pollination and pest suppression, reducing the net benefit (Mkenda et al. 2015). Thus, integrated management must consider floral resource provisioning, pesticide reduction and habitat connectivity to sustain both services (Mkenda et al. 2015; Li et al. 2023; Gaviria et al. 2024).

**TABLE 1** | Challenges in the application of syrphids and tachinids.

Challenge category	Syrphids	Tachinids
Mass rearing difficulties	Larvae depend on aphid prey and high-quality food sources, making large-scale breeding difficult; low egg production and pupal survival can limit rearing success (Dunn et al. 2020).	Many species are difficult to rear in laboratory conditions because larvae require live hosts and specific conditions; reproductive strategies and host associations are poorly understood (Stireman et al. 2006).
Limited ecological knowledge	Knowledge gaps in floral preferences, adult viability as pollinators and larval predatory efficiency under field conditions (Dunn et al. 2020).	Many tachinid species and host-parasitoid associations are poorly described; species identification often incomplete, complicating application and evaluation (Stireman et al. 2006).
Habitat and resource requirements	Adult syrphids require continuous floral resources; inadequate floral availability reduces longevity and potential service provision (Wratten et al. 2003; Dunn et al. 2020).	Host availability varies in space and time; absence of alternative hosts limits efficacy in certain seasons or landscapes (Stireman et al. 2006).
Species specificity and efficacy	Not all syrphid species are effective aphid predators; species composition must be known for effective deployment (Dunn et al. 2020).	Some host populations show resistance or reduced susceptibility to tachinid parasitism, resulting in poor pest suppression (O'Hara 2005).
Integration into management frameworks	Limited research and field validation hinder inclusion in integrated pest and pollination management strategies (Dunn et al. 2020).	Regulatory, logistical, and knowledge barriers (e.g., cross-region releases and overwintering conditions) complicate adoption in structured biocontrol programmes (Stireman et al. 2006).

## 5 | Challenges in the Application of Syrphids and Tachinids

The key obstacles to wider use of dipterans in pest management include difficulties with mass rearing, limited ecological knowledge, habitat and resource requirements, species specificity and efficacy, and integration into management frameworks (Table 2).

### 5.1 | Mass Rearing and Production Constraints

A major limitation to the large-scale application of both syrphids and tachinids is the challenge of mass rearing. Syrphid larvae are predatory, primarily feeding on aphids or other small arthropods, which complicates the development of cost-effective artificial diets and scalable breeding systems. Even within syrphid rearing programmes, ensuring sufficient nutrition for larval cohorts and achieving high survival rates through pupation remain significant constraints, limiting their potential for widespread augmentative releases (Dunn et al. 2020). Tachinids, in contrast, pose even greater challenges for large-scale application. As obligate parasitoids, their larvae develop exclusively within host insects, requiring a continuous and reliable supply of suitable hosts for rearing (Stireman et al. 2006). This dependence on live hosts complicates laboratory production and substantially increases logistical costs. Furthermore, the absence of standardized rearing protocols and the complexity of maintaining multi-trophic systems remain significant obstacles to the routine use of tachinids in augmentative biological control programmes (Van Driesche et al. 2010).

### 5.2 | Knowledge Gaps in Ecology and Biology

Effective biological control requires detailed understanding of the ecology and life histories of natural enemies. For syrphids, significant knowledge gaps remain regarding adult foraging behaviour, larval predatory efficiency in field conditions and their interactions with floral resources. Although syrphids are well documented as aphid predators in controlled studies, the translation of these findings into real-world crop systems has been limited due to insufficient field validation (Dunn et al. 2020). Additionally, variation in species composition and habitat preferences across landscapes complicates predictions of syrphid effectiveness in pest suppression. Tachinids face similar challenges, as their host specificity, oviposition strategies and host-parasitoid dynamics remain poorly understood. Although many tachinid species are capable of parasitizing economically important pests, incomplete documentation of host ranges and the complexity of host-selection behaviours limit the predictability and reliability of their outcomes in biological control programmes (Stireman et al. 2006). This gap in ecological knowledge constrains practitioners from selecting the most effective parasitoid taxa for specific pest complexes.

### 5.3 | Habitat and Resource Limitations

Habitat structure and resource availability are critical determinants of the success of syrphids and tachinids in agricultural

landscapes (Wratten et al. 2003). Adult syrphids rely on floral nectar and pollen for energy, and insufficient floral resources can drastically reduce adult longevity and reproductive output. Thus, cropping systems that lack continuous floral resources may not support effective syrphid populations, limiting their utility as biological control agents. Tachinids, on the other hand, depend on the spatial and temporal availability of suitable host populations. Seasonal fluctuations in host abundance can lead to mismatches between parasitoid presence and pest outbreaks, reducing the efficacy of biological control (Van Driesche et al. 2010). Landscape simplification and habitat fragmentation further exacerbate this issue by disrupting connectivity between parasitoids and their hosts, making biological control less reliable (Wratten et al. 2003).

### 5.4 | Species Specificity and Non-Target Effects

The specificity of interaction between natural enemies and their target pests also poses challenges. Not all syrphid species are equally effective predators of key pest species (Van Driesche et al. 2010). Some syrphid larvae exhibit generalist feeding behaviour, which may dilute their impact on dominant pest populations in complex agroecosystems (Dunn et al. 2020). This necessitates careful species selection and monitoring to ensure that augmentative releases target relevant pest taxa. Tachinids vary widely in host specificity, with some species exhibiting broad host ranges that may include non-target insects. Broad host range can raise ecological concerns about unintended impacts on non-pest species, especially in conservation biological control contexts (Van Driesche et al. 2010; Dunn et al. 2020). Therefore, the risk of non-target effects must be carefully evaluated before large-scale releases, adding an additional layer of complexity to their application.

### 5.5 | Integration With Management Frameworks

Although syrphids and tachinids provide ecosystem services relevant to pest management, their integration into formal IPM programmes remains limited. Regulatory and logistical barriers, such as the absence of standardized protocols for augmentative releases and limited extension support, impede adoption by practitioners (Van Driesche et al. 2010). Additionally, the widespread use of broad-spectrum insecticides in many cropping systems can undermine the effectiveness of biological control agents, reducing their survival and efficacy in the field.

Thus, addressing key challenges requires targeted research, effective habitat management and supportive policy measures. Priority research areas include optimizing rearing protocols for both syrphid and tachinid species, developing field-adapted release strategies and quantifying the combined benefits of pollination and pest control for farmers. Policy and extension initiatives should promote conservation biological control practices, such as flower strips and habitat diversification, while reducing pesticide use that disproportionately harms dipteran natural enemies. Integrating dipterans more broadly into IPM programmes can diversify ecosystem-based pest management strategies and strengthen the resilience of agroecosystems.

**TABLE 2** | Examples of Diptera with roles in biological control and ecosystem regulation.

Scientific name	Common name	Family	Role in biocontrol/ Ecosystem regulation	Citation
<i>Aphidolutes aphidimyza</i> (Rondani)	Aphid midge	Cecidomyiidae	Predator of aphids; used in augmentative biocontrol	Jandric et al. (2013, 2016) and Le Goff et al. (2016)
<i>Sphaerophoria rueppellii</i> (Wiedemann)	Rueppell's hoverfly	Syrphidae	Larvae feed on aphids; used in IPM	Bailey et al. (2022)
<i>Episyrrhus balteatus</i> (De Geer)	Marmalade hoverfly	Syrphidae	Aphid predator; supports conservation biocontrol	Burgio et al. (2025) and Wojciechowicz-Zytko and Dobinska-Graczyk (2025)
<i>Eupeodes corollae</i> (Fabricius)	Common hoverfly	Syrphidae	Larvae feed on aphids; important in crop protection	Burgio et al. (2025) and Wojciechowicz-Zytko and Dobinska-Graczyk (2025)
<i>Istochneta aldrichi</i> (Mesnil)	Tachinid fly	Tachinidae	Parasitoid of Japanese beetle ( <i>Popillia japonica</i> )	Gagnon et al. (2023)
<i>Compsilura concinnata</i> (Meigen)	Tachinid fly	Tachinidae	Generalist parasitoid; used to control spongy moth	Ichiki and Shima (2003), Elkinton and Boettner (2012) and Baranowski et al. (2019)
<i>Lespesia archippivora</i> (Riley)	Armyworm tachinid	Tachinidae	Parasitoid of lepidopteran pests	Oberhauser et al. (2007), Hay-Roe et al. (2016) and Geest et al. (2019)
<i>Ormia deplete</i> (Wiedemann)	Brazilian red-eyed fly	Tachinidae	Parasitoid of mole crickets	Brust et al. (2018) and Ray and Gillett-Kaufman (2018)
<i>Lixophaga diatraeae</i> (Townsend)	Tachinid fly	Tachinidae	Parasitoid of sugarcane borer ( <i>Diatraea saccharalis</i> )	Gaviria et al. (2024)
<i>Smiditia fumiferanae</i> (Tothill)	Tachinid fly	Tachinidae	Parasitoid of spruce budworm ( <i>Choristoneura fumiferana</i> )	O'Hara (2005) and Hébert et al. (2025)
<i>Cryptochaetum iceryae</i> (Williston)	Scale fly	Cryptochaetidae	Parasitoid of cottony cushion scale ( <i>Icerya purchasi</i> )	Thorarinnsson (1990) and Mendel (1991)
<i>Feltiella acarisuga</i> (Vallot)	Predatory gall midge	Cecidomyiidae	Feeds on spider mites; used in greenhouse crops	Topakci (2022)
<i>Hydrotaea aenescens</i> (Wiedemann)	Muscid fly	Muscidae	Predatory/parasitoid; used against house flies	Malik et al. (2007) and Burgio et al. (2025)
<i>Sciomyzidae</i> spp.	Snail-killing flies	Sciomyzidae	Larvae prey on snails, reducing pest/disease vectors	Murphy et al. (2012), Mc Donnell et al. (2014) and Williams (2025)
<i>Volucella inanis</i> (Linnaeus)	Hoverfly	Syrphidae	Ectoparasitoid of social wasps	Cingolani et al. (2025)
<i>Villa cana</i> (Meigen)	Bee fly	Bombyliidae	Parasitoid/predator; regulates pine processionary caterpillar	Cingolani et al. (2025)
<i>Exhyalanthrax</i> spp.	Bee fly	Bombyliidae	Investigated for tsetse fly control	Cingolani et al. (2025) and Rollinson and Cabrero (2025)

## 6 | Conservation Implications for Sustaining Ecosystem Services

The implications of dipteran contributions to biodiversity and ecosystem stability extend to conservation planning and ecosystem-service management. If dipterans serve both as bioindicators and functional contributors (pollination, decomposition and pest control), then protecting their habitat and diversity becomes integral to sustaining ecosystem services. For example, in landscapes where habitat fragmentation or land-use change reduces fly diversity (Toikkanen et al. 2022), the loss may cascade into reduced pollination of wild and cultivated plants, impaired nutrient cycling and weakened ecosystem resilience. Conservation of riparian strips, micro-habitats (dead wood and wetlands) and floral resource diversity is important to support dipteran assemblages (Ulinuha et al. 2025). Additionally, management of aquatic habitats for water quality not only benefits fish and amphibians but also supports aquatic dipteran communities integral to ecosystem structure (Adler and Courtney 2019; Shahidi-Hakak et al. 2022). Because true flies are often abundant, widely distributed and sensitive to micro-habitat changes, they provide efficient and cost-effective biomonitoring tools (Docile et al. 2015; Mezgebu et al. 2019). For instance, studies have shown that Chironomidae are effective bioindicators of environmental conditions, including water scarcity in the Upper San Pedro River Basin of south-eastern Arizona (Cañedo-Argüelles et al. 2016) and water quality in streams and rivers around Sebeta, Ethiopia (Mezgebu et al. 2019). Thus, integrating Diptera monitoring into conservation programmes can help detect early signs of ecosystem degradation (Cañedo-Argüelles et al. 2016; Chowdhury et al. 2023). From a policy perspective, recognizing the functional significance of dipterans expands the biodiversity conservation agenda beyond charismatic taxa and emphasizes multi-service functionality (pollination + indicator + decomposition). In agricultural-forest mosaic landscapes in countries such as Tanzania, this means that conservation interventions (e.g., restoration of wetlands, maintenance of forest fragments and inclusion of floral strips) should consider fly-friendly micro-habitats and adult/larval resource needs.

## 7 | Integrated Synthesis, Challenges, and Future Research Directions

Synthesizing current evidence, dipterans emerge as central, not peripheral, to biodiversity conservation and ecosystem stability. They function both as sentinels of environmental change (bioindicators) and as active contributors to essential ecosystem processes, including pollination, nutrient cycling and pest regulation (Docile et al. 2015; Burgio et al. 2025). Their conservation therefore yields substantial downstream benefits for plant reproduction, genetic diversity, ecosystem resilience and service provision. Yet dipteran communities face significant threats from habitat loss, pesticide exposure and climate change (Jaworski and Hilszczański 2013; Ojija et al. 2025), all of which alter community composition, reduce species richness and diminish functional contributions (Hallmann et al. 2017; Ulinuha et al. 2025). Research gaps persist across taxonomy, distribution, and life history traits, and most bioindicator studies remain biased toward aquatic or medically important taxa, with far fewer investigations of terrestrial fly communities in tropical forests or savannas. Similarly, the extent to which wild plant

reproduction depends on dipteran visitation in under studied regions remains unclear. Compounding these gaps, ecosystem service and valuation models rarely incorporate true flies explicitly, leading to systematic underestimation of their contributions. Addressing these limitations requires long term standardized monitoring, improved sampling technologies (e.g., malaise traps and optical sensing), and functional trait approaches that illuminate larval and adult habitat dependencies (Rydhmer and Selvan 2021). Conservation strategies should integrate habitat protection and restoration, pesticide management, maintenance of larval and adult resources and climate adaptive planning to sustain population connectivity and ecosystem service provision (Wojciechowicz-Zytko and Dobin'ska-Graczyk 2025). Embedding dipterans into biodiversity monitoring programmes, red list assessments and policy frameworks, especially in data deficient regions, will be essential for safeguarding their populations and the ecological functions they support (Mata et al. 2010; Burgio et al. 2025). Future research should prioritize long term population tracking, modelling climate and landscape impacts, mapping functional traits and quantifying ecosystem service contributions to strengthen dipteran conservation globally.

## 8 | Conclusion

Dipterans represent a multifunctional yet underutilized resource for sustainable agriculture and biodiversity conservation. Beyond syrphids, which provide essential pollination services in both agroecosystems and natural habitats, tachinid flies serve as key agents of natural pest regulation, offering cost-effective and environmentally friendly solutions for agricultural pest management. Their ecological roles in suppressing pest populations, supporting biodiversity and enhancing ecosystem resilience underscore the importance of integrating tachinid-based biological control into modern sustainable agriculture and conservation strategies. Achieving these benefits at meaningful scales, however, requires coordinated management that ensures the availability of floral resources, maintains habitat connectivity and minimizes pesticide use to support both adult and larval stages. In addition to pollination and biological control, true flies contribute significantly to overall ecosystem stability, nutrient cycling and ecological functioning across terrestrial and aquatic habitats. Despite their critical roles, their value is often underestimated, constrained by research gaps, mass-rearing challenges and limited incorporation into policy and management frameworks. Promoting dipteran conservation through long-term monitoring, habitat management and integration into integrated pest management (IPM) and biodiversity assessments is therefore essential for sustaining ecosystem services and enhancing resilience in rapidly changing landscapes.

### Author Contributions

**Fredrick Ojija:** conceptualization, writing – original draft, methodology, writing – review and editing, formal analysis, project administration, supervision, visualization. **Giovanni Bacaro:** conceptualization, methodology, writing – review and editing, supervision, project administration, visualization. **Christopher Mгимба:** methodology, conceptualization, writing – review and editing, supervision, project administration.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during this study.

## References

- Adler, P. H., and G. W. Courtney. 2019. "Ecological and Societal Services of Aquatic Diptera." *Insects* 10, no. 3: 1–23.
- Alikhan, M., K. Al Ghamdi, J. A. Mahyoub, and N. Alanazi. 2018. "Public Health and Veterinary Important Flies (Order: Diptera) Prevalent in Jeddah Saudi Arabia With Their Dominant Characteristics and Identification Key." *Saudi Journal of Biological Sciences* 25, no. 8: 1648–1663.
- Baethge, C., S. Goldbeck-Wood, and S. Mertens. 2019. "SANRA—A Scale for the Quality Assessment of Narrative Review Articles." *Research Integrity and Peer Review* 4, no. 5: 1–7.
- Bailey, E., L. Field, C. Rawlings, et al. 2022. "A Near-Chromosome Level Genome Assembly of the European Hoverfly, *Sphaerophoria rueppellii* (Diptera: Syrphidae), Provides Comparative Insights Into Insecticide Resistance-Related Gene Family Evolution." *BMC Genomics* 23, no. 198: 1–20.
- Baranowski, A. K., C. Conroy, G. H. Boettner, J. S. Elkinton, and E. L. Preisser. 2019. "Reduced *Compsilura concinnata* Parasitism of New England Saturniid Larvae." *Agricultural and Forest Entomology* 21, no. 3: 346–349.
- Borkent, C. J., and L. D. Harder. 2007. "Flies (Diptera) as Pollinators of Two Dioecious Plants: Behaviour and Implications for Plant Mating." *Canadian Entomologist* 139, no. 2: 235–246.
- Brust, G. E., W. Wakil, and M. A. Qayyum. 2018. "Minor Pests." In *Sustainable Management of Arthropod Pests of Tomato*, 183–214. Elsevier.
- Bugg, R. L., R. G. Colfer, W. E. Chaney, H. A. Smith, and J. Cannon. 2008. *Flower Flies (Syrphidae) and Other Biological Control Agents for Aphids in Vegetable Crops*. 1st ed. University of California, Agriculture and Natural Resources.
- Burgio, G., M. L. Dindo, T. Pape, D. Whitmore, and D. Sommaggio. 2025. "Diptera as Predators in Biological Control: Applications and Future Perspectives." *BioControl* 70, no. 1: 1–17.
- Cañedo-Argüelles, M., M. T. Bogan, D. A. Lytle, and N. Prat. 2016. "Are Chironomidae (Diptera) Good Indicators of Water Scarcity? Dryland Streams as a Case Study." *Ecological Indicators* 71: 155–162.
- Chowdhury, S., V. K. Dubey, S. Choudhury, et al. 2023. "Insects as Bioindicator: A Hidden Gem for Environmental Monitoring." *Frontiers in Environmental Science* 11: 1146052.
- Cingolani, M. F., M. C. Barakat, P. Cerretti, et al. 2025. "Dipteran Parasitoids as Biocontrol Agents." *BioControl* 70, no. 3: 285–300.
- Cook, D. F., S. C. Voss, J. T. D. Finch, R. C. Rader, J. M. Cook, and C. J. Spurr. 2020. "The Role of Flies as Pollinators of Horticultural Crops: An Australian Case Study With Worldwide Relevance." *Insects* 11, no. 6: 1–31.
- Dar, T. A., A. H. Mir, and M. Bharti. 2025. "Comparison of the Sweeping Net and Bait Method to Access the Species Diversity of Calliphoridae (Insecta: Diptera) in Kashmir Himalaya, India." *Journal of Asia-Pacific Biodiversity* 18, no. 1: 88–96.
- de Meyer, M., G. Goergen, J. Midgley, and K. Jordaens. 2024. "On the Identity of the Afrotropical Species of *Mallota* Meigen (Diptera: Syrphidae)." *European Journal of Taxonomy* 958: 242–290.
- Docile, T. N., R. Figueiró, L. H. Gil-Azevedo, and J. L. Nessimian. 2015. "Water Pollution and Distribution of the Black Fly (Diptera: Simuliidae) in the Atlantic Forest, Brazil." *Revista de Biologia Tropical* 63, no. 3: 683–693.
- Doyle, T., W. L. S. Hawkes, R. Massy, G. D. Powney, M. H. M. Menz, and K. R. Wotton. 2020. "Pollination by Hoverflies in the Anthropocene." *Proceedings of the Royal Society B: Biological Sciences* 287, no. 1927: 20200508.
- Dunn, L., T. M. Lequerica, C. R. Reid, and T. Latty. 2020. "Dual Ecosystem Services of Syrphid Flies (Diptera: Syrphidae): Pollinators and Biological Control Agents." *Pest Management Science* 76, no. 6: 1973–1979.
- Elkinton, J. S., and G. H. Boettner. 2012. "Benefits and Harm Caused by the Introduced Generalist Tachinid, *Compsilura concinnata*, in North America." *BioControl* 57, no. 2: 277–288.
- Faheem, M., S. Saeed, A. Sajjad, M. Razaq, and F. Ahmad. 2019. "Biological Parameters of Two Syrphid Fly Species *Ischiodon scutellaris* (Fabricius) and *Episyrphus balteatus* (DeGeer) and Their Predatory Potential on Wheat Aphid *Schizaphis graminum* (Rondani) at Different Temperatures." *Egyptian Journal of Biological Pest Control* 29, no. 2: 1–8.
- Faiman, R., A. S. Yaro, M. Diallo, et al. 2020. "Quantifying Flight Aptitude Variation in Wild *Anopheles gambiae* in Order to Identify Long-Distance Migrants." *Malaria Journal* 19, no. 1: 1–15.
- Gagnon, M.-E., J. Doyon, S. Legault, and J. Brodeur. 2023. "The Establishment of the Association Between the Japanese Beetle (Coleoptera: Scarabaeidae) and the Parasitoid *Istocheta aldrichi* (Diptera: Tachinidae) in Québec, Canada." *Canadian Entomologist* 155, no. 32: 1–11.
- Gaviria, J., G. Vargas, D. T. Chirinos-Torres, A. E. Díaz-Montilla, and T. Kondo. 2024. "Review of Tachinids and Other Dipteran Parasitoids and Predators as Biological Control Agents in Colombia, Ecuador, and Peru." *Ciencia y Tecnología Agropecuaria* 25, no. 3: 1–22.
- Geest, E. A., L. L. Wolfenbarger, and J. P. McCarty. 2019. "*Lespesia archippivora* (Diptera: Tachinidae) Survival and Sex Ratios Within Monarch Butterfly (Lepidoptera: Nymphalidae) Hosts." *American Midland Naturalist* 182, no. 2: 265.
- Hallmann, C. A., M. Sorg, E. Jongejans, et al. 2017. "More Than 75 Percent Decline Over 27 Years in Total Flying Insect Biomass in Protected Areas." *PLoS One* 12, no. 10: 1–21.
- Hawkes, W. L., T. Doyle, R. Massy, et al. 2024. "The Most Remarkable Migrants—Systematic Analysis of the Western European Insect Flyway at a Pyrenean Mountain Pass." *Proceedings of the Royal Society B: Biological Sciences* 291: 1–12. <https://doi.org/10.1098/rspb.2023.2831>.
- Hawkes, W. L., M. H. M. Menz, and K. R. Wotton. 2025. "Lords of the Flies: Dipteran Migrants Are Diverse, Abundant and Ecologically Important." *Biological Reviews* 100, no. 4: 1635–1659.
- Hay-Roe, M. M., R. L. Meagher, R. N. Nagoshi, and Y. Newman. 2016. "Distributional Patterns of Fall Armyworm Parasitoids in a Corn Field and a Pasture Field in Florida." *Biological Control* 96: 48–56.
- Hébert, C., J.-M. Béland, A. Dupont, and R. Berthiaume. 2025. "The Lethal and Sublethal Effects of Aerial Applications of *Bacillus thuringiensis* Subsp. *Kurstaki* on the Spruce Budworm and Its Parasitism." *Forests* 16, no. 11: 1–18.
- Ichiki, R., and H. Shima. 2003. "Immature Life of *compsilura concinnata* (Meigen) (Diptera: Tachinidae)." *Annals of the Entomological Society of America* 96, no. 2: 161–167.
- Inouye, D. W., B. M. H. Larson, A. Szymank, and P. G. Kevan. 2015. "Flies and Flowers III: Ecology of Foraging and Pollination." *Journal of Pollination Ecology* 16, no. 16: 115–133.
- Jandricic, S. E., S. P. Wraight, D. R. Gillespie, and J. P. Sanderson. 2013. "Oviposition Behavior of the Biological Control Agent *Aphidoletes aphidimyza* (Diptera: Cecidomyiidae) in Environments With Multiple Pest Aphid Species (Hemiptera: Aphididae)." *Biological Control* 65, no. 2: 235–245.

- Jandricic, S., S. Wraight, D. Gillespie, and J. Sanderson. 2016. "Biological Control Outcomes Using the Generalist Aphid Predator *Aphidoletes aphidimyza* Under Multi-Prey Conditions." *Insects* 7, no. 4: 1–15.
- Jaworski, T., and J. Hilszczański. 2013. "The Effect of Temperature and Humidity Changes on Insects Development Their Impact on Forest Ecosystems in the Expected Climate Change." *Forest Research Papers* 74, no. 4: 345–355.
- Jiang, S., H. Li, and K. Wu. 2025. "Evaluation on Biocontrol Efficacy of *Episyrphus balteatus* De Geer (Diptera: Syrphidae) Against *Aphis craccivora*, *Myzus persicae*, and *Megoura crassicauda*." *Insects* 16, no. 8: 1–14.
- Joshi, S., and C. R. Ballal. 2013. "Syrphid Predators for Biological Control of Aphids." *Journal of Biological Control* 27, no. 3: 151–170.
- Karimpour, Y. 2012. "On the Bee Fly (Diptera: Bombyliidae) Fauna From West Azarbaijan Province of Iran." *Biharean Biologist* 6, no. 2: 81–86.
- Kimura, M. T., and N. Tuno. 2024. "Phylogeny, Ecology, and Evolution of Mycophagous Drosophilidae (Diptera)." *Biological Journal of the Linnean Society* 142, no. 3: 247–260.
- Le Goff, G. J., A. Nicolas, R. Al Mohamad, and T. Hance. 2016. "Impact of Humidity on the Biological Development of *Aphidoletes aphidimyza* (Diptera: Cecidomyiidae)." *Journal of Economic Entomology* 109, no. 3: 1482–1486.
- Li, H., K. A. G. Wyckhuys, and K. Wu. 2023. "Hoverflies Provide Pollination and Biological Pest Control in Greenhouse-Grown Horticultural Crops." *Frontiers in Plant Science* 14: 1118388.
- Losey, J., and M. Vaughan. 2006. "The Economic Value of Ecological Services Provided by Insects." *Bioscience* 56, no. 4: 311–323.
- Malik, A., N. Singh, and S. Satya. 2007. "House Fly *Musca domestica*: A Review of Control Strategies for a Challenging Pest." *Journal of Environmental Science and Health, Part B* 42, no. 4: 453–469.
- Martini, M., E. Kaul, R. Miller, J. Gibbs, and K. Bobiwash. 2025. "Non-Native Plants in Road Verges Attract Pollinators Despite Associated Declines in Native Flowers." *Global Ecology and Conservation* 58: 1–14.
- Mata, R. A. D., M. McGeoch, and R. Tidon. 2010. "Drosophilids (Insecta, Diptera) as Tools for Conservation Biology." *Natureza & Conservação* 8, no. 1: 60–65.
- Mc Donnell, R. J., T. D. Paine, C. J. Mulkeen, and M. J. Gormally. 2014. "Effects of Temperature and Prey Availability on the Malacophagous Larval Stage of *Sepedon spinipes* (Scopoli) (Diptera: Sciomyzidae): Potential Biocontrol for Gastropod Vectors of Parasitic Diseases." *Biological Control* 70: 42–47.
- Mendel, Z. 1991. "Colonization Trials With *Cryptochetum iceryae* and *Rodok iceryae* for Improved Biological Control of *Lcerya purchasi* in Israel." *Biological Control* 1: 68–74.
- Mezgebu, A., A. Lakew, B. Lemma, and G. Beneberu. 2019. "The Potential Use of Chironomids (Insecta: Diptera) as Bioindicators in Streams and Rivers Around Sebeta, Ethiopia." *African Journal of Aquatic Science* 44, no. 4: 369–376.
- Mkenda, P., R. Mwanauta, P. C. Stevenson, P. Ndakidemi, K. Mtei, and S. R. Belmain. 2015. "Extracts From Field Margin Weeds Provide Economically Viable and Environmentally Benign Pest Control Compared to Synthetic Pesticides." *PLoS One* 10, no. 11: e0143530.
- Moquet, L., E. Laurent, R. Bacchetta, and A. Jacquemart. 2018. "Conservation of Hoverflies (Diptera, Syrphidae) Requires Complementary Resources at the Landscape and Local Scales." *Insect Conservation and Diversity* 11, no. 1: 72–87.
- Murphy, W. L., L. V. Knutson, E. G. Chapman, et al. 2012. "Key Aspects of the Biology of Snail-Killing Sciomyzidae Flies." *Annual Review of Entomology* 57, no. 1: 425–447.
- Oberhauser, K., I. Gebhard, C. Cameron, and S. Oberhauser. 2007. "Parasitism of Monarch Butterflies (*Danaus plexippus*) by *Lespesia archippivora* (Diptera: Tachinidae)." *American Midland Naturalist* 157, no. 2: 312–328.
- O'Hara, J. E. 2005. "A Review of the Tachinid Parasitoids (Diptera: Tachinidae) of Nearctic *Choristoneura* Species (Lepidoptera: Tortricidae), With Keys to Adults and Puparia." *Zootaxa* 938, no. 1: 1–46.
- Ojija, F., S. E. J. Arnold, and A. C. Treydte. 2019. "Impacts of Alien Invasive *Parthenium hysterophorus* on Flower Visitation by Insects to Co-Flowering Plants." *Arthropod-Plant Interactions* 13, no. 5: 719–734.
- Ojija, F., M. Mng'ong'o, B. N. Aloo, G. Mayengo, and M. Helikumi. 2025. "Effect of Global Climate Change on Insect Populations, Distribution, and Its Dynamics." *Journal of Asia-Pacific Entomology* 28, no. 3: 102442.
- Ojija, F., and L. Silabi. 2024. "Bees and Their Interactions With Flowering Plants in Disturbed and Semi-Natural Settings." *Journal of Asia-Pacific Entomology* 27, no. 2: 1–8.
- Rader, R., B. G. Howlett, S. A. Cunningham, et al. 2009. "Alternative Pollinator Taxa Are Equally Efficient but Not as Effective as the Honeybee in a Mass Flowering Crop." *Journal of Applied Ecology* 46, no. 5: 1080–1087.
- Raguso, R. A. 2020. "Don't Forget the Flies: Dipteran Diversity and Its Consequences for Floral Ecology and Evolution." *Applied Entomology and Zoology* 55, no. 1: 1–7.
- Rauf, A., S. Saeed, M. Ali, and M. H. Nadeem Tahir. 2021. "Comparative Efficiency of Native Insect Pollinators in Reproductive Performance of *Medicago sativa* L. in Pakistan." *Insects* 12, no. 11: 1–13.
- Ray, H., and J. L. Gillett-Kaufman. 2018. "Brazilian Red-Eyed Fly *Ormia depleta* (Wiedemann) (Diptera: Tachinidae)." *EDIS* 4: 1–3.
- Rehermann, G., C. Petig, S. Khalil, J. A. Stenberg, R. Meyhöfer, and P. G. Becher. 2026. "Flying Agents: Hoverflies as a Multitool for Pollination, Vectoring of Beneficial Microbes and Biological Control of Grey Mould Disease in Strawberries." *Journal of Pest Science* 99, no. 23: 1–13.
- Reynolds, S. K., C. S. Clem, B. Fitz-Gerald, and A. D. Young. 2024. "A Comprehensive Review of Long-Distance Hover Fly Migration (Diptera: Syrphidae)." *Ecological Entomology* 49, no. 6: 749–767.
- Ríos-Moyano, D., F. A. Rodríguez-Cruz, P. A. Hormaza-Martínez, and A. Ramírez-Godoy. 2025. "Characterization of Pollinators Associated With Cocoa Cultivation and Their Relationship With Natural Effective Pollination." *Diversity* 17, no. 3: 1–16.
- Rollinson, L., and A. Cabrero. 2025. "Species Discovery in Southern African Bee Flies (Diptera, Bombyliidae): A New Species in the Revised Genus *Enica* Macquart, 1834." *African Invertebrates* 66, no. 1: 73–115.
- Rydhmer, K., and R. Selvan. 2021. "Dynamic  $\beta$ -VAEs for Quantifying Biodiversity by Clustering Optically Recorded Insect Signals." *Ecological Informatics* 66: 101456.
- Shahidi-Hakak, F., M. H. Amid-Motlagh, and M. Khosravani. 2022. "A Quick Review of the Family Chironomidae (Order Diptera) With Effect on the Environment." *Trends in Medical Sciences* 2, no. 2: 1–5.
- Smith, M. A., N. E. Woodley, D. H. Janzen, W. Hallwachs, and P. D. N. Hebert. 2006. "DNA Barcodes Reveal Cryptic Host-Specificity Within the Presumed Polyphagous Members of a Genus of Parasitoid Flies (Diptera: Tachinidae)." *Proceedings of the National Academy of Sciences* 103, no. 10: 3657–3662.
- Ssymank, A., C. A. Kearns, T. Pape, and C. F. Thompson. 2008. "Pollinating Flies (Diptera): A Major Contribution to Plant Diversity and Agricultural Production." *Biodiversity* 9, no. 1: 86–89.
- Stireman, J. O., J. E. O'Hara, and D. M. Wood. 2006. "TACHINIDAE: Evolution, Behavior, and Ecology." *Annual Review of Entomology* 51, no. 1: 525–555.

- Thorarinsson, K. 1990. "Biological Control of the Cottony-Cushion Scale: Experimental Tests of the Spatial Density-Dependence Hypothesis." *Ecology* 71, no. 2: 635–644.
- Tiusanen, M., P. D. N. Hebert, N. M. Schmidt, and T. Roslin. 2016. "One Fly to Rule Them All—Muscid Flies Are the Key Pollinators in the Arctic." *Proceedings of the Royal Society B: Biological Sciences* 283, no. 1839: 1–6.
- Toikkanen, J., P. Halme, J. Kahanpää, and M. Toivonen. 2022. "Effects of Landscape Composition on Hoverflies (Diptera: Syrphidae) in Mass-Flowering Crop Fields Within Forest-Dominated Landscapes." *Journal of Insect Conservation* 26, no. 6: 907–918.
- Toivonen, M., A.-E. Karimaa, I. Herzon, and M. Kuussaari. 2022. "Flies Are Important Pollinators of Mass-Flowering Caraway and Respond to Landscape and Floral Factors Differently From Honeybees." *Agriculture, Ecosystems & Environment* 323: 1–11.
- Topakcı, N. 2022. "Spider Mite Predator Feltiella Acarisuga (Vallot, 1827) (Diptera: Cecidomyiidae) in Greenhouse Strawberry Cultivation in Antalya Province: Recognition, Population Dynamics and Parasitization by *Aphanogmus* sp." *Turkish Journal of Entomology* 46, no. 1: 25–36.
- Ulinuha, U., T. R. Hartke, P. Hidayat, D. Buchori, S. Scheu, and J. Drescher. 2025. "Riparian Zones Offset Community Decline in True Flies (Diptera) After Lowland Rainforest Conversion to Smallholder Cash Crops in Sumatra." *Biodiversity and Conservation* 34, no. 11: 3805–3823.
- Van Der Velden, J. 2024. "Hoverflies (Diptera, Syrphidae) in a Rural Garden and Their Potential for Citizen Science." *Contributions to Entomology* 74, no. 2: 193–198.
- Van Driesche, R. G., R. I. Carruthers, T. Center, et al. 2010. "Classical Biological Control for the Protection of Natural Ecosystems." *Biological Control* 54: S2–S33.
- Van Oystaeyen, A., E. Tuytens, S. Boonen, et al. 2022. "Dual Purpose: Predatory Hoverflies Pollinate Strawberry Crops and Protect Them Against the Strawberry Aphid, *Chaetosiphon fragaefolii*." *Pest Management Science* 78, no. 7: 3051–3060.
- Vlašánková, A., E. Padyšáková, M. Bartoš, X. Mengual, P. Janečková, and S. Janeček. 2017. "The nectar spur is not only a simple specialization for long-proboscid pollinators." *New Phytologist* 215, no. 4: 1574–1581.
- Whittington, A. E. 2019. "The Economic Significance of the Signal Fly Genus *Rivellia* robinsoni-Desvoidy (Diptera: Platystomatidae)." 49, no. 2: 135–160.
- Williams, C. D. 2025. "Niche Diversification and Differentiation as Exemplified by the Snail-Killing Flies (Sciomyzidae: Diptera)." *Wetlands* 45, no. 8: 1–5.
- Wojciechowicz-Zytka, E., and M. Dobin'ska-Graczyk. 2025. "Urban Green Space as a Reservoir of Predatory Syrphids (Diptera, Syrphidae) for Aphid Control in Cities." *Agronomy* 15: 1–18.
- Wotton, K. R., B. Gao, M. H. M. Menz, et al. 2019. "Mass Seasonal Migrations of Hoverflies Provide Extensive Pollination and Crop Protection Services." *Current Biology* 29: 2167–2173.e5.
- Wratten, S. D., M. H. Bowie, J. M. Hickman, A. M. Evans, J. R. Sedcole, and J. M. Tylianakis. 2003. "Field Boundaries as Barriers to Movement of Hover Flies (Diptera: Syrphidae) in Cultivated Land." *Oecologia* 134, no. 4: 605–611.