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Review

Trends in invasive root maggots (Diptera: Anthomyiidae) and prospects of frass fertilizer as a biorational control strategy

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ABSTRACT

Root maggots pose a growing global threat to food security, causing potential crop losses of up to 100 %, prompting the search for innovative and sustainable management strategies. In this review, we examine the global distribution of root maggots, evaluate the current management strategies and their effectiveness, and explore the potential of insect frass fertilizer as a novel, cost-effective, and multipurpose soil amendment for root maggot control. We report a wide distribution of *Delia* species in over 123 countries globally, with geographical specific distribution of individual species. Species such as *D. radicum, D. planipalpis, D. floralis* and *D. antiqua* strictly occur in Palaearctic and Nearctic regions whereas *D. steiniella*, *D. flavibasis*, *D. arambuorgi* and *D. coarctata* were restricted to the tropical climate of Sub-Saharan Africa. Notably, *D. platura* was the most widely distributed species, occurring across all bioregions. Furthermore, crop damage and yield loss were strongly influenced by factors such as soil type, climatic conditions, crop variety, cropping season, and the management approach. Despite recent advancements in integrated pest management, farmers still favour pesticides, which does not provide any advantage for long-term pest control. We present insect frass fertilizer as a promising alternative strategy for managing root maggots by inducing systemic resistance in plants, enhancing natural enemy populations, and exerting direct contacticidal effects. This information is essential for fostering cross-disciplinary collaboration among farmers, researchers, and policymakers, forming the basis for sustainable root maggot control, improved food security, and enhanced ecosystem resilience.

1. Introduction

Pests have been a major challenge to crop production since the advent of agriculture (Balter, 2007; Mueller et al., 2005), and their impact has intensified over time due factors such as land degradation, climate change and unsustainable farming practices. Insect herbivores are of particular interest due to their voracious feeding, which poses a significant threat to food security and often leads to the overuse of hazardous chemical pesticides (Wyckhuys et al., 2024). Often overlooked are the soil-borne herbivores characterised by numerous intractable pests that feed on plant root systems resulting in substantial yield losses. Although root herbivory is documented across multiple insect orders, including Lepidoptera, Diptera, and Coleoptera, the larval stages of Diptera cause the most significant crop yield losses due to their almost exclusive feeding on roots (Ambele et al., 2018; Eckman, 2015; Nyamwasa et al., 2017; Ouma et al., 2023; Poggi et al., 2021; Savage et al., 2016; Sulvai et al., 2016; Vernon and van Herk, 2022). For instance, root maggots can cause up to 100 % yield loss if not controlled (Dido et al., 2021; Goftishu et al., 2009; Macharia and Mueke, 1986; Tafa and Sakhuja, 2004).

Root maggots are a diverse group of insects belonging to the family Anthomyiidae, characterized by their endophytic feeding on a broad range of vegetable and field crops. They belong to the same dipteran clade Muscoidea with dung flies (Scathophagidae), latrine flies (Fannidae) and house flies (Muscidae), which are predominantly saprophagous (Ding et al., 2015; Gomes et al., 2021; Narayanan Kutty et al., 2019). However, Anthomyiids can be morphologically distinguished from other calyptrate muscoids by their long vein A1 extending to the margin and the presence of setulae on the scutellum's ventral surface (Gomes et al., 2021; Michelsen, 1991). Nearly 2000 species within the family

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Anthomyiidae have been described, but their distribution varies significantly across different biogeographic realms (Couri and Rodrigues-Júnior, 2012; Michelsen, 2014; Meraz-álvarez et al., 2020). Although Anthomyiids are generally phytophilous targeting forest trees, ornamental crops, and food crops, only a few species, particularly those in the genus *Delia*, have been reported to engender significant crop damage (Capinera, 2008; Hill, 1987; Meraz-álvarez et al., 2020; Savage et al., 2016). The most devastating *Delia* species include root maggots such as *Delia antiqua* (Meigen), *Delia radicum* (Linnaeus), *Delia florilega* (Zetterstedt), *Delia platura* (Meigen), *Delia floralis* (Fallén) and *Delia planipalpis* (Stein) and the cereal sprout maggots such as *Delia flavibasis* (Stein), *Delia arambourgi* (Seguy), and *Delia coarctata* (Fallen) (Ackland, 2008; Goftishu et al., 2009; Meraz-álvarez et al., 2020; Michelsen, 2014; Rogers et al., 2015; Savage et al., 2016; Soroka and Dosdall, 2011; Zeleke et al., 2017). Significant yield loss has been recorded in vegetables, such as cabbage, broccoli, rutabaga, onion, carrots, and cauliflower as well as field crops such as barley, wheat, beans and sorghum.

Root maggots occur in mixed populations, which vary in time and space, yet their spatial distribution, damage severity and effective management approaches are not well understood. Although thorough investigations have been made on root maggots, the information is fragmented due to the use of different names in various studies including *Delia* spp., *Anthomyia* spp., *Erioischia* spp., *Hylemya* spp., *Phorbia* spp., *Pegomya* spp., *Leptohylemyia* spp. and *Chortophila* spp. (Ackland, 1967, 1968, 2008; Boyes 1954; Ikeshoji et al., 1980; Kelleher, 1958; Kim and Eckenrode, 1984; McFerson et al., 1996; Meraz-álvarez et al., 2020; *Nair and McEwen, 1975*; Raw et al., 1968; *Stewart and Mckinlay, 1965*; Suwa, 1974; Savage et al., 2016; Van Emden, 1941; *Walgenbach et al., 1993*; Wantulla et al., 2022*). Consequently, there is a need to standardize the terminology and records of root maggots to better understand their distribution, yield loss potential, and management strategies*.

Management of root maggots primarily relies on heavy use of pesticides *(*Joseph and Zarate, 2015; Jacquet et al., 2022*). It is well-established that* overuse of persistent and systemic pesticides is now a primary driver of biodiversity loss, which in turn limits the associated ecosystem service and natural pest regulatory mechanisms (Jacquet et al., 2022; Meehan et al., 2011; van der Sluijs, 2020; Van Deynze et al., 2024). Frequent pesticide application is also associated with soil and water pollution, leading to chemical residues in food and the environment, which can have detrimental effects on human health (Fantke et al., 2012; Geiger et al., 2010; Jacquet et al., 2022; Panseri et al., 2019; Sánchez-Bayo and Wyckhuys, 2019). Several options are on the table to alleviate the environmental pressures that emanate from pesticide application. Cultural practices such as mixed cropping, adjustment of sowing dates, and autumn ploughing have been studied, yet they often result in limited suppression of root maggots (Tukahirwa and Coaker, 1982; Witkowska et al., 2018). In contrast, alternative approaches, such as physical barriers and stimulo-deterrent diversions, are complex to implement. Biological control strategies could help reduce overreliance on pesticides; however, they require constant supplementation, which is often associated with additional costs for the mass production of these biocontrol agents in controlled environments (Chen and Moens, 2003; Hemachandra et al., 2007; Hummel et al., 2010; Meadow et al., 2000). Moreover, most predators and parasitoids have low dispersal power and poor searching abilities, which limits their efficacy in the management of root maggots. Hence, notwithstanding the major advances in root maggot control over the past decades, further innovative strategies are needed to minimize the health and environmental risks associated with pesticide application.

Organic soil amendments provide a lucrative solution to root maggots by enhancing systemic plant resistance, increasing microbiota and arthropod diversity (which contribute to natural regulatory mechanisms), and exerting direct toxic effects (Barragán-Fonseca et al., 2023; 2022; Wantulla et al., 2023). However, solid-field level data is lacking to quantify the impact of soil amendment with organic compounds such as insect frass fertilizer on root maggot control. Most studies on the application of insect frass as a fertilizer in crop production have primarily focused on agronomic realm, yielding appealing spinoffs, while tangential attention has been given to the potential of these compounds in pest suppression. Therefore, in this study we conduct a retrospective assessment of the global distribution of root maggots, their damage and economic debts as well as management approaches. We use opensource data to map the spatial distribution of *Delia* spp. across different countries and biogeographic realms. We also analyse the potential of insect frass fertilizer as a regenerative strategy for the management of *Delia* species and provide critical recommendations on other methods that could be considered in the sustainable management of root maggots.

2. Distribution of root maggots and crop damage

2.1. Crucifer-feeding maggots

The cabbage root fly (D. radicum) is the most destructive pest of cruciferous crops, widely distributed in the Palaearctic and Nearctic regions (Biron et al., 2000; CABI, 2022a; Finch, 1989). Cabbage root fly is rarely reported as a pest south of 45°N, except at high elevations (Capinera, 2008). It has been previously identified under various names, including *Anthomyia brassicae* (Wiedemann) (Steene, 1989), *Erioischia brassicae* (Bouche) (Coaker and Williams, 1963; Hawkes, 1972), *Hylemya brassicae* (Bouche) (Hassan, 1973; Read, 1965), *Pegomya brassicae* (Bouche) (Szwejda, 1982b), *Phorbia brassicae* (Wiedemann) (den Ouden et al., 1993; Friend, 1932), *Chortophila brassicae* (Wiedemann) (Zohren, 1968), and *C. floccosa* (Macquart) (CABI, 2022a).

Delia radicum, originally native to Europe, is believed to have spread to the northeastern coast of North America during the 19th century and gradually spread eastwards (Biron et al., 2000; Griffiths, 1991) (Fig. 1). The closely related species is the turnip fly (*D. floralis*) which has also been referred to as *E. floralis* (Fallén) (Shaw, 1972), *H. crucifera* (Huckett) (Boyes, 1954), *H. floralis* (Fallén) (Taksdal, 1966), and *Phorbia floralis* (Fallén) (CABI, 2022b; Müller and Schnitzler, 1970). Both *D. floralis and D. radicum have similar origin and spatial distribution patterns across Europe and North America* (Biron et al., 2000; Capinera, 2008; CABI, 2022b) (Fig. 1).

The radish fly (D. planipalpis) closely resembles *D. radicum* and *D. floralis and* has previously been documented under various names such as *H. planipalpis* (Stein), *Pegomya planipalpis* (Stein), *Phorbia planipalpis* (Stein), *D. pilipyga* (Villeneuve), *C. planipalpis* (Stein), *C. pilipyga* (Villeneuve), *C. vilis* (Stein) and *H. anthracodes* (Malloch) (CABI, 2022c; EPPO, 2023a; Suwa, 1974; Savage et al., 2016). Despite limited studies on this pest, previous reference indicate significant infestations of cruciferous crops in Nearctic regions including Canada, Mexico and the United States (Hummel et al., 2009; Meraz-álvarez et al., 2020; Savage et al., 2016) (Fig. 1).

Crop damage is primarily engendered by specialist species, such as *D. radicum*, *D. floralis* and *D. planipalpis*, as well as generalists, such as *D. florilega* and *D. platura* (Broatch et al., 2006; Meraz-álvarez et al., 2020; Michelsen, 2014, 2007; Savage et al., 2016; Soroka et al., 2004; Soroka and Dosdall, 2011). Root maggots inflict damage on cruciferous crops primarily by feeding on the roots, with secondary feeding occurring on the petioles and stems. Herbivory symptoms can range from the wilting of a few leaves and then the entire plant in severe infestation, to stunting and reduced stands of transplants in fall/autumn and spring seasons (Capinera, 2008). Severe symptoms, such as wilting and dieback, often result from the significant distortion of root epidermal and vascular tissues caused by endophytic feeding. Between 5 and 10 actively feeding larvae are sufficient to cause death of cabbage seedlings, but later in the season, mature crops can tolerate higher density of maggots, provided there is an adequate water supply (Brooks, 1951; Capinera, 2008). Previous evaluations of the crop damage caused by root maggots have focused on crop loss yield (Griffiths, 1991; Straub and Davis, 1978; Taylor et al., 2001), and ranking of crop damage using severity scores (Dosdall et al., 1994; Shuhang et al., 2016). For instance, a yield

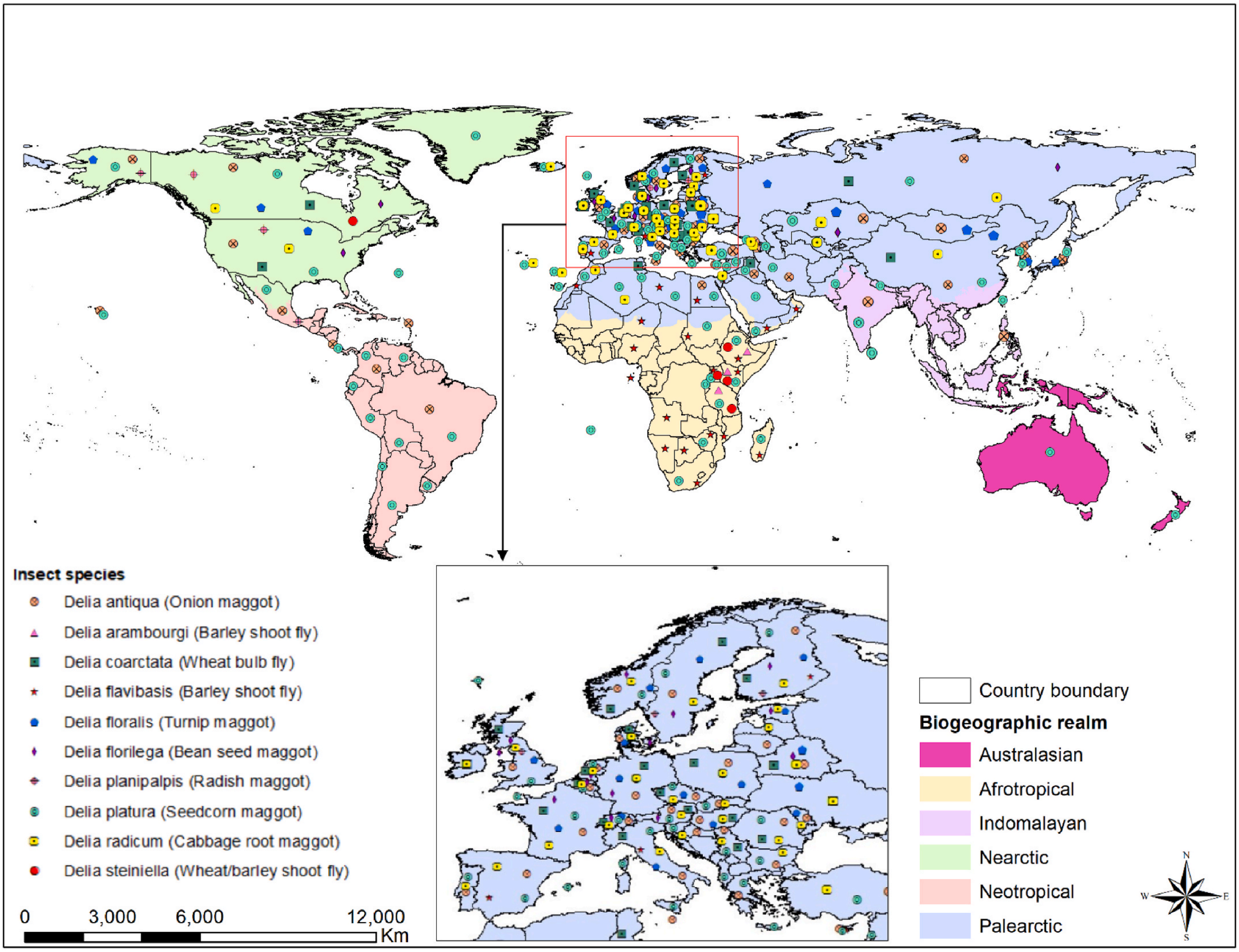

Fig. 1. Global distribution of *Delia* species. Source (Ackland, 2008; CABI, 2022c, 2022d, 2022e, 2022f, 2022b, 2022g, 2022h, 2022i, 2022a; EPPO, 2024a, 2024b, 2024c, 2024d; GBIF Secretariat, 2022; Michelsen and Baez, 2010; Ouma et al., 2023; Savage et al., 2016).

reduction of 19 % and 50 % in rapeseed (*Brassica napus* L.) and field mustard (*Brassica rapa* L.), respectively, was reported in Canada following infestation by *D. radicum* and *D. floralis* (Griffiths, 1991). In contrast, in France and Finland, yield losses in cabbage ranged from 50 to 100 % due to *D. radicum* (Havukkala, 1988; Shuhang et al., 2016) (Table 1). However, deliberate field studies are recommended to evaluate the potential damage caused by these pests in contemporary vegetable agroecosystems.

2.2. Onion bulb-feeding maggots

The onion fly (D. antiqua) is a highly devastating, soil-borne pest native to the Palaearctic region. Worldwide occurrences of onion maggots have been documented under various names, including A. antiqua (Meigen)*, A. ceparum* (Hoffmannsegg)*, H. antiqua* (Meigen)*, H. ceparum* (Meigen)*, Phorbia cepetorum* (Meade)*, Phorbia antiqua* (Meigen) *and Pegomyia ceparum* (Bouche) (CABI, 2022i; Ishikawa et al., 1983; Ikeshoji et al., 1980). The pest was first documented in Europe in 1826 and has since spread to other major onion-producing regions, including the United States, Canada, Asia, and parts of Africa (Ellis and Eckenrode, 1979). The three root maggot species commonly infesting *Allium* crops are the onion maggots (*D. antiqua*) and seed corn maggots (*D. florilega* and *D. platura*) (Collier and Finch, 2020; Ellis and Scatcherd, 2007; Mlynarek et al., 2020; Savage et al., 2016). Recent reports indicate an increasing incidence of the pepper fruit fly (*Atherigona orientalis)* infestations in onions in East Africa (Ouma et al., 2023), despite the species being primarily associated with other hosts including cabbage and cauliflower (*Brassica oleracea*), bell pepper (*Capsicum annuum*), orange (*Citrus sinensis*), melon (*Cucumis melo*), tomato (*Lycopersicon esculentum*), beans (*Phaseolus* spp.), and sorghum (*Sorghum bicolor*) (Suh and Kwon, 2016).

In the northern temperate zones, onion fly maggots undergo three generations annually during the growing season and overwinter as pupae in the soil before eclosing in spring to begin infestation (Vernon et al., 1987; Whitfield et al., 1985). The first-generation neonates of onion fly infest the host at the seedling stage, resulting in significant crop damage, with losses ranging from 20 to 80 % in the United States (Moretti, 2020; Nault et al., 2006; Taylor et al., 2001), 50–65 % in India (Gupta et al., 2021) and 25–84 % in Poland (Szwejda, 1982b) (Table 1). The second-generation maggots infest onion fields at the vegetative stage and cause relatively low levels of damage ranging from 1.2 to 5.2 % (Szwejda, 1982b). Although mature onion bulbs generally exhibit resistance to onion fly maggot infestation, mechanical damage sustained during crop management can create entry points for infestation, ultimately resulting in yield losses. Crop damage from onion fly maggots is often severe due to their association with Fusarium-induced soft rot. Evidence suggests that mated adult flies are attracted to volatile exudates emitted by plants infected with soft rot pathogens, with emerging larvae playing a critical role in disseminating the disease inoculum to

Table 1
Crop damage and yield loss by root maggots.

Host	Pest	Root damage index score	Yield loss	Country	Reference
Field mustard (*B. rapa*)	*D. radicum* and *D. floralis*	1.8–2.5	50 %	Canada	(Dosdall et al., 1994; Griffiths, 1991)
Rapeseed/canola (*B. napus*)	*D. radicum* and *D. floralis*	0.6–0.7	19 %	Canada	(Dosdall et al., 1994; Griffiths, 1991)
Brown mustard (*B. juncea*)	*D. radicum* and *D. floralis*	0.6–1.6	–	Canada	Dosdall et al. (1994)
White mustard (*B. alba*)	*D. radicum* and *D. floralis*	0.25–3.0	–	Canada	Dosdall et al. (1994)
Cabbage (*B. oleracea*)	*D. radicum*	4.1–6	–	France	Shuhang et al. (2016)
Cabbage (*B. oleracea*)	*D. radicum* and *D. floralis*	2.0–5.0	–	Southern Finland	Havukkala (1988)
Rutabaga (*B. napus*)	*D. radicum*	2.0	–	Canada	Malchev et al. (2010)
B. napus and *B. rapa*	*Delia* spp.	19 %	–	Canada	Soroka et al. (2004)
Turnip (*B. rapa* var. *rapa*)	*D. floralis*	–	≤40 %	Canada	Capinera (2008)
Cruciferous (*Brassica* spp.)	*D. radicum*	–	24–60 %	United Kingdom	(Finch, 1989; Strickland, 1965)
Cruciferous (*Brassica* spp)	*D. radicum* and *D. platura*	40–60 %	–	Finland	Vänninen et al. (1999a)
Onion (*A. cepa*)	*D. antiqua* and *D. platura*	–	20–80 %	NY, United States	(McFerson et al., 1996; Moretti, 2020; Nault et al., 2006; Straub and Davis, 1978; Taylor et al., 2001)
Onion (*A. cepa*)	*D. antiqua* and *D. platura*	–	>65 %	California US	Wilson et al. (2015)
Onion (*A. cepa*)	*D. antiqua*	–	24.6–83.7 %	Poland	(Szwejda, 1982b)
Onion (*A. cepa*)	*D. antiqua*	–	50–65 %	India	Gupta et al. (2021)
Onion (*A. cepa*)	*D. antiqua*	–	50–100 %	Netherlands	Loosjes (1976)
Garlic (*A. sativum*)	*D. platura*	–	25.4–37.6 %	Tunisia	Harbi et al. (2022)
Soybean (*G. max*)	*D. platura*	–	10–15 %	Hungary	Bosnyákné et al. (2016)
Maize (*Z. mays*)	*D. platura*	–	33.3–88.9 %	India	Chaudhary et al. (1987)
Field crops	*D. platura*	–	30–60 %	United States	Gill et al. (2013)
Green beans (*P. vulgaris*)	*D. florilega*	–	20–30 %	Poland	Kozłowski and Tomczyk (2016)
Snap bean (*P. vulgaris*)	*D. florilega*	–	11–78 %	United States	(Vea and Eckenrode, 1976; Webb et al., 1978)
Wheat (*T. aestivum*) and Barley (*H. vulgare*)	*D. coarctata*	–	25–30 %	Romania	Perju and Peterfy (1970)
Wheat (*T. aestivum*)	*D. coarctata*	–	≤22 %	England	Bardner (1968)
Barley (*H. vulgare*)	*D. arambourgi*	25.6–50.8 %	–	Kenya	Bullock (1965)
Wheat (*T. aestivum*)	*D. steiniella*	56.5–74.5 %	–	Ethiopia	Jobie and Gebremedhin (2005)
Barley (*H. vulgare*)	*D. favibasis*	–	≤100 %	Ethiopia	(Dido et al., 2021; Goftishu et al., 2009; Tafa and Sakhuja, 2004)
Barley (*H. vulgare*)	*D. favibasis*	–	76.9–81.9 %	Kenya	Macharia and Mueke (1986)

Semi-quantitative damage index score: 0 = no root damage, 1 = <10 % root damage, 2 = 11–25 %, 3 = 26–50 %, 4 = 51–75 %, 5 = 76–100 %, 6 = Root is damaged deeply and only a small core of the tap root left (Dosdall et al., 1994; Shuhang et al., 2016).

healthy plants (Hausmann and Miller, 1989a). However, the dynamics of these mutualistic interactions remain poorly understood. Infested young plants exhibit a flaccid morphology characterised with drooping leaves. These symptoms often appear in localised clusters within the field, resulting from aggregated oviposition and trivial movement of larvae to neighbouring healthy plants.

2.3. Seedcorn maggot complex

Seedcorn maggots (D. platura and D. florilega) represent the most ubiquitous taxa of root herbivores. Delia platura is undoubtedly the most globally widespread polyphagous anthomyiid with significant abundance in vegetable gardens and field crops (Figs. 1 and 2) (CABI, 2022e; Darvas and Szappanos, 2003; Michelsen and Baez, 2010; Saumure et al., 2006). This species is also known by various names such as *H. cilicrur* (Rondani), *C. cilicrura* (Rondani), *H. platura* (Meigen), *H. cilicrura* (Rondani), *Pegomyia fusciceps* (Zetterstedt), *Phorbia cilicrura* (Rondani) and *Phorbia platura* (Meigen) (CABI, 2022e; EPPO, 2024b; Savage et al., 2016). *Delia platura* has evolved to thrive in diverse climatic conditions across nearly all biographic zones (CABI, 2022e) (Fig. 1), whereas *D. florilega* is confined to Northern and Central Europe, extending into high altitudes of the Mediterranean sub-region. *Delia florilega* has been extensively recorded under various names, including *D. liturata*

Fig. 2. *Delia platura*, the most invasive and polyphagous species native to the Palaearctic realm with worldwide distribution. Source: Ouma et al. (2023).

(Meigen), *D. trichodactyla* (Rondani), *H. liturata* (Meigen), *Phorbia trichodactyla* (Rondani), *Phorbia florilega* (Zetterstedt), *Phorbia liturata* (Meigen), *H. trichodactyla* (Rondani) and *H. florilega* (Zetterstedt) (EPPO, 2024d; Savage et al., 2016; Suwa, 1974). *Delia platura and D. florilega are frequently misidentified due to their striking morphological similarity*.

Delia platura is responsible for the most significant soybean yield loss in Europe and America, with up to three generations per cropping season. The first and second generations infest the hypocotyl, causing plant death and are regarded as the most significant threat to crop production (Bosnyákné et al., 2016; Ellis and Scatcherd, 2007). *Seedcorn maggots reportedly cause soybean damage ranging from 10–15 % in Hungary* (Bosnyákné et al., 2016) *and corn damage from 33.3– 88.9 % in India* (Chaudhary et al., 1987). Soybeans and maize exhibit relatively higher tolerance to root maggot damage, with a range of 20–40 maggots per seed required to cause significant damage, which can range from dark-brown streaks on the cotyledons to snakehead-like deformities (Hesler et al., 2018; Vea et al., 1975). However, infestation by up to five maggots per seed is sufficient to reduce the stand of snap and lima beans. The heightened susceptibility of lima beans may be attributed to their slower germination rate, which is further exacerbated by cold, wet spring conditions that promote seed rot. Hesler et al. (2018) observed extensive damage when low soil temperatures and excessive moisture followed immediately after sowing, leading to delayed germination. Nevertheless, the economic impact of seedcorn maggots is challenging to quantify, as soil conditions and weather patterns significantly influence the extent of damage.

2.4. Barley and wheat bulb flies

This taxon comprises of D. coarctata, D. flavibasis, D. arambourgi and *D. steiniella*. *Delia coarctata* is a prevalent pest in the Palaearctic region, and it is also known by several synonyms including *A. leptogaster* (Zetterstedt), *H. garbigliettì* (Rondani), *H. coarctata* (Fallén), *Leptohylemyia coarctata* (Fallén), *Musca coarctata* (Fallén) and *Phorbia coarctata* (Fallén) (CABI, 2022d; Jones, 1970; Michelsen, 1983; Perju and Peterfy, 1970; Raw et al., 1968; Suwa, 1974). *Delia coarctata* was first detected and identified in Sweden by Fallén in 1825 under the name *Musca coarctata* (Fallén) (Michelsen, 1983) (Fig. 1). The barley fly (*D. flavibasis*) on the other hand is the species previously described as *Chortophila linearis* by Adams in 1905 (Malloch, 1924). In the early 20th century, Malloch examined the "paratypes" of Linearis and concluded that *Linearis* Adams and *Flavibasis* Stein referred to the same species (Ackland, 2008; Malloch, 1924). Both *D. arambourgi* and *D. steiniella* are sporadic pests of barley, predominantly found in the highland regions of Kenya, Tanzania, and Ethiopia (Ackland, 2008; Bullock, 1965; Jobie and Gebremedhin, 2005).

Unlike other anthomyiid pests, wheat bulb flies typically oviposit on bare soils and not adjacent to the host, likely because, under natural conditions, bare soils are entirely invaded by couch grass (*Agropyron repens* L.), a natural host. Upon hatching, the neonates must locate plant seedlings by detecting primary metabolites, such as sugars, amino acids and carbon dioxide, and secondary metabolites, such as 6-methoxybenzoxazolin-3-one (Marriott and Evans, 2003; Rogers and Evans, 2013, 2014). Barley yield losses due to *D. favibasis and D. arambourgi* have been estimated to range from 77 to 82 % in Kenya and reach 100 % in Ethiopia, under high infestation conditions (Dido et al., 2021; Macharia and Mueke, 1986; Tafa and Sakhuja, 2004).

Delia coarctata reportedly cause significant economic yield losses, reaching up to 4 t ha^{-1} in Europe, particularly under conditions of high infestation (Leybourne et al., 2022; Rogers et al., 2015). However, this contradicts observations from the United Kingdom, which have shown that unless winter infestations reach a threshold of 250 adult flies or 100 eggs per m^2, *D. coarctata* populations do not cause damage significant enough to warrant management (Ellis et al., 2009; Rogers et al., 2015; Young and Cochrane, 1993). Therefore, a more robust scientific foundation is necessary to assess the potential yield losses caused by *D. coarctata* across Europe.

3. Management of root maggots

Root maggots engender substantial yield loss worldwide, but their management is constrained by their cryptic feeding behaviour. Their populations often exhibit patchy distributions that gradually expand following a negative binomial distribution and this can be attributed to the tendency of mated female flies to oviposit preferentially on previously damaged plants (Neveu et al., 2002; Whitfield et al., 1985). Predicting patchy distribution of insects with first-order effects is relatively straightforward due to a correlation between their population densities and environmental factors such as vegetation, soil type, moisture and light. In contrast, second-order effects involve intrinsic population processes that can generate patchiness even in environmentally homogeneous settings (Dalthorp and Dreves, 2008; Soroka et al., 2004; Whitfield et al., 1985). Consequently, environmental covariates may provide limited insight into the location of patches driven by second-order dynamics. Notably, first- and second-order effects may result in similar dispersal patterns, yet their management approaches differ. For instance, infestations driven by first-order effects can be mitigated through targeting treatments applied directly to infested fields whereas management of root maggot infestations driven by second-order effects may involve spatial rotation or the deliberate avoidance of heavily infested fields.

3.1. Cultural control of root maggots

3.1.1. Modification of sowing and harvesting dates

Root maggots are multigenerational pests and the level of damage is commensurate with the duration that crops remain in the field. As such, adjustment of the sowing and harvesting dates may play a significant role in mitigating their infestation. Previous studies have documented increased root maggot damage in early planted compared to late sown crops (Silver et al., 2018; Valantin-Morison et al., 2007). Similarly, Rekika et al. (2008) reported significantly higher damage rate of 4.8 tunnels per root on early-planted radishes, compared to those planted two weeks later (2.4 tunnels/root). These results can be attributed to the increased exposure of early planted crops to the initial generation of spring adults. However, early planted crops can also evade infestation by enabling timely establishment before the emergence of the first-generation maggots. Higley and Pedigo (1984) observed that modifying planting time results in only a partial reduction in root maggot damage, as maggot populations may remain high in various favoured sites despite a decline in the overall population. As such, knowledge of biology and the peak fly emergence period is crucial in deciding the sowing and harvesting dates to avoid root maggot infestations. Therefore, understanding the voltinism and peak emergence periods of flies is crucial for determining optimal sowing and harvesting dates to effectively mitigate root maggot infestations, since these flies have a complicated life cycle including summer diapause, overlapping generations and subterranean feeding (Joseph and Martinez, 2014; Soroka et al., 2004; Turnock and Boivin, 1997).

3.1.2. Field sanitation

Maintaining field sanitation is essential for effective management of root maggot populations. Crop residues reportedly act as a suitable host for autumn and early spring generations of root maggots when left in the field (Capinera, 2008). For instance, previous studies have shown that gravid onion flies are attracted to the exudates of rotting onions for oviposition (Hausmann and Miller, 1989b; Hoepting et al., 2004; Miller and Cowles, 1990). Thus, onion bulbs that are crushed or damaged during harvesting and left in the field at the end of the season serve as suitable hosts for onion maggots during the off-season. Therefore, removing volunteer crops and covering onion cull piles after harvesting is recommended to reduce the spring onion maggot populations

(Madder and Mcewen, 1982). Additionally, farmers are advised to adopt crop harvesting methods that minimize crop damage, thereby preventing the build-up of overwintering root fly populations.

3.1.3. Mixed cropping approach

Crop diversification interferes with the ability of mated female flies to locate and differentiate between host and non-host crops using visual and olfactory cues ultimately limiting infestation (Afrin et al., 2017; Khan et al., 2016). Intercropping cabbage with clover has been associated with a 36 % and 24 % reduction in oviposition and larval infestation, respectively, a 34 % increase in the predation of *D. radicum*, and a 57 % increase in marketable cabbage yield (Ryan et al., 1980). Furthermore, intercropping Brussels sprouts *(Brassica oleracea* var. *gemnifera*) with spurry (*Spergula arvensis*) has been demonstrated to reduce *D. radicum* infestation by 98.8 % (Theunissen and Den Ouden, 1980), whereas brussels sprouts intercropped with two rows of beans reduced oviposition and root damage by 23–43 % (Tukahirwa and Coaker, 1982). In contrast, intercropping Brussels sprouts with two rows of beans resulted in a 23–43 % reduction in oviposition and root damage. The effect of crop diversification on herbivore pest control is founded on the appropriate/inappropriate landings' theory (Finch and Collier, 2000), which holds that female flies are unable to visually differentiate between a host and non-host intercrop when both are green. As such mixed cropping interferes with host-finding behaviours increasing the rate of inappropriate landings ultimately reducing the oviposition rate on the host (Parsons, 2010). However, for crop diversification to be effective, the companion crop must be well-established and exhibit a phenology that is relatively synchronised with that of the main crop.

3.1.4. Push-pull strategy

Another crucial cultural control approach is the stimulo-deterrent diversion strategy, commonly referred to as the 'push-pull strategy.' This method involves utilizing a repellent intercrop to deter pests from the main crop, while a trap crop is employed to attract and manage the pests. The push-pull strategy has been to be highly effective in the management various pests across multiple crops including *Helicoverpa* spp. in cotton and tomato (Duraimurug and Regupathy, 2005; Srinivasan et al., 1994), lepidopteran pests in cauliflower and cabbage fields (Srinivasan and Moorthy, 1991), *Sitona lineatus* in peas and beans (Cook et al., 2007; Smart et al., 1994), *D. radicum* in cabbage (Lamy et al., 2018), *Drosophila suzukii* in red raspberry (Wallingford et al., 2018) and *D. antiqua* in onions (Miller and Cowles, 1990). For instance, the treatment of onion seedlings with cinnamaldehyde repellent and an the use of cull onion as a trap crop reduced oviposition on seedlings by 96 % (Miller and Cowles, 1990), whereas dimethyl disulfide reduced oviposition on Broccoli plants by 20–60 % (Table 2) (Ferry et al., 2009; Kergunteuil et al., 2012). Chinese cabbage has been extensively investigated as a potential pull crop due to its distinct attraction to *D. radicum. However, the combined* repulsive effect of dimethyl disulfide and the enhanced attractiveness of Chinese cabbage through Z-3-hexenyl acetate have not yielded promising results in the control of *D. radicum* (Lamy et al., 2018). This may be attributed to methodological limitations and a limited understanding of the role of volatile organic compounds in modulating multitrophic interactions.

3.1.5. Resistant varieties

The use of resistant cultivars is arguably the most sustainable approach for controlling root maggot infestations. Previous research has revealed resistant traits to root maggots in *Sinapis alba,* making it a promising candidate for the development of resistant varieties through breeding (Jyoti et al., 2001). Ultimately, predictive models have been developed to aid in the development of root maggot-resistant rutabagas, using *S. alba* as a reference crop (Malchev et al., 2010). Similarly, germplasms from *S. alba* have been utilised to confer resistance to canola, resulting in a 24 % increase in yield (Ekuere et al., 2005). Notwithstanding the major advances in breeding for resistance against root maggots over the past decades, only limited and short-lived resistance has been achieved in cruciferous crops.

3.2. Physical barriers and traps

Physical barriers, such as exclusion fences and non-woven fibres, as well as traps like water traps and sticky traps, are commonly employed in the monitoring and management of *Delia* fly populations (Blackshaw et al., 2012; Bravo-Portocarrero et al., 2020; Dapsis and Ferro, 1983; Finch, 1990). Vertical interception nets have previously been employed to control low-flying *Delia* adults achieving up to 80 % suppression of cabbage root fly populations in rutabaga fields (Blackshaw et al., 2012; Bomford et al., 2000; Vernon and Mackenzie, 1998). Similarly, non-woven fibres of ethylene vinyl acetate, when placed at the base of onion and broccoli plants, have been shown to reduce oviposition on individual plants by 64–96 % (Hoffmann et al., 2001). Unlike exclusion barriers, which are vertically positioned to intercept flying adults, the number of insects captured by sticky and water traps depends on factors such as the trap's attractiveness, population density and the responsiveness of the insect (Finch and Skinner, 1974; Hamer et al., 2024). Nevertheless, the relative abundance of *Delia* species captured on sticky and water traps may not precisely reflect the true population density or the extent of damage caused by these species. This discrepancy could be attributed to fluctuations in transient populations over time, which are influenced by their phenological patterns and the physiological status of their host plants.

3.3. Biological control of root maggots

3.3.1. Entomopathogenic fungi

Various fungal species possess innate ability to infect and induce epizootics in *Delia* spp. leading to premature mortality. Notably, species such as *Strongwellsea castrans* and *Entomophthora muscae* are widely recognised as natural entomopathogenic fungi (EPF) specifically targeting *Delia s*pecies (Eilenberg et al., 1992, 2020, 1992; Eilenberg and Jensen, 2018; Finch, 1989; Nair and McEwen, 1973; Thomsen and Eilenberg, 2000). Past laboratory mesocosms have documented up to 75 % mortality of *D. antiqua* following inoculation with spores of *Paecilomyces farinosus* and *Paecilomyces fumosoroseus* (Majchrowicz et al., 1990; Poprawski et al., 1985). Other species, such as *Beauveria bassiana* and *Metarhizium anisopliae*, have demonstrated 50–100 % mortality of *D. radicum* and *D. antiqua* in in vitro studies, with larval mortality rates of 38–39 % under field conditions (Davidson and Chandler, 2005; Meadow et al., 2000; Razinger et al., 2014b). However, infection by entomopathogenic fungi (EPF) is primarily percutaneous, requiring the pathogen to establish adequate contact with the insect host for successful colonization and efficacy. In addition to the protective exoskeleton of root maggot pupae, environmental factors and humoral immunity further constrain the effectiveness of EPFs in controlling root maggot populations (Fernandes et al., 2015; Jaronski, 2010; Müller et al., 2008; Tupe et al., 2017; Withanage et al., 2024). Achieving an optimal lethal dose often requires the target pest to come into contact with thousands of propagules, which often requires frequent supplementation from laboratory cultures or augmentation of natural populations.

3.3.2. Entomopathogenic nematodes

Entomopathogenic nematodes (EPNs) are key biological agents for managing *Delia* spp. *infestation, as they inhabit the soil and are directly exposed to root feeding larvae. Although the efficacy of EPNs vary significantly due to numerous factors, species from the* families *Heterorhabditidae and Steinernematidae* have consistently demonstrated the greatest potential in suppressing root maggots (Chen et al., 2003a,b; Trejo-Meléndez et al., 2024; Withanage et al., 2024). Six species of the genera *Steinernema*, including *S. feltiae, S. carpocapsae, S. affine, S. arenarium, S. riobravus, S. glaseri,* and *S. bicornutum* along with three species of the

Table 2
The efficacy of different approaches to root maggot control.

Approaches	Practice/component	Outcome	Crop	Pest	Country	Reference
Cultural	Adjusting the sowing and harvesting dates	4.8 tunnels/root (early planted) compared to 2.4 tunnels/root (2.4 tunnels/root) planted two weeks later.	Radish (*R. sativus*)	*D. radicum*	Canada	Rekika et al. (2008)
	Early ploughing (in autumn)	Autumn ploughing reduced pupae survival by 30–80 %	Brussels sprouts, cabbages and swede plant	*D. radicum*	England	Finch and Skinner (1980)
	Intercrop with clover (*Trifolium repens*)	Clover intercrop reduced oviposition by 11 % in the field and 81 % in the laboratory	Cabbage (*B. oleracea* var. *capitata*)	*D. radicum*	Ireland	Ryan et al. (1980)
	Intercrop with lettuce (*Lactuca sativa*)	Lettuce intercrop reduced larval rate by 56 %	Cabbage (*B. oleracea* var. *capitata*)	*D. radicum*	Ireland	Ryan et al. (1980)
	Intercrop with spurry (*Spergula arvensis*)	Spurry intercrop reduced infestation by 98.8 %	Brussels sprouts (*B. oleracea* var. *gemnifera*)	*D. radicum*	Netherland	Theunissen and Den Ouden (1980)
	Intercrop with French beans (*Phaseolus vulgaris*)	Reduced egg numbers by 50–60 % with 40 % ground cover by beans; Reduced pupation and root damage index by arrange of 20–36 % and 23–39 %, respectively	Brussels sprouts (*B. oleracea* var. *gemnifera*)	*D. radicum*	United Kingdom	Tukahirwa and Coaker (1982)
	Soil amendment with insect exuviae	Reduced fly eclosion by 50 %	Brussels sprouts (*B. oleracea* var. *gemnifera*)	*D. radicum*	Wageningen, Netherlands	Wantulla et al. (2022)
Behaviour modification	Stimulo-deterrent diversion/push-pull strategy	Reduced oviposition on onion seedlings by 58–96 %	Onion (*A. cepa*)	*D. antiqua*	Michigan, United States	Cowles and Miller (1992)
	Stimulo-deterrent diversion/push-pull strategy	Reduced oviposition by 30 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	France	Lamy et al. (2018)
Physical methods	Net covers	Net covers reduced plant damage by 41.83 %	Radish (*R. sativus*)	*D. radicum*	Wellesbourne, United Kingdom	Witkowska et al. (2018)
	Exclusion fences	Reduced crop damage by about 59–62 %	Rutabaga (*B. napus* var. *napobrassica*)	*D. radicum*	Canada	(Bomford et al., 2000; Vernon and Mackenzie, 1998)
	Non-woven fibre as physical barriers	Reduced oviposition by about 64–96 %	Broccoli (*B. oleracea* L. var. *Italica*) and Onion (*A. cepa*)	*D. radicum* and *D. antiqua*	United States	Hoffmann et al. (2001)
Biological Control	Entomopathogenic fungi (*Beauveria bassiana*)	100 % adult fly mortality	Laboratory evaluations	*D. radicum*	United States	Meadow et al. (2000)
		27.19–31.82 % larval mortality	Rutabaga (*B. napus* var. *napobrassica*)	*D. radicum*	Slovenia	Razinger et al. (2014b)
	Entomopathogenic fungi (*Metarhizium anisopliae*)	50 % adult fly mortality	Laboratory evaluations	*D. radicum*	United States	Meadow et al. (2000)
	Entomopathogenic fungus (*M. anisopliae* and *I. fumosorosea*)	Reduced root damage by 20–70 %	Cabbage (*B. oleracea* var. *capitata*)	*D. floralis*	Finland	Vänninen et al. (1999b)
	Entomopathogenic nematode (*S. feltiae*)	12–32 % and 26–73 % mortalities after two and four days, respectively	Laboratory evaluations	*D. radicum*	Belgium	Chen and Moens (2003)
	Entomopathogenic nematode (*S. feltiae and S. glaseri*)	14.0 and 12.0 % larval morality	Corn plants	*D. platura*	Canada	Riga et al. (2001)
	Entomopathogenic bacteria (*Bacillus thuringiensis)*	Reduced egg numbers by 44 %	Brussels sprouts (*B. oleracea* var. *gemnifera*)	*D. radicum*	Canada	Obadofin and Finlayson (1977)
	Entomopathogenic bacteria (*Bacillus thuringiensis)*	30.7 ± 10.2 % larval mortality	Laboratory entomopathogenic tests	*D. radicum*	Germany	Razinger et al. (2014a)
	Parasitoids (*A. bilineata* and *T. rapae*)	33–65 % pupae mortality	Swede (*B. napus* var. *napobrassic*)	*D. radicum*	United Kingdom	Hemachandra et al. (2007)
	Parasitoid (*A. bilineata*)	7.27–81.69 % pupae mortality	Canola (*B. napus*)	*D. radicum*	Canada	Hummel et al. (2010)
	Parasitoids (*Aphaereta pallipes* and *A. bilineata*)	17 and 20.7 % pupae mortality, respectively	Onion (*A. cepa*)	*D. antiqua*	Canada	Tomlin et al. (1985)
	Predator (*Bembidion quadrimaculatum*)	Reduced onion egg and maggot survival by 17–70 % and 55–57 %, respectively	Onion (*A. cepa*)	*D. antiqua*	United States	Grafius and Warner (1989)
	Predator mite (*Hypoaspis miles*)	Reduced *D. radicum* damage by 58 %	Radish (*R. sativus*)	*D. radicum*	Netherlands	Ferry et al. (2007)
	Sterile insect technique	Reduced fly population by 10 % in the first year	Onion (*A. cepa*)	*D. antiqua*	Netherlands	Ticheler et al. (1980)
Chemicals insecticides	Neonicotinoids (Clothianidin)	Achieved larvae mortality range: 79.0–92.6 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	United States	Joseph and Zarate (2015)
	Bifenthrin, Zeta-cypermethrin (Pyrethroid)	Achieved larvae mortality range: 58.0–84.0 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	United States	Joseph and Zarate (2015)

(*continued on next page*)

Table 2 (*continued*)

Approaches	Practice/component	Outcome	Crop	Pest	Country	Reference
	Thiamethoxam + Chlorantraniliprole (Neonicotinoids + Diamide)	Achieved larvae mortality range: 42.0–77.0 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	United States	Joseph and Zarate (2015)
	Cyclaniliprole & Cyantraniliprole (Ryanodine receptor activator)	Achieved larvae mortality range: 16.0–59.0 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	United States	Joseph and Zarate (2015)
	Spinetoram (Spinosyn)	Achieved larvae mortality range: 56.0–94.0 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	United States	Joseph and Zarate (2015)
	Tolfenpyrad (Pyridazinone)	Achieved larvae mortality range: 91.0–99.0 %	Broccoli (*B. oleracea* L. var. *Italica*)	*D. radicum*	United States	Joseph and Zarate (2015)
Resistant Cultivars	Germplasm for resistance from *Sinapis alba* L.	Yield increased by 24 %	Canola (*B. napus*)	*D. radicum & D. floralis*	Canada	Ekuere et al. (2005)

genera *Heterorhabditis* namely *H. megidis, H. bibionis* and *H. bacteriophora,* have been primarily studied as parasites of *Delia species.* (Bracken, 1990; Chen and Moens, 2003; Jaramillo et al., 2013; Kapranas et al., 2020). A laboratory study by Chen and Moens (2003) revealed a significant mortality of cabbage root maggot, ranging from 26 to 73 %, after four days of exposure to *S. feltiae*, whereas *S. glaseri* exhibited the lowest larval mortality of 5.6 %. Although Riga et al. (2001) reported similar pathogenicity by *S. feltiae* and *S. glaseri* on *D. platura,* numerous research findings highlights that *S. feltiae* possesses a distinctive ability to control *Delia species* compared to other EPNs (Chen et al., 2003a,b; Schroeder et al., 1996). However, entomopathogenic nematodes (EPNs) require moist conditions for effective movement and infectivity, making them less effective in dry soils. Furthermore, most EPNs are prone to rapid degradation in the soil due to their limited shelf life or exposure to ultraviolet radiation, thus requiring constant augmentation of the natural populations.

3.3.3. *Entomopathogenic bacteria*

Entomopathogenic bacteria, such as *Bacillus thuringiensis*, have gained significant attention as a biocontrol agents for managing insect pests across various families. Previous studies have revealed 31–44 % suppression of cabbage root fly larvae and eggs following exposure to *B. thuringiensis* subsp. *kurstaki* (Obadofin and Finlayson, 1977; Razinger et al., 2014a). Moreover, the application of *B. thuringiensis* subsp. *thuringiensis* has been associated with 15 % increase in crop yield (Havukkala, 1988). *Although B. thuringiensis* subsp. *israelensis* has demonstrated high efficacy against several dipteran flies, such as mosquitoes (Culicidae), black flies (Simuliidae), and mushroom flies (Sciaridae and Phoridae) (Ben-Dov, 2014; Brühl et al., 2020; Houston et al., 1989; Keil, 1991; Lacey, 2007), it has proven ineffective against root flies (Lasa et al., 2025). Numerous Cry- and Cyt-toxin-based *B. thuringiensis* pesticides are commercially available, but they rely on oral ingestion by target insects to be effective, which limits their efficacy under field conditions (Bravo et al., 2007). Other entomopathogenic bacteria such as *Photorhabdus* and *Xenorhabdus* bacteria offers alternative solution, yet their dependence on nematode symbionts constrain their application (Nielsen-LeRoux et al., 2012; Waterfield et al., 2009). Although plant root-colonizing *Pseudomonas* bacteria have shown promising pathogenicity against a broad spectrum of herbivorous insects (Kupferschmied et al., 2013; Sarkhandia et al., 2023), their efficacy on root flies remains unknown.

3.3.4. *Parasitism*

A diverse complex of egg, larval and pupal parasitoids have shown considerable suppression of root maggots in their native range. *Delia* species are naturally parasitised by arthropods belonging to the orders Hymenoptera and Coleoptera including the cynipid wasp (*Trybliographa rapae)* and staphylinid beetles (*Aleochara bipustulata*, and *Aleochara bilineata)* (Hemachandra et al., 2007; Joseph et al., 2015; Nava-Ruiz et al., 2021; Soroka et al., 2001). Species such as *A. bilineata, A. bipustulata* and *T. rapae have been documented to induce 31–65 % pupal mortality under greenhouse and field conditions* (Hummel et al., 2010; Turnock et al., 1995) (Table 2). In Mexico, a braconid wasp (*Aphaereta pallipes*) has been reported to exhibit a broader host range with moderate parasitism compared to *A. bilineata* and *T. rapae (*Nava-Ruiz et al., 2021*)*. Although parasitism holds significant potential for managing root maggots, natural populations of parasitoids are often insufficient to reduce infestations below economic damage thresholds. Therefore, periodic release of mass-reared parasitoids is recommended to ensure effective biological control. However, this strategy may still be limited by significant cost implications and logistical complexities synchronising released parasitoid populations' life cycle and the susceptible stages of root maggot flies.

3.3.5. *Predators*

Researchers have uncovered a broad list of invertebrate predators which often substantial levels of mortality. Significant egg predation has been observed among carabid species such as *Agonum* spp., *Amara* spp., *Bembidion* spp. *Calathus* spp., *Elaphrus* spp., *Harpalus* spp. and *Pterostichus* spp. (Finch, 1996; Hummel et al., 2012) *as well as* Stephylinids such as *Anotylus rugosus, Atheta* sp., *Aleochara* spp. *Creophilus maxillosus, Falagria* sp., and *Philonthus* spp. (Tomlin et al., 1985). A high level of egg and larval predation, ranging from 17 % to 70 %, has been recorded with *B. quadrimaculatum*, while predatory mites, such as *Hypoaspis miles*, have been associated with approximately a 58 % reduction in *D. radicum* damage (Ferry et al., 2007; Grafius and Warner, 1989). Although beetles are essential predators of root maggots, their dispersal capacity is often limited, which may restrict their ability to regulate pest populations across different locations. Given that all the aforementioned natural enemy guilds significantly contribute to the broader functioning of agroecosystems, they warrant more thorough consideration and scientific validation (Wyckhuys et al., 2024). Enemy conservation strategies, such as mulching, intercropping and the establishment of refugee habitats, are essential for the rapid re-colonization of fields following pesticide application and tillage.

3.4. Chemical pesticides

Carbolic acid and carbon bisulfide were the primary methods used to controlling root maggots as early as the 19th century (Cook, 1881). In the early 20th century, mercury chlorides became widely favoured as seed coatings, seedbed drenches and furrow dust. However, the discovery of organochlorine compounds in the 1940s marked a significant breakthrough in root maggot control, leading to the development of chlordane and hexachloride insecticides, which were utilised as post-emergence drenches and dust. Subsequently, insecticides such as heptachlor, dieldrin, and aldrin were developed, leading to efficient control of *D. radicum* in cabbage (Davis and Mcewen, 1965; Forbes and King, 1957). However, in the 1960s, resistance of root maggots to organochlorine insecticides became widespread, particularly in Canada and the United States (Finlayson and Noble, 1966; Niemczyk, 1965; Read, 1965). In addition, organochlorines were linked to severe environmental and human health risks, which led to their ban in the 1960s (Finlayson and Noble, 1966; Niemczyk, 1965; Read, 1965).

Currently, the control of root maggots principally relies on the use of organophosphate insecticides, particularly chlorpyrifos which is favoured due to its relatively low water solubility and reduced susceptibility to leaching (Dugger et al., 2024; Joseph and Zarate, 2015; Joseph and Iudice, 2020). Other alternatives, such as neonicotinoid, pyrethroid, diamide, ryanodine receptor activator, spinosyn and pyridazinone insecticides, have been developed with diverse modes of action, achieving over 75 % larval mortality (Cornelsen et al., 2024; Joseph and Zarate, 2015). These chemicals are typically applied either by directly drenching the soil surface or as seed coatings prior to planting. Film-coating of seeds using insecticides such as chlorpyrifos and imidacloprid is preferred, as it offer effective protection against root maggots at low application rates (Jyoti et al., 2003). Due to the persistent nature and environmental risks of soil-applied insecticides, alternative control strategies involving adulticides have been explored, with inconsistent results. For instance, significant mortality of adult root flies has been reported following ingestion of turnip baits treated with bifenthrin, zeta-cypermethrin, cyantraniliprole, and spinetoram, highlighting their potential as effective adulticides (Dugger et al., 2024). In contrast, while Lasa et al. (2025) reported a rapid knockdown effect from contact applications of bifenthrin and lambda-cyhalothrin, a high rate of fly recovery was recorded within 24 h. Overall, the rate of pesticide application has increased significantly over the past decades, possibly driven by the growing demand for food resulting from the burgeoning human population coupled with the rise in pesticide resistance. Reducing yield losses from root maggot infestations in a sound and environmentally responsible manner is indispensable to ensuring food security while conserving nature. As such, a conscientious prioritization of biodiversity-based measures is recommended to bolster ecosystem resilience and reduce the need for chemical intervention in modern agriculture (Deguine et al., 2023).

4. Prospects for management of root maggots using insect frass fertilizer

The production of edible insects result in residual streams comprising of insect excreta, chitinous exuviae and undigested substrates, which have gained significant attention as alternatives to conventional fertilisers and pesticides (Barragán-Fonseca et al., 2022; Wantulla et al., 2022; Bordiean et al., 2020; Lagat et al., 2021; Lopes et al., 2022; Magara et al., 2019; Tanga et al., 2018; Tanga and Kababu, 2023; van Huis, 2021). Insect farming is becoming an increasingly common practice among farmers, with the frass by-product gaining recognition as critical lever for enhancing crop productivity and soil bioremediation. Although scientific attention has been inordinately skewed towards the agronomic aspects of crop production, the potential of insect frass as a fertilizer for pest control shows promise and merits rigorous scientific evaluation (Barragán-Fonseca et al., 2022; Chia et al., 2024; Onyango, 2023). Soil amendment with insect frass holds significant potential for suppressing root maggot populations and promoting climate-resilient agri-food production systems through the various mechanisms outlined below.

4.1. Regulation of tritrophic interactions

Enrichment of soil with insect frass fertilizer may enhance plant resistance by modifying antibiosis, antixenosis (non-preferences), tolerance and recovery from insect herbivory (Birkhofer et al., 2008; Garratt et al., 2018; Gu et al., 2022). Both mineral and organic fertilizers have been shown to influence the defensive traits and pest herbivory through "bottom-up" effects (Comadira et al., 2015; Han et al., 2016; Gu et al., 2022; Rashid et al., 2017). For instance, excessive application of nitrogen fertilizers has been previously reported to not only promote vigorous plant growth but also influence pest colonization and development (Bala et al., 2018; Han et al., 2022; Islam et al., 2017; Jafary-Jahed et al., 2020; Virla et al., 2023; Wale et al., 2006). Maintaining optimal soil fertility is crucial for maximizing crop productivity while simultaneously reducing pest pressure (Gu et al., 2022).

Chitin-rich insect frass fertilizer may also stimulate the production of secondary metabolites that simultaneously repel herbivorous pests while attracting enemy guilds. However, chitin is a stable carbohydrate polymer composed of repeating units of 2-(acetylamino)-2-deoxy-D-glucose and is insoluble in most common organic and inorganic solvents (Pillai et al., 2009; Shamshina et al., 2020). Therefore, it must be deacetylated into its more soluble derivative, chitosan, using various chemical or biological methods (El Knidri et al., 2018). Under natural environmental conditions, chitin is enzymatically degraded to chitosan by chitinases, such as endochitinases, exochitinases, and β-N-acetylhexosaminidases, produced by soil-borne microbes such as *Flavobacterium* spp. and actinomycetes strains 5A and 8A (Andronopoulou and Vorgias, 2004; Dahiya et al., 2006). Recent studies have demonstrated the efficacy of griding insect exuviae and bioligical extraction in accelerating the release of chitin and chitosan (Anedo et al., 2024; Kisaakye et al., 2024; Lagat et al., 2021). Chitosan, has been shown to elicit the production of secondary metabolites such as phenolics, alkaloids, flavonoids and terpenoids as well as enhance the expression of defensive genes (Gai et al., 2019; Kahromi and Khara, 2021; Mukhtar Ahmed et al., 2020). Additionally, chitosan may promote the reduction of reactive oxygen species, such as singlet oxygen, hydrogen peroxide, and superoxide anions, which trigger a cascade of reactions that lead to the activation of plant defense enzymes (Maffei et al., 2007; War et al., 2012). For instance, simple phenolics, such as salicylates, may function as antifeedants against insect herbivores such as *Operophtera brumata* (L.), thereby reducing larval growth and minimisin crop damage

(Simmonds, 2003). In contrast, flavonoids, such as isoflavonoids, flavans, flavonones, flavan 3-ols, proanthocyanidins, flavones and flavonols have been shown to inhibit infestation by various herbivorous insect species (War et al., 2012).

Moreover, the application of insect-composed fertilizer may induce indirect plant defence against root maggots by attracting their natural enemies (i.e., top-down effects). Utilizing chitin-rich insect frass fertilizer could reduce the damage by root maggots by augmenting the diversity of natural enemies such as *A. bilineata* and *A. pallipes (*Nava-Ruiz et al., 2021; Tomlin et al., 1985*)*. Garratt et al. (2011) observed a positive correlation between organic soil amendment and the abundance of natural enemy populations, suggesting that crops fertilised with organic materials release volatile organic compounds that attract the predators and parasitoids of herbivorous insects. The link between frass fertilizer and the richness of natural enemies can be further attributed to enhanced mycorrhizal colonization, which induces the production of terpenoids, specifically β-caryophyllene and β-ocimene that attracts the natural enemies and beneficial arthropods (Guerrieri et al., 2004; Heinen et al., 2018; Hempel et al., 2009; Ninkuu et al., 2021; Pangesti et al., 2015; Wooley and Paine, 2011). Previous observations indicated a higher frequency of flower visitation and an increased seed set in plots with a greater abundance of mycorrhizal plants compared to the control (Cahill et al., 2008; Gange and Smith, 2005). Although insect frass fertilizer may promote mycorrhizal colonization of plant roots, thereby enhancing biological control of herbivorous pests, there is a significant gap in the scientific understanding of this approach, particularly regarding its efficacy in controlling root maggots.

4.2. Enrichment of beneficial soil microbiome

The application of insect-composed fertilizer may also augment the diversity of beneficial microbes that are antagonistic to root maggots. Soil amendment with black soldier fly (BSF) frass fertilizer has been reported to reduce cabbage root fly emergence by up to 50 % compared to synthetic fertilizers, demonstrating its significant potential for pest control (Wantulla et al., 2022). Furthermore, studies evaluating the potential of mealworm frass in managing cabbage root fly have yielded contrasting results (Bai, 2015; Wantulla et al., 2022). These discrepancies may be attributed to variations in frass chitin levels, which play a crucial role in enhancing the abundance of beneficial soil microbes (Nurfikari and de Boer, 2021). For example, exuviae from black soldier fly larvae contain 10.18–11.85 % chitin, whereas mealworm exuviae has 7.9–8.6 % chitin content (Lagat et al., 2021; Nurfikari and de Boer, 2021), depending on the extraction method.

Insect frass fertilizer may also mitigate root maggot damage by enhancing microbial diversities, which plays a crucial role in nutrient uptake, tissue regrowth, and the tolerance of both biotic and abiotic stress (Ali et al., 2017; Herman et al., 2008; Kempel et al., 2009; Ma et al., 2024). For instance, bacteria isolated from mealworm frass including *Klebsiella*, *Brevibacillus*, *Sphingobacterium*, *Paenibacillus* and *Pseudomonas,* have been shown to elicit the production of plant growth hormones, such as auxins and gibberellins (Kim et al., 2012; Nehra et al., 2016; Sivasakthi et al., 2014; Xie et al., 2016), while also functioning as biocontrol agents against pests and diseases (Cabanás et al., 2018; Poveda et al., 2019; Sivasakthi et al., 2014). Furthermore, soil-borne microorganisms, such as *Pseudomonas* spp. and *Bacillus* spp., as well as mycorrhizal fungi, have the capacity to induce systematic plant resistance against insect herbivory, while simultaneously promoting seed germination, root development and nutrient assimilation (Aziz et al., 2015; Barragán-Fonseca et al., 2022; Poveda et al., 2019; Pozo and Azcón-Aguilar, 2007; Segarra et al., 2009; Van Wees et al., 2008; Wantulla et al., 2022; Widnyana and Javandira, 2016). Fungi isolated from mealworm frass, such as *Cladosporium*, *Wallemia*, and *Aspergillus* have also been previously shown to possess the ability to solubilise phosphorus in the soil and improve plant drought stress tolerance (Díaz-Valderrama et al., 2017; Poveda et al., 2019). Despite significant advances in the use of insect frass as a fertilizer in crop production over the past few decades, insect farming may still be in its infancy. Therefore, additional scientific research is needed to validate these mechanisms, particularly in relation to their effectiveness against root maggots.

4.3. Direct toxicity against root maggots

Chitin derived from the exuviae of mass produced insects has been previously reported to exhibit both contact and residual insecticidal properties against insects from various families *(*Abd Manan et al., 2024; Onyango, 2023; Rabea et al., 2005; Zhang et al., 2003*)*. For instance, synthetic and natural N-alkyl chitosan (NAC) derivatives induced 72 % mortality in third-instar larvae of *Spodoptera littoralis (Boisduval) following contact exposure* (Rabea et al., 2005). *Similarly,* chitosan ethyl carbamate and chitosan N-diethyl phosphate achieved considerable mortality against *Helicoverpa* spp., *Myzus* spp., and *Liriomyza huidobrensis* (Blanchard) (Rabea et al., 2005). Moreover, synthetic chitosan has demonstrated up to 90 % efficacy in controlling *Metopolophium dirhodum* (Walker) and *Rhopalosiphum padi* (L.) (Rabea et al., 2005). Despite the high potential of chitin in controlling herbivorous pests, previously studied synthetic sources of chitin are costly and inaccessible to farmers, particularly in resource-poor countries of the Global South. Insect chitin is emerging as a promising approach for the cost-effective and sustainable management of herbivores. However, further rigorous scientific validation is needed to fully understand its pesticidal effects against root maggots.

5. Conclusion

This review has revealed that root maggots (*Delia* spp.) are major threats to vegetables and field crops globally with some species limited to specific geographic regions. Although various control methods have been explored, there has been minimal success due to cryptic feeding habits, climate change, and pesticide resistance, among others. The yield losses due to root maggots varies with host crops, with vegetables being the most affected. The review established high potential in using multipurpose organic soil amendments such as insect frass fertilizer despite their low adoption rate. Future efforts should be devoted towards understanding the efficacy of insect frass fertilizer in the management of root maggots to generate the information necessary for use as a biorational input in various agricultural production systems.

CRediT authorship contribution statement

Lawrence O. Onyango: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dennis Beesigamukama:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **James W. Muthomi:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Conceptualization. **John W. Kimenju:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Sevgan Subramanian:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Segenet Kelemu:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Funding acquisition. **Chrysantus M. Tanga:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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