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Emerging threat of *Liriomyza* spp. (Agromyzidae, Diptera) in horticultural crops: Species distribution, habitat shift and its semiochemical-based management strategies

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Abstract

The genus *Liriomyza* (Diptera: Agromyzidae) has recently gained a reputation as a highly invasive and damaging leafminers group causing heavy economic damage in horticultural crops globally. The rising pest status of *Liriomyza* species is linked to climate change, protected cultivation, agricultural intensification, globalisation and movement of infested planting material, resulting in rapid geographic spread and host range expansion. The overreliance on broad-spectrum insecticides has led to insecticide resistance, pest resurgence, imbalance of predator-prey population dynamics and environmental pollution, thus making eco-friendly control approaches imperative. Among such approaches, kairomone and herbivore-induced plant volatiles (HIPVs) based strategies appear as very promising tools for species-specific monitoring and pest management. The current review provides an overview of the recent research on *Liriomyza* species diversity, invasion history, biology, adaptations to new environments, as well as morphological and molecular taxonomy. It also gives insight into ecological factors influencing habitat shift and host interactions, including host recognition, response of plants to herbivory, hormonal modulation and volatiles-based communication. Finally, recent achievements in semiochemical-based management, involving host plant volatiles, kairomones, synomones and HIPVs along with advanced trap designs, molecular diagnostics and artificial intelligence-based pest monitoring are considered as sustainable part of integrated pest management (IPM).

Keywords: habitat shift; herbivore-induced plant volatiles; invasive leafminer; semiochemicals

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Introduction

Horticultural crops, including fruits, vegetables, ornamental crops, spices, medicinal and aromatic plants and plantation crops form an important part of the world's agriculture system since they make a significant contribution to food and nutritional security, human health, employment generation and economic development. Along with providing vitamins, minerals, dietary fiber, antioxidants and various bioactive compounds, the horticultural products also offer livelihood opportunities to millions of farmers and play an important role in international and domestic trade (1). In the past decades, the global demand for horticultural products has been increasing due to population growth, urbanisation, changes in consumer preferences and greater attention to healthy food consumption (2). Among the horticultural commodities, vegetables constitute an important and rapidly expanding sector, including crops such as tomato, potato, onion, chilli, cucurbits, brassicas and legumes, as well as several fruit and ornamental crops. According to the latest FAOSTAT data, the vegetable production has grown to about 1.2 billion tonnes in 2023, showing an increase by 26 % in comparison with 2010 (2). This fact demonstrates the growing importance of horticultural crops for the food and nutritional security (2). The productivity of horticultural crops has become more difficult to maintain because these high-valued crops are always under abiotic stresses such as drought, heat stress, salinity, waterlogging, nutrient imbalance and climate variability as well as biotic constraints like insect pests, mites, nematodes, plant pathogens and weeds that negatively affect crop productivity, growth, quality and marketability (3–5). Among these constrains, the insect pests have been recognised to be one of the main factors limiting horticultural production globally. According to the Food and Agriculture Organization, plant pests and diseases are responsible for losses of

approximately 40 % of annual crop production globally. In addition, invasive insect pests cause substantial economic damage, estimated at more than US$70 billion annually (2). At the same time, climate warming would cause an additional increase in pest-induced crop losses due to higher survival, reproduction and geographical spread of the pests (6). Pest pressure remains one of the major factors threatening global food production despite technological advancements in crop protection (7). The intensification in the production of horticultural crops, the practice of cultivation under protected environments, movement of planting material due to international commerce and climatic changes have increased the occurrence and spread of many species of invasive insects affecting the horticultural systems (1, 8, 9).

Among the insect pests, the Agromyzid leafminers, *Liriomyza* have gained importance as one of the most invasive pest insects attacking horticultural crops throughout the world. While earlier known as minor pests, *Liriomyza* spp. is becoming important economic pests due to various factors such as globalisation, transportation of infested planting material, protected cultivation, climatic changes, intensive monoculture cultivation practices and indiscriminate use of insecticides that enable these pests to rapidly expand into new areas (8, 10). Further, increase in greenhouses, polyhouses and shade-net cultivation practices have also provided conducive climatic conditions for their year-round survival, overlap of generations and continuous reproduction resulting in higher infestation pressure on high-value horticultural crops (11, 12). In India, *Liriomyza* spp. has also become economically important pests of vegetables, ornamental, pulses and other horticultural crops, mainly in intensive cultivation systems where repetitive use of insecticides disturbed natural enemy complex and also resulted in development of insecticide resistance (11). Of the approximately 400 described species of *Liriomyza*, only a limited number have attained major economic importance, including *Liriomyza trifolii* (American serpentine leafminer), *L. sativae* (vegetable leafminer), *Liriomyza huidobrensis* (pea leafminer) and *Liriomyza bryoniae* (tomato leafminer). These pests are distributed in many parts of Asia, Africa, Europe, Oceania and Americas and causing great production constraints in both open field and protected cultivation systems (10, 13). Their ecological plasticity, wide host adaptability and invasive ability have transformed *Liriomyza* spp. as major pests to sustainable horticultural production systems. Reliable field identification is a well-known issue because these four economically significant species are closely related and have similar morphologies. Adult females, immature larvae and pupae typically lack reliable diagnostic external characters and only the male genitalia can be confidently separated morphologically. This method is time-consuming, requires specialised taxonomic knowledge and cannot be applied to the non-adult life stages that are most intercepted at ports of entry (14). *Liriomyza huidobrensis* and the cryptic species *Liriomyza langei* are examples of closely related taxa that are practically indistinguishable by external anatomy and can only be confidently identified with DNA sequence data (14). Due to these limitations, mitochondrial cytochrome c oxidase subunit I (COI) barcoding and other molecular markers should be viewed as an essential supplement to morphological identification rather than its replacement. This is especially true for invasion surveillance, early detection of new incursions and quarantine diagnostics, where quick and clear species-level confirmation is crucial for regulatory decision-making.

The economic significance of *Liriomyza* spp. lies mainly in their wide distribution of feeding damage and extremely high host range. The adult females puncture leaf tissue to feed and oviposit and produce multiple stippling wounds, while the larvae bore through the mesophyll tissue and create serpentine tunnels that grow larger as the larvae develop (10). The infestation leads to decreased chlorophyll level, decreased efficiency of photosynthesis, chlorosis, necrosis, early leaf senescence and defoliation and finally causes plant growth retardation, yield loss and poor quality (11). Besides the direct injury from feeding, the oviposition wounds provide a pathway for fungi and bacteria to infect the plant, adding additional crop damage (10). Even though substantial advancements have been achieved in the fields of biology, ecology, invasion and pest management of *Liriomyza* spp., their effective and sustainable pest management still remains a critical issue in horticultural production systems. The most common strategy for pest management is based on continuous use of broad-spectrum insecticides, which led to rapid development of insecticide resistance, disruption of populations of natural enemies, pest resurgence, environmental pollution and pesticide residue in horticultural products (15). Hence, it becomes essential to develop alternative and environmentally safe methods of pest management, providing the minimal possible impact on the environment and able to suppress the pest population efficiently. One of such alternatives, semiochemical-based pest management, includes herbivore-induced plant volatiles (HIPVs), host plant volatiles, pheromones and kairomones (16, 17). The major factors associated with *Liriomyza* outbreaks, insecticide resistance and semiochemical-based management are summarised in Fig. 1. This strategy has several advantages, such as high host specificity, low use of insecticides, compatibility with biological control and low environmental impact (17). Therefore, this review critically examines the transition of *Liriomyza* spp. from minor pests to significant pests in horticultural ecosystem by evaluating the ecological and anthropogenic factors responsible for their habitat shift. It also discusses the current status, practical limitations and future perspectives of semiochemical-based management as one of the components of integrated pest management programmes.

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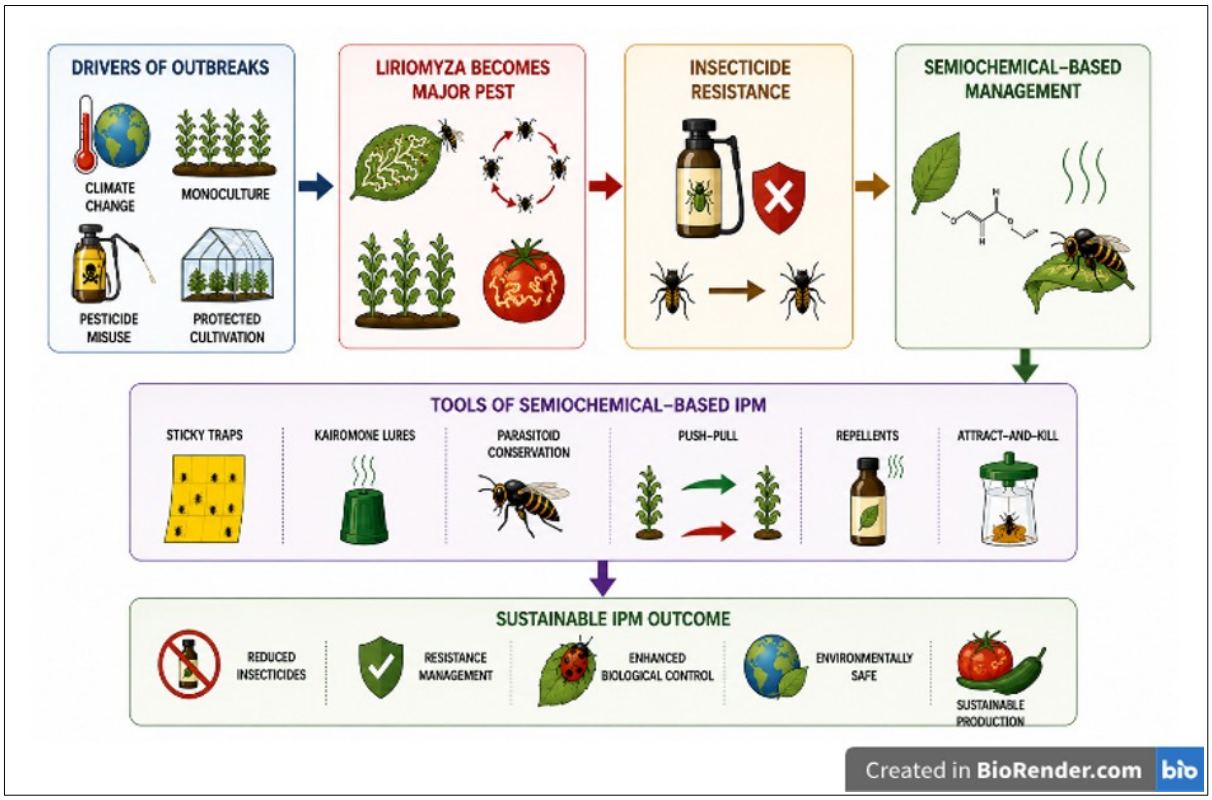


Fig. 1. Schematic representation of outbreak drivers, insecticide resistance and semiochemical-based management of *Liriomyza* spp.

Literature search methodology

This review was prepared through a comprehensive literature search of peer-reviewed research articles, review papers, books and authoritative databases. Literature was retrieved from Web of Science, Scopus, PubMed, Google Scholar, CAB Abstracts, ScienceDirect, SpringerLink, Wiley Online Library, EPPO Global Database, CABI Invasive Species Compendium, FAOSTAT and reports published by the Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC). The literature published between 1987 and 2025 was considered to capture both the foundational and the most recent developments on *Liriomyza* spp.

The search was performed using combinations of the keywords *Liriomyza*, leafminer, Agromyzidae, invasive species, habitat shift, climate change, protected cultivation, host plant volatiles, HIPVs, semiochemicals, kairomones, synomones, integrated pest management, biological control, insecticide resistance and horticultural crops. Publications were selected based on their relevance to the distribution, invasion history, ecology, habitat shift and semiochemical-based management of economically important *Liriomyza* species, with preference given to peer-reviewed and authoritative sources.

Studies were included if they reported original data, reviews, or authoritative technical reports on the distribution, biology, ecology, invasion history, habitat shift, host associations, or semiochemical-based management of *Liriomyza* species in horticultural crops; conference abstracts without full peer review, non-English publications lacking a translatable abstract and articles that did not provide verifiable species-level identification were excluded. Using this search and screening strategy, approximately 260 records were initially retrieved, of which around 82 peer-reviewed articles, book chapters and institutional reports met the eligibility criteria following screening of titles, abstracts and full texts and were included in this review.

For conceptual clarity, this review uses "habitat shift" as a broad, umbrella term describing a directional change in the spatial or ecological occurrence of a species driven by changing environmental or anthropogenic conditions. This is distinguished from related but non-equivalent terms used elsewhere in the invasion ecology literature: "range expansion" refers to the enlargement of a species' established geographic range into previously unoccupied areas; "range extension" denotes a discrete, often isolated, record of occurrence beyond the previously documented range boundary; "host expansion" describes the incorporation of new plant hosts within an already-occupied geographic range; and "seasonal redistribution" refers to short-term, reversible movement of populations among habitats, hosts, or altitudes within the same range in response to seasonal climatic variation. Throughout this review, "habitat shift" is used as the overarching term, while the more specific terms above are applied only where the underlying evidence supports that particular process.

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Global distribution and invasion history

Origin and global spread of *Liriomyza* spp.

The global distribution and relative incidence of economically important *Liriomyza* species (Fig. 2). The genus *Liriomyza* is one of the most species-rich genera of leafminer flies comprising more than 400 species distributed around the world's temperate and tropical zones. Up to 20–25 species have been found to be economically significant as capable to infest crops and adapt to various agroecosystems and invasions into new geographical areas (10, 13). The genus *Liriomyza* belongs to the family Agromyzidae within the order Diptera (Insecta). Several species of this genus are economically important agricultural pests, particularly *Liriomyza bryoniae*, *L. huidobrensis*, *L. sativae* and *L. trifolii*, which are recognised as important leafminer species of horticultural crops (18). Most species of *Liriomyza* have limited geographical distribution, but there are some invasive species such as *L. trifolii*, *L. sativae, L. huidobrensis* and *L. bryoniae* that successfully invaded different agroecosystems of tropical, subtropical and temperate zones. The rapid dispersal of this group was associated with international trade of ornamental plants, vegetable seedlings and fresh produce, as well as intensive protected cultivation and favourable climatic conditions in new areas (3). The history of invasion of *L. trifolii* represents one of the first and most successful examples of the dispersal of agricultural pests. This species native to America was spread rapidly during the 1970's and 1980's through the transportation of ornamental plants and greenhouses crops. Now it is widely spread across Asia, Europe and Africa. Invasion success was associated with a high reproductive potential, a wide range of hosts, adaptation to protected cultivation and development of insecticide resistance, which allows *L. trifolii* to compete effectively with other local leafminer species (18). Likewise, another species *L. sativae* native to America expanded greatly in Southeast Asia, Australia, the Pacific Islands, the Middle East and Africa (19). Several economically important species of *Liriomyza* are found in India with respect to their association with vegetable, ornamental and pulse crops. Out of these, *L. trifolii* is the most widely reported and economically dominant invasive species in vegetable and ornamental crops, followed by *L. sativae* and *L. huidobrensis*. These three invasive species are the cause of major economic infestations in vegetables and ornamentals throughout the country (11, 20). Other species such as *L. brassicae, L. chinensis and L. bryoniae* are localised and usually associated with particular host plants or agroecological regions (19, 21). While *L. trifolii* has been reported from different vegetable growing states such as Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra, Gujarat, Uttar Pradesh and Himachal Pradesh, *L. sativae* is predominant in tropical and subtropical vegetable growing systems. On the other hand, *L. huidobrensis* has mostly been found in cooler or high-altitude production systems. *L. chinensis* is mainly confined to onion and garlic growing zones, whereas *L. brassicae* is found only in Brassica crops (11, 22).

Host range and crop associations

The key economic importance of *Liriomyza* species is mainly determined by their broad host range and close relation to many horticultural cropping systems. Among economically important species, *L. trifolii* has one of the broadest host ranges as it infests more than 400 plant species that belong to more than 30 botanical families (13). *Liriomyza sativae* is mostly connected with vegetable production systems in tropical and subtropical regions and usually attacks crops that belong to such families as Cucurbitaceae, Solanaceae and Fabaceae. This feature makes a significant contribution to its seasonal abundance and successful establishment in the invaded areas (18). Because different thermal measures reflect diverse biological stresses, mean temperature alone should not be used to assess temperature effects on *Liriomyza* populations. While maximum temperature captures brief exposure to potentially deadly or stressful situations, mean temperature mostly reflects the overall thermal environment experienced over a period. Cumulative thermal exposure combines exposure time and temperature intensity, whereas the length of exposure above a critical temperature can decide whether a brief heat episode results in significant death or reversible stress. Therefore, whether yield-loss estimations are linked to various temperature measurements, infestation times, host crops, or experimental settings, they should not be directly compared across research. For instance, research on the development of *L. sativae* demonstrates that rising temperatures can reduce embryonic development. Therefore, whether yield-loss estimations are linked to various temperature measurements, infestation times, host crops, or experimental settings, they should not be directly compared across research. For instance, research on *L. sativae* growth reveals that while rising temperatures can abbreviate immature development, they can also significantly increase mortality, especially during the pupal stage (23). The thermal stress can have a different effect on fecundity than developmental rate. Similarly, reproductive responses may be reasonably steady within a moderate temperature range but diminish when temperatures beyond the upper optimum.

Consequently, assessments of climate-related yield risk should report the thermal metric used, the duration and frequency of heat exposure and the developmental or reproductive stage affected rather than treating all temperature-related effects as equivalent. Yield losses due to *L. sativae* may reach 10 to 100 % depending on crop species, infestation level and management techniques (24). In comparison with other invasive species, *L. huidobrensis* is especially adapted to temperate and high-altitude production systems. Serious larval mining leads to reduction of leaf area, chlorophyll content and photosynthetic activity, which impacts crop yield negatively. In ornamental

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crops, even mild mining causes a decrease in its aesthetic quality and commercial value, so that it leads to serious economic losses (13). The damage in solanaceous crops caused by *L. huidobrensis* may reach up to 70 % through serious leaf mining (10). Instead of a single linear relationship, temperature affects *Liriomyza* biology through a number of interacting factors. Changes in mean temperature can shorten generation time and speed up development under mild conditions, which may increase the number of generations that are finished in a growing season. However, exposure over the upper thermal optimum may affect survival, pupal emergence and reproductive performance, so temperature extremes can elicit a distinct reaction. For instance, *L. sativae* can develop across a relatively broad thermal range, but pupal mortality increases markedly at temperatures near the upper limit, whereas *L. huidobrensis* shows an optimum for immature survival around 20–25 °C and severe developmental constraints at higher temperatures (23, 24). The duration of heat exposure is also important: a short heat pulse may induce physiological acclimation, whereas prolonged exposure can reduce feeding and fecundity. In *L. huidobrensis*, short-term exposure to 32–35 °C increased thermotolerance but simultaneously reduced adult feeding and fecundity, demonstrating a trade-off between heat resistance and reproduction (24). The host range of *Liriomyza* species plays an important role in the epidemiology of the pests and pest outbreaks. Constant cultivation of susceptible vegetable and ornamental crops and alternative hosts in the form of weeds provides continual food sources that support overlapping generations during the whole year. Therefore, host diversity not only supports rapid population development but also makes pest control more complicated through provision of source population outside of cultivated fields. Such features turned *Liriomyza* species into major constrains in horticultural production (11).

Economic impact assessment

Pest density, crop, cultivar, growing stage and management techniques all have a significant impact on the economic impact of *Liriomyza* infestation. According to reports, yield losses for *L. sativae* might vary from 10 % to 100 % depending on the crop and infection conditions (22). More thorough field evaluations of *L. huidobrensis* in Peru revealed production losses in potatoes ranging from 22 to 51 %, depending on the season and depth of infestation, with economic injury levels differing among cultivars based on crop value and foliar damage (22). *Liriomyza huidobrensis* decreased productivity in Brazilian tomato production by up to 15 %, with an economic harm level of 3.24 larvae per leaf and an estimated control cost of US$335.38 ha^{-1} (22). These findings demonstrate that the economic consequences of *Liriomyza* infestation cannot be represented by a single global loss estimate and should instead be assessed using crop-, region- and species-specific injury–yield relationships (Table 1).

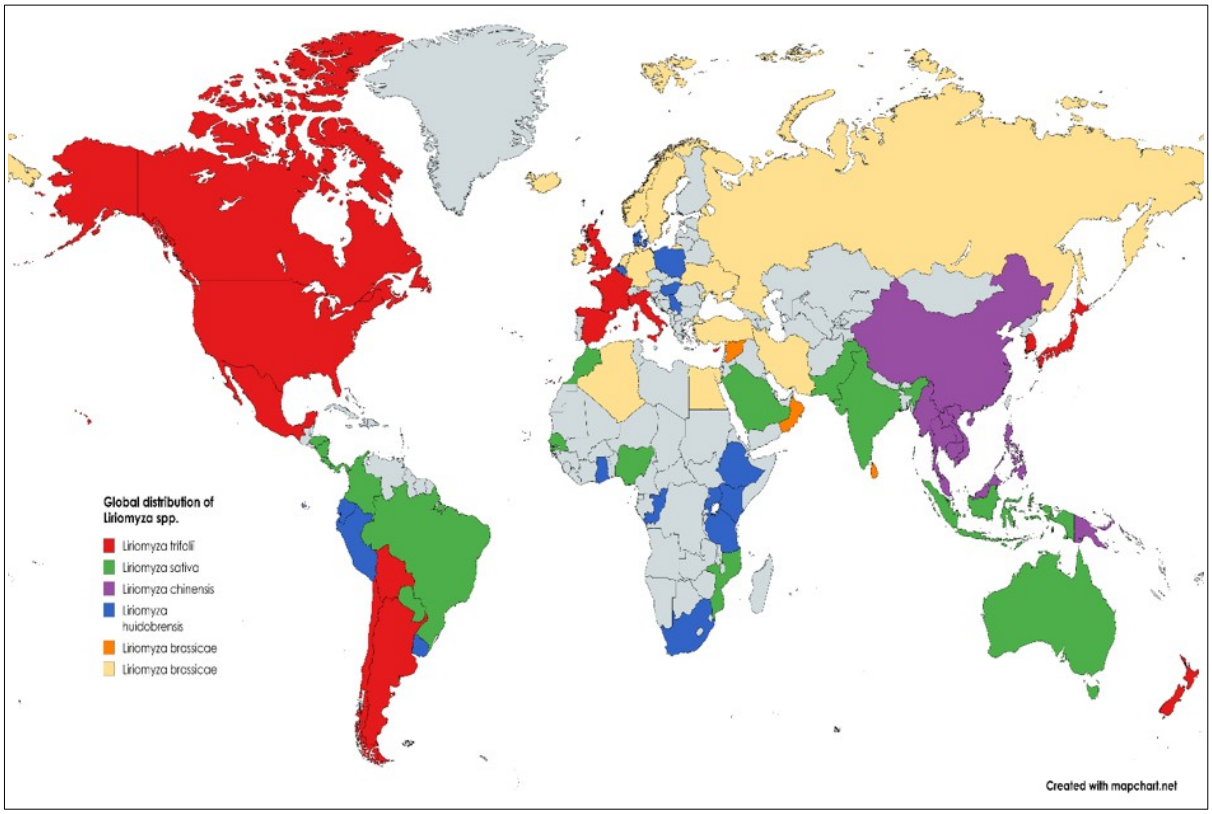


Fig. 2. Global distribution of economically important Liriomyza species. [Source: 19–21]

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Table 1. Major *Liriomyza* species of their common names, origin, global distribution and their host crops

Species	Common name	Origin	Introduced/established distribution	Host crops	Reference
Liriomyza trifolii (Burgess)	American serpentine leafminer	North America	Central and South America, Europe, Africa, Asia and Oceania	Tomato, celery, beans, cucurbits, chrysanthemum and other vegetables and ornamentals	(25, 26)
Liriomyza sativae (Blanchard)	Vegetable leafminer	America	Asia, Africa, Australia	Tomato, celery, chrysanthemum, cucurbits, beans and peas	(25)
Liriomyza huidobrensis (Blanchard)	Pea leafminer	South America	Europe, Africa, Asia, North America and Oceania	Potato, lettuce, celery, beans, peas, cucumber and ornamentals	(25, 26)
Liriomyza bryoniae (Kaltenbach)	Tomato leafminer/ Potato leafminer	Southern Europe	Central and Northern Europe, Morocco in North Africa	Tomato and cucumber	(27)
Liriomyza chinensis (Kato)	Onion leafminer	East Asia	Asia (China, Japan, Malaysia, Mongolia, Kazakhstan, Russia)	Onion, garlic and *Allium* crops	(28)
Liriomyza brassicae (Riley,1884)	Mustard leafminer	North America	Asia, Africa and Europe	Cabbage, mustard and *Brassica* crops	(28)
Liriomyza strigata (Meigen, 1830)	Leafminer fly	Europe	Reported from parts of North Africa and Asia	Legumes and vegetables	(28)
Liriomyza langei (Frick, 1951)	Chrysanthemum leafminer	California	No clearly documented introduced range; distribution should not be conflated with *L. huidobrensis*	Chrysanthemum and ornamentals	(28)
Liriomyza congesta (Becker, 1903)	Legume leafminer	Mediterranean – European region	Records from eastern Palaearctic/Oriental regions and India; introduction status uncertain	Broad bean, pea, alfalfa and other Fabaceae	(28)
Liriomyza cicerina (Rondani, 1875)	Chickpea leafminer	Mediterranean region	Reported in North Africa, the Middle East and India; introduced status in India uncertain	Chickpea (*Cicer arietinum*), wild onion	(28)
Liriomyza helianthin	Sunflower leafminer	North America	No clearly established introduced range confirmed	Sunflower and Cocklebur	(28)
Liriomyza pusilla	Asteraceae leafminer	Europe	Recorded in parts of Asia and Australia; introduction status uncertain	Asteraceae	(25)
Liriomyza taraxaci (Hering, 1927)	Dandelion leafminer	Palaearctic region	Canada and United States	*Taraxacum* spp.	(28)
Liriomyza sonchi (Hendel,1931)	Sow-thistle leafminer	Europe	Records from parts of Asia; introduced status uncertain	*Sonchus* spp.	(28)
Liriomyza plantaginis	Plantain leafminer	Palearctic region	No reliable introduced range established	*Plantago* spp.	(28)
Liriomyza ranunculi	Buttercup leafminer	Europe	No clearly documented introduced range	*Ranunculus* spp.	(28)
Liriomyza artemisiae	Artemisia leafminer	Temperate Asia	North American records have been documented; introduction status requires caution	*Artemisia* spp.	(28)
Liriomyza valerianae	Valerian leafminer	Europe	No clearly documented introduced range	*Valeriana* spp.	(28)
Liriomyza euphorbiae	Spurge leafminer	Northern Asia	European records reported; introduction status not clearly established	*Euphorbia* spp.	(28)
Liriomyza salicis	Willow leafminer	Northern Asia (Palea region)	No clearly documented introduced range	Willow (*Salix*)	(28)

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Abiotic influence on *Liriomyza* dynamics

Climatic variables such as temperature, precipitation, humidity, wind speed and direction are important in determining the development, reproduction, dispersion, migration and adaptation of pests. Moreover, there were indirect effects from the interactions among insect species, host plants and natural enemies (29). Agromyzid leafminer developed optimally at a constant temperature of 25 °C, where the developmental rates increased with approaching 30°C. The temperatures over 30 °C were unfavourable for leafminers leading to the larval mortality (30). In the tropical highlands, where the average minimum temperatures were below 22 °C, *L. huidobrensis* developed successfully. Meanwhile, *L. sativae* completed development successfully across the broader temperature range of 21 °C to 36 °C. Thus, the findings helped make better forecasts of how climate changes could affect the distribution of leafminer flies. The temperature-dependent competitive exclusion interaction was discovered among the species, where *L. sativae* appeared at temperatures less than 22 °C in the absence of *L. huidobrensis*. Also, the efficiency of parasitoids in suppressing the leafminer populations depended on the type of host plant (31). Developmental patterns of *L. huidobrensis* and *L. trifolii* in different temperatures showed distinct differences. *L. huidobrensis* took more time to develop an embryo at 25°C and 30°C, but less time at 15°C than *L. trifolii.* The larval development of *L. huidobrensis* was slower at 20°C, 25°C and 30°C, while its pupal development was faster at 15°C, 20°C and 25°C. *Liriomyza trifolii* showed the highest survival rate at 20 °C, whereas the lowest survival rate was noted in *L. huidobrensis* at 15 °C. *Liriomyza huidobrensis* reached maturity without emerging at 30°C. The lower developmental thresholds in *L. huidobrensis* were 7.3 °C and 8.1 °C, which were lower than *L. trifolii's* (9.9–10.7 °C). Additionally, the developmental time of *L. trifolii* was prolonged at 15 °C and shortened at 30 °C (32, 33).

In *L. sativae*, adult longevity was inversely related to the increase in temperature and relative humidity, with the longer lifespan of females. There were the extended oviposition periods at higher temperatures and relative humidity showed a significant effect. The oviposition remained constant between 18 °C and 30 °C but decreased at 32 °C. Despite all the factors, *L. sativae* laid from 75 to 92 % of eggs on the adaxial surface of cowpea leaves (23). The correlation analysis showed that there were significant negative correlations between the infestation rate of the leafminer and several abiotic factors, like maximum temperature, minimum temperature, average temperature, evening relative humidity, morning, evening and average vapour pressure and average vapour pressure deficit. In addition, sunshine duration and evaporation showed significant negative correlations with the number of mines, leaf infestation and larvae, whereas leaf infestation percentage alone showed a significant positive correlation with evaporation (34).

Characteristics of *Liriomyza* spp.

Morphological identification

Liriomyza spp. are relatively small insects (usually yellow-black). A key diagnostic wing-venation character of the genus is that the costa extends to vein M1+2, rather than terminating at R4+5 as in the closely related genera *Phytomyza* and *Chromatomyia*; within the genus, this costal vein terminates precisely at the point where M1+2 meets the wing margin in most species, but extends slightly beyond it in *L. sativae* and *L. trifolii* (18). These species have differences in more precise morphological characters such as colour of scutellum, frons pattern and the male genitalia that complicates the traditional morphological identification (35). Eggs are white, oval and 0.25 mm long and are laid inside leaf tissue. The identification of this species at the genus or species level was impossible at this point. The larvae had three instars beginning with the size of 0.5 mm to 3.0 mm (35). The freshly hatched larvae of *L. sativae* and *L. trifolii* were transparent, then became yellow-orange. The pupae were oval-cylindrical with the length of 2.0 mm, having characteristic tricorn-shaped posterior spiracles and were yellowish-orange or golden-brown in color (36). The adults were tiny, less than 2 mm in length, the wings ranging in length from 1.25 to 1.9 mm. The head was yellow, having red eyes, while the thorax and abdomen were mainly grey and black and the ventral side and legs were yellow. The wings were clear.

The common morphological features of *Liriomyza* leafminers were the reclinate and backward directed fronto-orbital setulae and dark pre-scutellar area with the characteristic yellow scutellum that could be dark. Their wings have a costa that reaches vein M1+2 and small discal cell. The subcosta was bent distally and ended separately in the costa, having a second outer crossvein (dm-cu) in the majority of species. The two main parts of the stridulatory organ in male leafminers were scraper, a chitinised ridge on the hind femur and file – low chitinised scales on the connecting membrane between the abdominal tergites and sternites (18). The identification of any specific *Liriomyza* species was accomplished through the analysis of the male genitalia especially the distiphallus part (14). The distinct features of the genus *Liriomyza* were the colour of the base of the vertical setae, structure of the anepisternum and mesonotum and the medial furrow on the abdominal tergites in males (14) (Table 2).

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Table 2. Morphological diagnostic features for the identification of major *Liriomyza* species

Speciesa	Abdominal colour pattern	Thoracic microsetae	Wing Morphology	Male genitalia (diagnostic character)	Identification	Reference
Liriomyza brassicae	Yellow median furrow present only on the 2nd visible tergite	Shortest microsetae (≈4.13 µm); moderate density	Wing shape similar to *L. sativae* and *L. trifolii*	*Distiphallus* distinct from other species	Distinguished mainly by short thoracic microsetae and genitalia	(14)
Liriomyza bryoniae	Yellow median furrow extends to the 3rd visible tergite	Medium-length microsetae with intermediate density	Wing resembles *L. huidobrensis*	*Distiphallus* bowl-shaped; differs from *L. huidobrensis* in ventral view	Easily recognized by abdominal colour pattern and genitalia.	(21)
Liriomyza chinensis	No distinct abdominal colour pattern; mesoscutellum pale grey	Longest and densest thoracic microsetae (≈9.60 µm)	Wing shape clearly distinct from other species	*Distiphallus* unique and easily distinguished	Easily separated by grey scutellum, absence of abdominal pattern and long microsetae.	(14)
Liriomyza huidobrensis	Yellow median furrow only on the 2nd visible tergite	Medium-length microsetae with lowest density	Wing closely resembles *L. bryoniae*	*Distiphallus* similar to *L. bryoniae* but mesophallus bears paired sclerotised lateral stripes	Identification should rely mainly on genitalia	(19)
Liriomyza sativae	Yellow median furrow only on the 2nd visible tergite	Medium-length microsetae; intermediate density	Wing shape similar to *L. brassicae* and *L. trifolii*	*Distiphallus* larger and more strongly sclerotised than in *L. trifolii*	Requires examination of male genitalia for reliable identification.	(19)
Liriomyza trifolii	Yellow median furrow extends across the 2nd–5th visible tergites	Long microsetae with high density	Wing similar to *L. sativae* and *L. brassicae*	*Distiphallus* differs subtly from *L. sativae*; best seen in lateral view	Most easily recognised externally by the extensive abdominal yellow median furrow	(19)

Molecular confirmation of leafminer species

Molecular methods, particularly DNA barcoding based on the mitochondrial *COI* gene, provide an important complement to morphological identification of *Liriomyza* species (22). Hence, it could help to improve the resolution of species at the higher level and inclusion of cryptic species' identities (35). A phylogenetic analysis that uses 2965 bp of DNA sequences data from the mitochondrial *COI* gene, nuclear ribosomal 28S gene and nuclear cinnamyl alcohol dehydrogenase (*CAD*) gene included 86 species in 21 genera in the Agromyzidae family. Analyses using both parsimony and Bayesian showed that Agromyzinae and Phytomyzinae were monophyletic groups. Some genera such as *Liriomyza*, *Melanagromyza* and *Agromyza* were monophyletic, while other genera like *Aulagromyza, Chromatomyia* and *Phytomyza* were polyphyletic or paraphyletic. This kind of analysis provided important information regarding the evolution of this Agromyzidae family (37). In the mitochondrial genome of *L. huidobrensis* (16,239 bp), there is an A+T rich region and 37 genes. There were an important sequence and structural divergence between *L. trifolii* and *L. sativae* in H51-H100 region of the srRNA. Region with high sequence divergence including ND2, ND3, ND6, ATP6, ATP8, CYTb and A+T regions could be used as molecular markers (38).

Population genetics and invasion pathways

Genetic structure and gene flow can shed light on the invasion history of *Liriomyza* spp., according to a growing body of evidence from molecular research. Microsatellite analysis of *L. sativae* populations from 12 provinces in China showed high levels of gene flow, comparatively low genetic diversity and moderate population differentiation. An overall pattern of south-to-north migration suggested a significant role for human-mediated movement (39). Peru was found to be the ultimate source of the major invasive lineages in a more recent phylogeographic analysis of *L. huidobrensis* based on mitochondrial COI and COII sequences from native and introduced populations. The low genetic diversity of introduced populations was consistent with founder effects and population bottlenecks (37). Genome-wide phylogenomic investigation of *L. trifolii* revealed modest geographic difference among many populations and various host-associated lineages, although the history of invasion into Asia was compatible with a genetically distinct Chinese group (40). By identifying source populations, possible bridgehead populations and migratory patterns, these results collectively show that population genetics can supplement distribution data. Future research that combines genome-wide markers, extensive geographic sampling and intercepted specimens may yield more reliable evidence for identifying freshly established populations and tracking recent invasion paths.

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Physiological and reproductive adaptations

Adaptability is one of the key characteristics of *Liriomyza* spp., which makes this leafminer so successful in terms of colonisation of new habitats. Thermal tolerance is species-specific rather than uniformly wide across the genus: under controlled experimental conditions, *L. sativae* completes development between 21 °C and 36 °C, whereas *L. huidobrensis* develops successfully below 22°C and *L. trifolii* has a narrower lower developmental threshold (9.9–10.7 °C) than *L. huidobrensis* (7.3–8.1 °C) (31, 33, 34, 37). This species-specific thermal plasticity allows each species to reproduce and survive within its own climatic range. Another physiological adaptation for coping with thermal and chemical stresses is high expression of heat shock proteins and high levels of detoxification enzymes, which allows them to survive in environments contaminated with pesticides (35). Additionally, there are some reproductive features such as short generation time, high fecundity and high development rates, which make the population grow exponentially when favourable conditions are provided. Adaptation to the consumption of different plants and the ability to colonise new agroecosystems is due to the presence of gut microbiota in the leafminers, which may be connected with the ability to digest new plants. Thus, this set of physiological adaptations provides the invasive abilities of *Liriomyza* spp. that allow them to survive in the horticultural systems in both tropical and temperate climates (35). The successful expansion of the habitat for *Liriomyza* spp. is ensured by various physiological adaptations, which include thermal tolerance, enhanced detoxification and beneficial relationships with gut microorganisms. All these mechanisms ensure the establishment of populations in different agroecological zones, colonising novel hosts and coping with anthropogenic pressure. Temperature plays an important role in the distribution of *Liriomyza* spp. and in their population dynamics. In economically important species, the *L. sativae* has higher heat tolerance compared to *L. huidobrensis*, which makes it possible for the former to become dominant in the tropical and subtropical zones because of high temperatures favourable for development, high fecundity and successful colonisation. In contrast, the *L. huidobrensis* is comparatively more resistant to cold weather and high altitudes, which results in the domination of the species in temperate and mountainous zones of production. The difference in thermal tolerance is one of the factors contributing to the shifts in the species composition and distribution under current climate warming (16). Detoxification is mediated by cytochrome P450 monooxygenases (CYP450s), glutathione S-transferases (GSTs), carboxylesterases (CarEs) and ATP-binding cassette (ABC) transporters, which enable *Liriomyza* spp. to exploit chemically defended host plants and evolve resistance to commonly employed insecticides. It was shown through comparative transcriptome profiling that several insecticide- and xenobiotic-induced detoxification-related genes are highly upregulated in *L. trifolii* and *L. sativae*, which implies that detoxification systems serve an important role not only in resistance development but also in ecological adaptation (41–43). Gut-associated microflora serves as an adaptive trait in leafminers. Several bacterial genera including *Wolbachia*, *Pseudomonas*, *Enterobacter*, *Serratia* and *Enterococcus* were found in various *Liriomyza* species and assumed to be responsible for nutrients assimilation, degradation of plant allelopathic chemicals, detoxification of xenobiotics and maintaining gut homeostasis. Despite the ongoing research aimed at revealing specific roles of microbial communities, there is some evidence suggesting that changes in the composition of leafminer gut microbiota can positively affect their adaptation to new host plants and environmental conditions thus ensuring habitat expansion and invasion success (42).

Ecological plasticity and invasive potential

Ecological changes such as global warming, modified greenhouse microclimates, year-round crop cultivation, intensive fertilisation and monoculture can facilitate the expansion of *Liriomyza* spp. into new agroecological zones. The climate compatibility is considered as one of the crucial factors since the temperature influences the development speed, the survival and the voltinism of *Liriomyza* spp (43). Most of the species are thermoplastic and therefore are able to adapt to extreme conditions of temperature and colonise the unsuitable areas (30). Moreover, the trade has led to intercontinental transport of the insects. The change in vulnerability of the plants involved the physiological changes of the host plant due to alteration in climatic conditions and changes in volatile profile (15). Global warming and the increase in the frequency of warm season can presumably lead to the increase in the number of climatically suitable niches for heat-resistant species like *L. sativae* for colonisation in previously marginal zones (43). The polyphagy is another important ecological factor that promotes the expansion of the habitat in *Liriomyza* spp., since leaf miners are characterised by large host range that involves vegetable, ornamental and weed plants (27). The weed hosts can serve as reservoirs during the absence of crops and the local movement and reinfestation become facilitated (44). Such host continuity transforms the agro habitat to the landscape level and creates favourable conditions for the increase in the population size and spatial spreading at the faster pace. The habitat suitability for *Liriomyza* spp. can be improved by the intensive agriculture in high nitrogen fertilised stands through increasing the host density and quality (44). The land use simplification and monoculture decrease the ecological resistance by decreasing functional diversity and disrupting the natural enemy communities (45). The protected cultivation practices such as greenhouses and net houses promote the expansion of the leaf miners since such systems provide shelter from the adverse climatic conditions and constant supply of the host plants (46). Additionally, globalisation and international trade of plant material have played an important role in

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the development of *Liriomyza* spp. that allows rapid establishment of long-distance dispersal and introduction into new locations with ecological condition (42). Habitat range extension also depends on the interactions between invasive *Liriomyza* spp. Invasive species' dominance along the altitudinal and climatic gradients depends on competitive superiority based on temperature, which influences the range expansion process (41). Thus, it could be predicted that the distribution of *Liriomyza* will face another reorganisation due to the climate change effect on physiological performance and competition among the species.

Drivers of habitat shift and pest emergence

Climate change and ecological niche expansion

Climate change has been one of the primary drivers of the distribution, abundance and seasonality of pest insects in agricultural ecosystems (44). The rise in temperature, changes in precipitation regimes and an increase in extreme weather events impacted the suitability of various agro ecosystems for herbivorous insects (44). Climate-driven changes in species distributions are frequently accompanied by shifts in pest phenology, allowing invasive herbivores to exploit newly suitable environments and extend their seasonal activity. Such changes highlight the importance of incorporating climate-based risk assessment into future management strategies for *Liriomyza* spp. (47). Concerning invasive agromyzid flies, *Liriomyza* spp. demonstrated a rapid response to climate change because the development and reproduction of this pest are closely related to climatic constraints (14). Temperature is considered one of the most critical abiotic factors that shape the life-history traits of *Liriomyza* spp. (44). Specifically, increases in temperature promote egg production, reduce development time of larvae and pupae and shorten the overall developmental period (44). Consequently, shorter generation times may allow *Liriomyza* spp. to complete a greater number of successive generations within a growing season, potentially increasing population growth and infestation pressure (44). An increase in the number of voltinism leads to enhanced proliferation of *Liriomyza* species' growth, survival and reproduction are significantly influenced by temperature; however, different species react differently to temperature. Variations in heat tolerance might affect a species' relative distribution, competitive performance and abundance (44). According to experimental data, *L. sativae* may thrive in warmer environments but *L. huidobrensis* is more severely restricted by high temperatures. This suggests that warming may encourage species replacement rather than a consistent growth in all *Liriomyza* populations (44). *Liriomyza* spp., which in turn causes more severe infestation of vegetable crops (11). In addition, winter temperature shapes the geographic distribution of this pest (9). A mild winter season reduces the number of stressful days for insects, which increases their survival rate and facilitates colonisation of new habitats that were previously unsuitable for their occupation (42). As a result, invasive populations of *Liriomyza* spp. are expanding their ranges to the north and to higher altitudes (9). In addition, the response to climate change was found to depend on species-specific attributes because different invasive species of *Liriomyza* demonstrate distinct adaptations to temperature variability (38). The *L. sativae* possesses superior reproductive potential at increased temperatures, enabling it to dominate in subtropical and tropical vegetable crops (38).

Liriomyza huidobrensis is adapted to high altitudes and cooler environments, thereby thriving in the highlands (38). In contrast, regarding *L. trifolii*, it demonstrated a broader thermal tolerance range allowing it to occupy a wide range of habitats from temperate to subtropical (13, 20). Biotic and abiotic factors that promote the spread of leafminers, the expansion of their distribution range occurs through man-made activity (8). Specifically, the long-distance transportation of goods contributes to the introduction of invasive species to new areas, whereas the continuous cultivation of perennial crops provides them with continuous access to host plants (8). Moreover, the usage of protected cultivation systems in association with favourable climate conditions facilitates the colonisation process (46). Both ecological and anthropogenic factors should be taken into consideration when assessing the progress of pest invasion (8).

Climate change may also modify the geographical suitability of *Liriomyza* populations by altering temperature, precipitation and host-plant conditions (42). However, climate-based distribution models should not be interpreted as direct predictions of pest abundance because climatic suitability represents only one component of establishment. Host availability, crop phenology, interspecific competition and natural-enemy pressure can modify the realised distribution of a species (38). The current literature therefore supports combining ecological niche modelling with physiological and field-based studies to improve predictions of future *Liriomyza* expansion. The implications of climate change on the distribution of invasive leafminers, the use of ecological niche models became widespread as an effective method to predict future spread patterns (9). They indicate that the area of distribution of multiple species of *Liriomyza* spp. will increase as a result of climate change (9). Therefore, these predictive models are essential for the regulation of pest outbreaks at local levels and for the development of integrated pest management strategies at regional levels (3). The majority of the research on the impact of climate change on the ecological characteristics of *Liriomyza* spp. is conducted under lab conditions (44). However, it is crucial to understand how these pests respond to multiple simultaneous environmental variables such as the combined effect of temperature, atmospheric CO2 concentration and water content on the physiology of leafminers and their host plants (11). Thus, the current understanding of the impact of climate change on

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leafminers is limited, which makes the need for further research inevitable (44). Moreover, the future studies should combine the use of ecological modelling and field investigations in order to improve the accuracy of predictions (9).

Protected cultivation and altered microclimates

The practice of protected cultivation has changed the role of *Liriomyza* spp. pests by providing favourable microclimatic conditions suitable for year-round population survival and reproduction (46). Protected cultivation can facilitate *Liriomyza* establishment by reducing environmental fluctuations and maintaining suitable host plants throughout much of the year (11, 46). Stable temperature, humidity and airflow can reduce weather-related mortality, while continuous crop production permits successive generations to develop without the seasonal interruption commonly experienced in open-field systems (11, 46). However, the effect of protected cultivation is not exclusively favourable to the pest. Changes in light quality, crop microclimate and the movement of parasitoids can modify pest–natural-enemy interactions, while repeated insecticide applications may further weaken biological regulation (45, 46). Unlike field cultivation, greenhouse and net house systems provide protection from changes in temperature, humidity and wind, which leads to elimination of environmental stress and uninterrupted population development (48). Year-round cultivation of crops suitable for hosts to eliminate seasonal disruptions of host availability and results in continuous overlapping of population generations (11). Moreover, the use of protected cultivation facilities impacts the ecological relationships responsible for population regulation in an environment. The limited movement of parasitoids and predators and regular applications of insecticides can reduce effectiveness of biological regulation of pests' populations (45). In addition, the modification of light quality caused by the usage of greenhouse covering materials leads to changes in behaviour of insects including orientation and searching for the hosts, while at the same time affects growth of plants and their secondary metabolism (49, 50). Protected cultivation alters airflow, solar radiation and humidity, thereby creating relatively stable microclimatic conditions that can enhance insect survival while reducing mortality associated with adverse weather conditions. These favourable environmental conditions frequently permit the continuous pest establishment supported by preventive monitoring and biological control programmes (50).

Agricultural intensification and monoculture

Intensification of agriculture changes the ecological factors which controls the *Liriomyza* populations in horticulture (44). Year-round cultivation of crop pests reduces seasonal disruption in host availability leading to continuous existence of generations (11). In such case, the regulation of population depends mainly on the crop management and not on seasonality. Landscape simplification is another factor contributing to pest establishment by increasing host availability and decreasing the heterogeneity of habitat (51). Uniform cropping system facilitates the dispersal of adult flies between host plants and reduces the availability of non-host habitats, where parasitoids and predators occur (51). As a result, the ecological regulation of *Liriomyza* population decreases and reliance on chemical control increases (48). Also, the nutritional regime of the crops affects host suitability of the plants. Increased input of nitrogen results in higher nitrogen concentration in the foliage and modifications in emissions of volatile organic compounds involved in host selection (14). These physiological effects increase the egg laying preference of pests and improve the larval performance.

Human-mediated dispersal and colonisation of novel plant hosts

Translocation of planting materials, ornamentals and fresh produce through human activities has become the primary method of dispersal of *Liriomyza* spp. across the different geographical regions, resulting in multiple invasions of novel production systems (8, 25). The presence of host species suitable for insect development and reproduction is a requisite factor (13). Thus, the colonisation of a new region becomes an ecologically selective process, rather than the result of accidental introduction of *Liriomyza*. After arrival, the survival of the invasive population is conditioned by the presence of cultivated and wild hosts that ensure the existence of a proper microhabitat, leaf characteristics and feeding substrate for the larvae (20, 21). Weed species and volunteer crop plants ensure the existence of residual populations during crop-free periods and facilitate the invasion of novel horticultural areas (51). Therefore, colonisation becomes a product of multiple factors of invasion, such as propagule pressure, host suitability and connectivity of habitats (8).

Interspecific competition and species replacement

Interspecific competition can contribute substantially to changes in the distribution and relative abundance of closely related *Liriomyza* species, particularly when they exploit the same host plants and occupy overlapping ecological niches. Competition may occur through shared resources, including host leaves, oviposition sites and feeding sites and may be expressed through differences in resource-use efficiency, developmental rate and reproductive performance. In addition to direct resource competition, asymmetric interactions may arise when one species is better able to acquire or exploit limiting resources, resulting in reduced survival or reproductive output of the other species. Such competitive effects can become particularly important when population densities are high and suitable host plants are limited (35, 52).

Temperature adds an important environmental dimension to these interactions because it can alter the relative fitness of competing species. Rather than determining species distributions independently of biotic interactions, temperature may change the intensity and outcome of competition by favouring one species over

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another at particular thermal conditions. This process is referred to as temperature-dependent competitive exclusion, in which the ability of one species to persist in the presence of a competitor varies with temperature. For example, *L. huidobrensis* has a narrower upper thermal tolerance than *L. sativae*, with high temperatures around 28–29 °C strongly reducing adult emergence, whereas *L. sativae* occurs across a broader temperature range. Field observations in Guatemala further showed that *L. sativae* occurred at temperatures below 22 °C mainly where *L. huidobrensis* was absent, indicating that the distribution of the two species cannot be explained by temperature alone but reflects an interaction between physiological tolerance and interspecific competition. Thus, environmental temperature can modify the competitive advantage of one species and indirectly determine the realized distribution of the other (35, 38).

Experimental evidence also demonstrates that competitive outcomes can change across temperature regimes. In mixed-species cultures, both *L. sativae* and *L. trifolii* showed reduced net reproductive rates compared with single-species cultures, confirming strong interspecific competition. However, *L. sativae* had a greater competitive advantage at lower temperatures, whereas *L. trifolii* performed relatively better at higher temperatures. Therefore, neither species can be considered a universally superior competitor; instead, relatively small differences in thermal performance can shift the balance of competition and influence which species becomes dominant under particular climatic conditions (38). These findings indicate that competitive displacement in *Liriomyza* should be viewed as the outcome of interacting biotic and abiotic mechanisms, rather than as a simple replacement of one species by another. Thermal tolerance determines the environmental conditions under which a species can maintain viable populations, while resource overlap and differences in reproductive performance determine how species perform when they occur together. In addition, parasitoid pressure and host-plant characteristics may modify these interactions, further complicating predictions of species dominance across landscapes. Consequently, future assessments of *Liriomyza* range expansion should integrate thermal physiology, resource competition, reproductive performance and natural-enemy effects rather than relying solely on climatic suitability models (35, 48).

Therefore, climate warming should not be interpreted simply as causing a general increase in *Liriomyza* abundance. Instead, warming may reorganise species composition by changing the relative fitness and competitive advantage of different congeners (35). This distinction is particularly important for surveillance because management recommendations based only on total leafminer abundance may overlook species replacement and associated differences in thermal tolerance, host range and insecticide susceptibility.

Plant–insect interactions

The interactions between plants and insects define the potential of *Liriomyza* spp. to colonise, survive and become a pest in horticultural environments by affecting host choice, insect performance and host defence. Unlike adults, which feed and lay eggs by piercing leaf tissue using a serrated ovipositor, larvae develop inside the mesophyll maintaining a close connection with the host tissues during whole the life cycle stage (20, 21). This type of behaviour protects them from adverse environmental conditions and some natural enemies and provides continuous food source, thus improving the larval survival and development (13). As a result, the result of infestation depends not only on the density of insects but also on the interaction between behaviour of insects and host responses. Host exploitation starts with the host identification and acceptance. First, the adult insects find a suitable host based on visual cues and then decide to feed and lay eggs basing on the properties of leaf surface and chemical cues produced by the host plant (53, 54). After oviposition, larvae begin mining in mesophyll leaving characteristic serpentine mines that grow during the development (20). Leaf mining leads to the destruction of chloroplast-rich mesophyll tissues and decrease in photosynthetic activity, alteration in assimilate distribution and reduction of plant productivity especially during intense infestation (21). However, there are differences in the extent of injury depending on the type of host because leaf anatomy, nutritional state and constitutive defence mechanism affect the ability of larvae to develop in different ways (14). Therefore, the host suitability is an emergent characteristic of plants and insects' response to the host instead of availability of the host. Mining also triggers the activation of host defence response. The disruption of mesophyll tissues and larvae's feeding activate the endogenous signals causing changes in metabolic processes related to defence mechanism (55). These defence reactions include physiological reprogramming, production of protective compounds and redistribution of assimilates from damaged to healthy tissues (55).

Defence signalling is obtained through hormonal signaling pathways including jasmonic acid, salicylic acid, ethylene and abscisic acid, which act together to regulate the expression of defence genes after herbivore attacks (54). These different pathways ensure that plants selectively respond to herbivore injury by adjusting the priority of defence and limiting the metabolic cost of defence activation (55).

Leafminer feeding activates a network of plant defence pathways in which jasmonic acid (JA), salicylic acid (SA), ethylene (ET) and abscisic acid (ABA) can interact to regulate direct and indirect plant defence responses (55). Among these pathways, JA has been demonstrated to play an important role in resistance to *L. trifolii*. Feeding by *L. trifolii* increased JA accumulation and induced JA-responsive defence genes in *Arabidopsis*, whereas JA-insensitive coi1-1 plants showed reduced feeding resistance and supported

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development of the subsequent generation (56). Similarly, exogenous JA treatment of sweet pepper induced the accumulation of the defensive metabolite caffeoyl putrescine and increased resistance to *L. trifolii*, as indicated by reduced feeding punctures and oviposition (57). In bean plants infested with *L. huidobrensis*, adult feeding punctures increased JA and JA-related gene expression, whereas larval feeding activated both JA- and SA-associated responses (58). Larval feeding also induced the emission of methyl salicylate and the terpenoid (E, E)-4,8,12-trimethyl-1,3,7,11-tridecatetraene (TMTT), while combined application of JA and SA significantly increased TMTT emission (58). parasitoid attraction. The JA–SA-mediated increase in TMTT emission further enhanced parasitoid orientation, demonstrating a mechanistic link between hormone signalling, volatile production and indirect defence against *L. huidobrensis* (58). Evidence also indicates that leafminer-induced hormonal signalling can influence insect performance beyond the feeding site. In tomato, *L. trifolii* infestation altered plant hormonal responses and below-ground volatile production, which subsequently accelerated the development of conspecific pupae (58). Ethylene and ABA may also participate in the broader hormonal network activated by herbivory; however, compared with JA and JA–SA interactions, direct experimental evidence linking these pathways independently to *Liriomyza* performance remains limited (59).

The hormone-controlled defence mechanism also changes the production of secondary metabolites and volatile organic compounds that have an effect on the behaviour of herbivores and indirectly defend the plant by attracting the parasitoids and predators (17). Therefore, defence not only involves protection against injury but also plays a role in ecological interactions at higher trophic levels. Interactions between plants and *Liriomyza* are reciprocals in the sense that neither the insect nor the host operates alone during the infestations. Insect feeding behaviour regulates the extent of plant response, while induced defences affect the performance and survival of herbivores and interactions with natural enemies (14). These complex interactions serve as the basis for exploiting the host-derived volatiles through semiochemicals for improved monitoring and biological control of *Liriomyza* spp. in horticultural crop systems.

Semiochemical-based management strategies

Host plant volatiles

Host plant volatiles (HPVs) play an important role in the initial orientation of *Liriomyza* adults towards suitable host plants (16, 53, 54). However, evidence indicates that host recognition is influenced by the composition and relative concentration of volatile blends rather than by a single universally attractive compound (53, 54). Consequently, the behavioural activity of an individual compound under laboratory conditions may not necessarily predict its performance as a field lure. Variation in volatile emissions with plant species, cultivar, developmental stage, nutritional status and environmental conditions can further contribute to inconsistent responses (15, 44, 49). Instead of being attracted by a particular compound, the *Liriomyza* adults recognise the mixture of volatile chemicals, which means that the host orientation depends on the blend composition and concentrations rather than on a single attractive compound (16). The composition of HPVs differs depending on the type of the plant, cultivar and the development stage of the plant and is additionally affected by the nutrition and environment and thus affects the variation of leafminer infestation geographically and temporally (44). This shows that the process of host location is a context-dependent process where volatile cues interact with phenology and the environment of the plant to affect the behaviour of the insect. Thus, the lures developed based on single compounds tend to have inconsistent results in the field because they cannot replicate the complexity of naturally emitted volatile mixtures (16). A thorough knowledge of the host volatile profiles is therefore ecologically essential for identifying behaviourally active compounds that can then be included in lure formulations for monitoring and behavioural control of *Liriomyza* spp. as part of an integrated pest management strategy (60).

Herbivore induced plant volatiles

Herbivore-induced plant volatiles make up a dynamic part of plant defence strategy responsible for mediating ecological relationships between host plants, herbivores and natural enemies. In contrast to constitutive plant volatiles, HIPVs are produced after herbivore damage and depend on the physiological condition of the affected plant. Composition of HIPVs includes green leaf volatiles, terpenoids, benzenoids, phenylpropanoids and other volatile organic compounds and varies depending on plant species, insect, infestation level and environmental factors (16, 17). Such variability allows HIPVs to serve as informative signals rather than simple by-products of wounding. In relation to *Liriomyza* spp., volatile chemicals produced by the plants may act as kairomones helping the insect to find the hosts and oviposit on them. Adult leafminers use volatile signals combined with visual and tactile stimuli to distinguish different host plants, meaning that their behaviour is mediated by specific composition and concentration of volatile blend components and not single components (55). The green leaf volatiles, particularly (Z)-3-hexenol and (Z)-3-hexenyl acetate, act as host-finding cues in many *Liriomyza* species, but their effectiveness depends on the composition of the blend and crop context (15).

Host plant volatiles and HIPVs should be distinguished according to their temporal origin and ecological context. The HPVs are constitutively emitted or continuously released plant volatiles that provide information about host identity and physiological condition, whereas HIPVs are emitted or quantitatively altered following herbivore attack or herbivore-associated damage. Importantly, the same chemical

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compound cannot be assigned a universal ecological function solely on the basis of its chemical identity. Its function as an attractant, repellent, kairomone or synomone depends on the receiver, concentration, blend composition, release context and experimental conditions.

For example, bean volatiles containing green leaf volatiles and other host-associated compounds elicited electrophysiological and behavioural responses in *Liriomyza sativae,* indicating a role in host location rather than demonstrating that each individual compound is independently attractive (53, 54). Similarly, a seven-component blend identified from cowpea and kidney bean volatiles was attractive to *L. sativae* in field trapping experiments, with α-ionone and β-ionone implicated in host-searching behaviour (15). These findings support the use of volatile blends as host-location cues, but do not justify assigning the same ecological function to each constituent compound.

The distinction is also important for HIPVs. In *L. huidobrensis*, female puncturing of host leaves induced the release of green leaf volatiles, terpenoids and oximes. Among the compounds tested individually, (Z)-3-hexenol and (Z)-3-hexenyl acetate elicited strong antennal responses and attracted both males and females in laboratory behavioural assays. These compounds also promoted mating-related encounters on host leaves (61). Thus, under these experimental conditions, these induced volatiles functioned as attractive host-associated cues; they should not automatically be described as repellents or general-purpose kairomones in other ecological contexts.

Conversely, methyl salicylate provides a clearer example of a plant-derived kairomonal cue under defined conditions. In greenhouse experiments with *Liriomyza bryoniae*, synthetic methyl salicylate increased adult catches when combined with yellow sticky traps and its attractiveness depended strongly on the simultaneous visual stimulus. The authors therefore interpreted methyl salicylate as a kairomone in that specific plant–insect context (62). Such evidence emphasises that ecological terminology should be linked to the demonstrated receiver and experimental context rather than to the chemical compound alone. The HIPVs may additionally function as synomones when they benefit both the emitting plant and its natural enemies. Leafminer-induced volatile blends can attract parasitoids that exploit these cues to locate infested plants or hosts. However, the response of parasitoids depends on volatile blend composition, release dynamics and environmental conditions. Therefore, the ecological role of an individual volatile should be described only when its behavioural effect has been experimentally demonstrated for a defined *Liriomyza* species, receiver and assay.

The ecological significance of HIPVs lies not only in the mediation of herbivore behaviour due to its function as synomone beneficial for both the plant and natural enemies. Natural enemies like *Diglyphus isaea* and *Opius* spp. use HIPV blends to find infested host plants and hidden leafminer larvae, which improves their efficiency in finding prey and biological control (17,63). Parasitoid attraction by HIPVs is affected by the composition of the blend, release dynamics and environmental conditions, the efficient tritrophic interaction is based on the integrity of whole volatile blend rather than individual volatile components. Such ecological relationships provide the basis for semiochemical management. Rather than using general insecticides, volatile blends showing specific behavioural activity can be used in attractant lures, semiochemically enhanced sticky traps and controlled-release devices for monitoring and biological control purposes (63). However, field efficiency of semiochemicals is variable due to emission dynamics related to crop phenology, climate conditions and background vegetation. Semiochemical approaches are especially relevant for *Liriomyza* because these pests are polyphagous and increasingly associated with insecticide resistance, so behaviour-based IPM offers a lower-residue complement to chemical control rather than a full replacement at present (64).

Tritrophic interaction mediated by HIPVs are illustrated in Fig. 3. The tritrophic relationships also have synomones or volatiles, which are beneficial for both the receiver and the sender in relation to the host plants and leafminers and their parasitoids (14). The plants under attack have also been shown to emit synomones that act as an attraction to parasitoid insects such as *Diglyphus isaea* and *Opius* spp., thereby helping in the reduction of leafminer populations and restoring the ecological balance (65). These interactions constitute the core of sustainable management approaches since use of synomone signals will lead to positive changes in biological control practices and reduced use of insecticides (Table 3).

Pheromones and mating behaviour

In several economically important dipteran and lepidopteran pests, the chemical ecology of mating in *Liriomyza* has not yet been well studied. Indeed, there is no sex pheromone that is produced either by females or males and is fully identified or commercially used in major pest species of *L. trifolii, L. sativae* and *L. huidobrensis* (35). The mate recognition occurs through behavioural interactions at short distances with the help of visual, behavioural and contact chemosensory mechanisms rather than pheromone-mediated communication at longer distances. The cuticular hydrocarbons (CHCs) play a role in species recognition and mating in agromyzids; however, the behavioural functions of CHCs in *Liriomyza* are mostly hypothetical and need experimental proof (66, 67). In contrast to several lepidopteran pests in which female-produced sex pheromones have been well characterised and successfully exploited for monitoring and mating disruption, the chemical basis of sexual communication in *Liriomyza* spp. remains poorly understood. To date, no species-specific sex pheromone has been chemically identified,

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experimentally validated and developed for practical use in the major pest species *L. trifolii*, *L. sativae* and *L. huidobrensis* (35). Therefore, the absence of a validated sex pheromone should not be interpreted as evidence that chemical cues are absent from mating behaviour in these flies. In *L. huidobrensis*, sexual communication involves substrate-borne vibrational duets, indicating that mating interactions may rely strongly on short-range multimodal signals rather than on a long-range volatile sex pheromone (61). Cuticular hydrocarbons and other contact-associated chemical cues may also contribute to mate recognition in agromyzid flies, but their specific behavioural roles in *Liriomyza* remain insufficiently demonstrated (67). It is therefore more accurate to state that conventional pheromone-based approaches such as mating disruption and pheromone-baited trapping are not currently available for *Liriomyza* spp. because a validated species-specific sex pheromone has not yet been identified. This represents an important research gap and future studies should combine behavioural assays, chemical profiling, electrophysiological approaches and molecular analyses to determine whether sex-specific volatile, contact or other chemical signals are involved in mating communication. Such work could potentially identify novel semiochemical targets for species-specific monitoring or management. This means that currently, pheromone-based techniques such as mating disruption, pheromone trapping and attract-and-kill techniques cannot be used for the management of leafminers.

Table 3. Herbivore-induced plant volatiles associated with *Liriomyza* spp. and their ecological significance

Species	Semiochemical/ Compound	Category	Biological function	Citation
Liriomyza sativae	Limonene	Monoterpene	Antennal response	(53)
Liriomyza sativae	β-Ocimene	Terpenoid	Host recognition	(53)
Liriomyza sativae	Eugenol	Phenylpropanoid	Behavioural response	(53)
Liriomyza sativae	(Z)-3-Hexenol	Host plant volatile (HPV)	Attracts adults; host location	(53)
Liriomyza sativae	(Z)-3-Hexenyl acetate	HPV	Host orientation	(53)
Liriomyza sativae	1-Octen-3-ol	HPV	Electroantennographic response	(50)
Liriomyza bryoniae	(Z)-3-Hexenol and (Z)-3-Hexenyl acetate	Green leaf volatile	Host plant recognition and host odour preference	(52)
Liriomyza bryoniae	Methyl salicylate (MeSA)	Kairomone	Attraction of male and female flies	(62)
Liriomyza huidobrensis	(Z)-3-hexenyl-acetate and (Z)-3-hexenol	Herbivore-induced plant volatiles (HIPVs)	Attraction of male and female flies	(61)

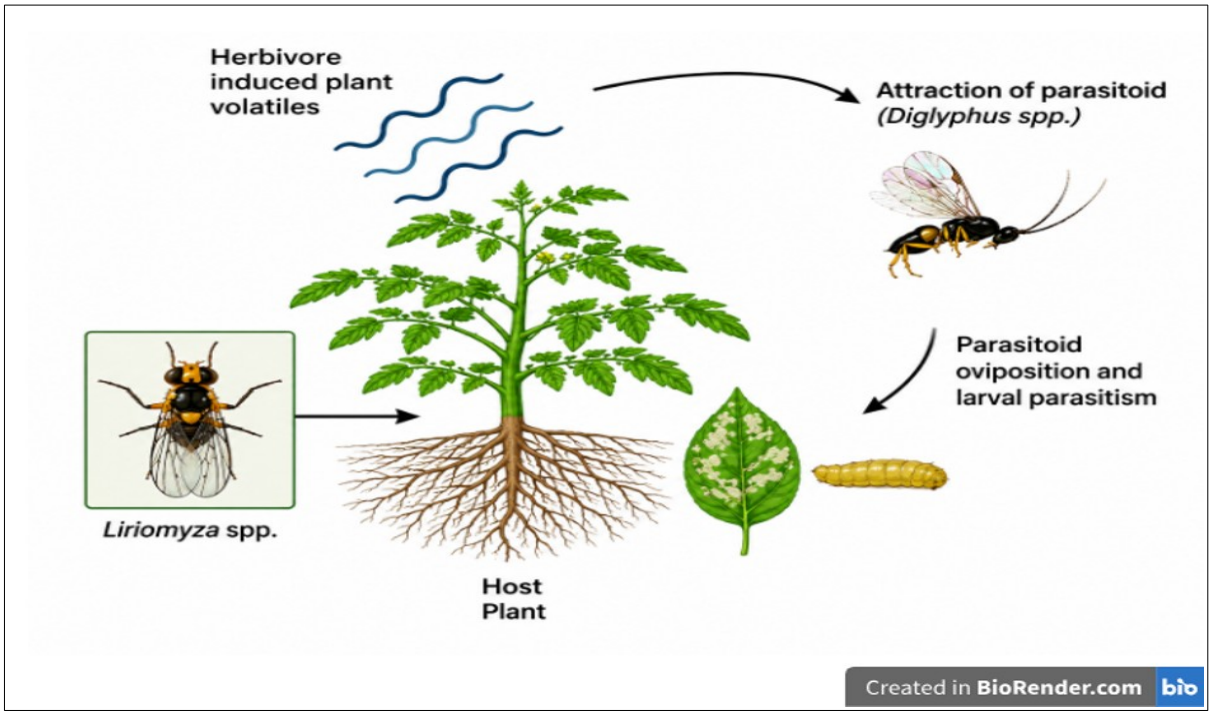


Fig. 3. Tritrophic interaction mediated by herbivore induced plant volatiles.

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Attractant-based monitoring

Attractant-based monitoring provides a practical approach for detecting adult *Liriomyza* populations and determining their seasonal activity. However, an important limitation is that many currently investigated attractants are derived from host-plant volatiles or general food-related odours that may be perceived by more than one agromyzid species. This is partly related to the broad and overlapping host ranges of economically important *Liriomyza* species, which can result in shared responses to common green leaf volatiles and other host-associated compounds (16, 53, 54). For example, *L. sativae* responds to several green leaf volatiles as well as host-associated compounds such as limonene, indicating that attraction is mediated by a combination of general and host-related chemical cues rather than by a single diagnostic compound (53, 54). The development of completely species-specific attractants is therefore possible in principle but may be difficult to achieve using common host-plant volatiles alone. Closely related *Liriomyza* species may share components of their host-plant odour environment, particularly when they exploit the same crop or plant family. Consequently, a compound that is attractive to one species may also elicit behavioural responses in sympatric congeners. This limitation does not necessarily mean that species-specific monitoring is unattainable. Instead, specificity may depend on identifying species-specific ratios, combinations or blends, rather than searching for a single compound that is exclusively attractive to one species. Indeed, studies on *L. sativae* have shown that a seven-component blend derived from cowpea and kidney bean volatiles was attractive in field trapping experiments, suggesting that blend composition can provide greater behavioural information than individual compounds alone (54).

The feasibility of species-specific attractants is further complicated by variation in plant cultivar, crop growth stage, herbivory and environmental conditions, all of which can alter volatile emission and consequently modify insect responses (16, 53). Therefore, the most promising strategy is likely to combine species-biased chemical blends with visual cues, trap colour and crop-specific deployment, rather than relying on a single volatile compound. Such integrated attractant systems could improve monitoring specificity while retaining the practical advantages of inexpensive sticky traps. At present, however, evidence remains insufficient to conclude that a universally species-specific chemical lure can be developed for the major *Liriomyza* species. Research should therefore prioritise comparative chemical ecology among sympatric species, identification of species-discriminating blend ratios and validation of candidate blends under field conditions.

Push–pull strategies

Push–pull strategies take advantage of insect behavioural reactions through the combination of repellent stimuli ("push") that repel colonisation with attractive stimuli ("pull") that cluster insects within trapping zones (68, 69). Even though the strategy is quite effective against several agricultural pests, application of the strategy against *Liriomyza* species is still in the initial development stage. Some examples of possible repellent ("push") stimuli can be repellent plant volatiles, reflective mulches and certain botanical essential oils that might affect the host locating or egg-laying behaviour, while the attractive ("pull") stimuli will include traps baited with attractants placed near borders of the crops or greenhouses (70). The effectiveness of complete push–pull systems applied for *Liriomyza* spp. and the efficiency of many semiochemicals is inconsistent under field conditions. The future research must focus on the development of compatible pairs of repellent and attractants, the optimisation of delivery techniques and the incorporation of biological control methods to develop push–pull systems for protected cultivation and horticulture in the open field (67).

Repellents and anti-ovipositional compounds

The use of repellents and anti-ovipositional compounds is one of the environmentally safe ways to reduce leafminer infestations through disrupting the host locating and oviposition processes. Botanical insecticides and plant essential oils have been widely researched since they usually pose low mammalian toxicity and are consistent with integrated pest management approaches. As a botanical product, azadirachtin, which was obtained from *Azadirachta indica* A.Juss., consistently reduced adult feeding punctures, oviposition and larval mining of some horticultural crops (71). For *L. sativae*, rosemary essential oil acted as a repellent and at sublethal doses it deterred oviposition and feeding, making it a candidate push-pull component rather than only a toxicant (72). Moreover, such compounds as limonene, thymol, citral have been proved to possess repellent or oviposition-deterrent properties against leafminers in laboratory and field experiments (72).

Synthetic lures and controlled-release formulations

The successful application of the semiochemical-based approach to pest control requires not only the isolation of biologically active compounds but also the development of suitable delivery devices which would ensure an adequate release rate of the volatile in the field conditions. The effectiveness of a semiochemical lure depends not only on the biological activity of the compound but also on release rate, dispenser characteristics and environmental stability (67, 73, 74). Controlled-release formulations can prolong volatile emission and reduce the frequency of lure replacement (73, 74). Nevertheless, delivery technology cannot compensate for an attractant that lacks consistent behavioural activity under field conditions. Therefore, the principal bottleneck for *Liriomyza* semiochemical management remains the identification and validation of robust species-relevant attractant blends, rather than the availability of increasingly sophisticated dispensers alone.

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The field performance of semiochemical lures depends not only on compound identity but also on release kinetics, dispenser material and environmental stability. Optimising release rates is therefore essential for maintaining consistent attractiveness throughout the trapping period (72). Controlled release dispensers can increase volatility life span, decrease the need for repeated lures substitution and improve the trapping performance during prolonged periods of monitoring (75). Traditional delivery devices, such as silicone rubber septa, polyethylene vials and polymer matrices, have been extensively studied due to their ability to provide constant volatile release (74). Recently, biodegradable polymers, microencapsulation technology and nanocarrier based delivery devices have become promising solutions that can improve volatile stability, UV resistance and minimise environmental impact (67). Even though significant progress has been made in controlled release technology, its application to the management of *Liriomyza* is hindered by the scarcity of validated attractants for the species. Thus, controlled release formulation technology cannot solve the problem of semiochemical-based management until bioactive compounds are isolated during chemical ecological studies

Integration of semiochemicals into integrated pest management

Compatibility with biological control

Biological control is an important component of integrated pest management (IPM) for *Liriomyza* spp., with parasitoids such as *Diglyphus isaea*, *Dacnusa sibirica* and *Opius* spp. contributing to suppression of leafminer populations (20,76). Among these natural enemies, *D. isaea* and *Opius* spp. have particularly relevant behavioural associations with plant-derived volatiles and therefore provide a useful basis for integrating semiochemical approaches with biological control. Female *D. isaea* are attracted to volatile cues released from bean plants damaged or mined by *L. trifolii*, indicating that HIPV-mediated host location can naturally facilitate parasitoid foraging. Similarly, *Opius dissitus*, a parasitoid associated with *L. huidobrensis*, responds to herbivore-induced volatiles including (Z)-3-hexenol, demonstrating that plant-derived semiochemicals can function as cues for locating leafminer-infested plants (76–78). These observations suggest that semiochemical strategies based on ecologically relevant HIPV blends may be more compatible with biological control than indiscriminate deployment of highly attractive synthetic odours. The compatibility should not be assumed solely because a compound attracts the pest. A synthetic lure may also attract, arrest or redirect parasitoids if the same volatile is involved in their host-searching behaviour. This could potentially alter parasitoid distribution, increase time spent around traps or interfere with the natural volatile gradients used to locate infested plants. In contrast, semiochemicals deployed exclusively on pest traps and positioned away from parasitoid release or host-infestation zones may reduce such interference. Evidence from *D. isaea* and *O. dissitus* indicates that parasitoids can use relatively general plant-damage signals, including green leaf volatiles, for host-habitat location (77, 78). Therefore, the use of broad-spectrum host volatiles as pest attractants requires behavioural selectivity testing against the principal parasitoids before field deployment.

The timing and spatial placement of semiochemical applications are consequently important for maintaining biological-control efficacy. Semiochemical-baited traps should preferably be deployed at monitoring locations or field borders rather than directly within parasitoid release zones. Where augmentative parasitoids are released, lures should be evaluated before and after parasitoid establishment to determine whether they alter parasitoid searching behaviour or distribution. Semiochemical application should also be synchronised with pest monitoring so that unnecessary continuous exposure of natural enemies is avoided. In particular, attractant-based mass trapping should be concentrated during periods of increasing adult leafminer activity, while parasitoid releases should be maintained in areas where mined leaves and suitable host stages are abundant. The most appropriate integration strategy is therefore not simply to combine attractants with parasitoid releases, but to design their deployment around complementary behavioural functions. Pest attractants can be used for early detection and localised removal of adults, whereas HIPV-based approaches that enhance parasitoid attraction may potentially strengthen host-searching behaviour. Nevertheless, evidence for direct field compatibility remains limited for *Liriomyza* systems and species-, crop- and compound-specific evaluations are required. Future studies should quantify parasitoid attraction, residence time, host-searching efficiency, parasitism rate and reproductive performance in the presence of candidate semiochemicals before recommending them for combined IPM programmes (63, 73).

Integration with selective insecticides

Monitoring that relies on semiochemicals makes it possible to base the application of insecticides on the occurrence of pests and not on regular calendar spraying, thus making it possible to improve the precision of chemical control as a part of integrated pest management programmes. Offering early detection of adult population dynamics, semiochemical-based monitoring helps to act promptly when the threshold level of economic significance is exceeded, which prevents the application of excessive insecticide treatments and consequently, the selection pressure leading to the development of insecticide resistance (68). In case the chemical intervention is required, selective insecticides should be used, since they do not negatively affect the activity of beneficial arthropods and are much easier to implement as a part of IPM programme compared to broad-spectrum insecticides (36). The repetitive application of insecticides remains

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one of the significant limitations for the management of *Liriomyza*, since it resulted in resistance, resurgence and disturbance of natural enemies' populations (13).

Precision agriculture and decision-support systems

Incorporation of semiochemicals for monitoring within precision agriculture technologies has improved IPM in terms of timely and evidence-based pest management decisions (79). Semiochemically baited sticky traps combined with automatic imaging systems, sensors and wireless communication technologies help to monitor continuously the population of *Liriomyza* with decreased reliance on manual scouting and increased accuracy of pest surveillance (80). Combined with weather data, crop phenology and economic threshold values, these monitoring data may be utilised within decision support systems (DSS) to achieve an optimal timing for biological control agent release and selective insecticide use thus avoiding excess pesticide application (67). However, there is still a lack of practical implementation of precision agriculture technologies for *Liriomyza* spp. Most smart monitoring systems were designed for some other economically important insect pests and their accuracy of functioning regarding leafminer species within different horticultural production systems was not tested (74). Moreover, there are many factors that may affect the effectiveness of the automated monitoring systems including trap design, variable environmental conditions and differentiation between the closely related *Liriomyza* species. All these limitations point to the necessity of developing standard monitoring procedure and validation of field conditions of the monitoring procedure based on the precision agriculture technologies and decision support systems for *Liriomyza* spp (80).

Challenges and research gap

Although much has been achieved in terms of the biology and semiochemical ecology of *Liriomyza* spp., there are still some limitations that have hindered the implementation of semiochemical-based management. First, there is the lack of species-specific attractants for the reliable monitoring of economically important *Liriomyza* spp., for example, *L. trifolii, L. sativae* and *L. huidobrensis* in diverse agroecosystems. Responses of the flies to host plant volatiles and herbivore-induced plant volatiles depend on host species, crop phenology, environmental factors and geographical populations and hence making universal lures is difficult (63).

Quarantine and biosecurity measures are essential for limiting the international movement of *Liriomyza* spp., particularly because immature stages can remain concealed within infested plant material. The International Standards for Phytosanitary Measures (ISPM) provide a framework for inspection and sampling of traded consignments, with ISPM 23 addressing inspection procedures and ISPM 31 providing guidance for representative sampling and testing of consignments (40, 81). These measures are particularly relevant to *Liriomyza* because larvae and pupae may remain undetected in vegetables, cut flowers and plants for planting. For example, European and Mediterranean Plant Protection Organization (EPPO) identifies the movement of infested planting material as an important pathway for *L. sativae* and *L. trifolii* and recommends repeated inspection of host plants before export (17). Therefore, early detection, accurate species identification, pre-export inspection, phytosanitary certification and post-entry surveillance should be integrated into biosecurity programmes to reduce the probability of establishment and subsequent spread. Most semiochemicals are environmentally unstable in the sense that they are easily photodegraded, oxidised and broken down by rainfall and high temperature, hence limiting their longevity and effectiveness (67). Despite success in developing controlled release formulations, the efficacy and performance of such lures under diverse cropping systems and climatic conditions have not been adequately investigated. Furthermore, most of the research has been undertaken using laboratory settings or small-scale experiments, with few studies done through multi-locational field evaluation in order to assess the performance of the lure, trap deployment strategy and integration with IPM programs. There is also the limitation of an incomplete knowledge of the chemical ecology of *Liriomyza*, especially regarding pheromone-mediated mediated communication, olfactory receptor mechanisms, intraspecific communication and behavioural responses under various environmental conditions are concerned (80). The adoption of semiochemical-based management can be constrained by the cost and availability of lures, traps and replacement dispensers, particularly for smallholder farmers. Limited access to locally available products and technical knowledge may further reduce farmer confidence in adopting these technologies. Farmer adoption can also be affected by the slower or less immediate pest suppression perceived with trapping compared with conventional insecticides. For example, 27 % of farmers in a Bangladesh study discontinued pheromone trapping after adoption, citing time requirements, inadequate materials and limited technical knowledge (82). Regulatory requirements for registration, quality assurance and phytosanitary compliance may increase the time and cost required for commercialisation of semiochemical products. Therefore, affordable formulations, reliable supply chains, farmer training and streamlined regulatory frameworks are essential for wider adoption of semiochemical-based IPM. In addition, the effects of climate variability, crop management and genetic variation of different geographical populations on the semiochemical-mediated behavior are not well-known.

Future perspectives

Management of *Liriomyza* spp. in the future must incorporate recent developments in the areas of artificial intelligence, precision agriculture, nanotechnology and chemical ecology to create sustainable and climate-resilient management strategies. The application of artificial intelligence, including deep learning, smart

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sticky traps, unmanned aerial vehicles and Internet of things-based technology may facilitate rapid detection and assessment of *Liriomyza* populations, while the use of precision IPM tools such as geographic information systems, remote sensing and decision support systems will allow site-specific interventions. Simultaneously, nanotechnology-based controlled-release formulations may help to achieve a sustained volatile release under diverse environmental conditions, which may increase the efficacy of semiochemicals used in field situations. The incorporation of biological control, resistance breeding, cultural practices and insecticides into multi-modal management programmes will help to overcome problems associated with the excessive reliance on insecticides and to protect natural enemies. Also, the future studies should focus on the influence of climate change on distribution and host adaptation of *Liriomyza* spp., as well as semiochemicals-mediated interactions of these insects with each other and the environment. Such approaches will promote development of more effective pest prediction and management systems, which will help to create environmentally sustainable and economically efficient management strategies for *Liriomyza* spp.

Conclusion

Liriomyza spp. has been transformed from sporadic leafminers to pests because of globalisation, intensive horticultural practices, insecticide resistance and climate change. While the use of insecticides allows for the rapid suppression of pests, it is a limited strategy due to sustainability limitations and problems associated with the development of insecticide resistance and insecticides negative impact on natural enemies and the environment. Semiochemical-based technologies provide a promising opportunity for the development of environmentally sustainable tools for pest monitoring and management. However, specific problems associated with lure specificity, environmental stability, commercial applicability and the understanding of the chemical ecology of *Liriomyza* spp. must be addressed before widespread applications of semiochemical technologies in horticulture. Future research incorporating chemical ecology, molecular biology, nanotechnology, artificial intelligence and precision agriculture may considerably advance development of cost-effective and climate-resilient pest management strategies.

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Authors' contributions

RS and ET prepared and drafted the manuscript. NSP provided guidance and supervision throughout the writing process. SA, KM and HS critically reviewed and revised the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT to improve language and readability, with caution. After using the tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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