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Laboratory evaluation of insecticides for the control of *Delia planipalpis* (Diptera: Anthomyiidae), a nascent pest of broccoli (Brassicaceae) in Mexico

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Abstract

The radish fly, *Delia planipalpis* Linnaeus (Diptera: Anthomyiidae), is an emerging pest of broccoli and brassicaceous crops (Brassicaceae). The fly oviposits close to the stem of broccoli plants, and larvae feed within the stem and then pupate in the soil. Due to *D. planipalpis*'s recent appearance as a pest, no insecticides are registered for its management in Mexico. This study evaluated the efficacy of 13 synthetic and biological insecticides against different developmental stages through laboratory bioassays. Neonicotinoid-based products were highly toxic to the larvae, especially when applied *via* root irrigation, with thiamethoxam, clothianidin, and imidacloprid showing systemic activity. Thiamethoxam- and spinetoram-based products were also effective when applied to the stem oviposition site as a spray. A clothianidin-based product demonstrated moderate ovicidal activity, and bifenthrin had moderate residual activity against adult flies. A pyriproxyfen-based product effectively suppressed adult emergence. Products based on spirotetramat, neem (Meliaceae), and *Tagetes* (marigold) (Asteraceae) extracts and the microbial insecticide *Bacillus thuringiensis* var. *israelensis* (Bacillaceae) were ineffective against this pest. Spinosad and *Sterneinema feltiae* (Rhabditida: Steinernematidae) were not highly effective but could be used together with other control strategies in organic production. Neonicotinoids, spinetoram, and pyriproxyfen are promising options to validate in field trials for the management of *D. planipalpis* in broccoli.

Introduction

Mexico is the world's fifth largest producer of broccoli (Brassicaceae) and the second largest exporter, with a production of 686 000 tonnes of this crop and an estimated value exceeding US$200 million (ProducePay 2022). Broccoli is grown intensively throughout the year in Mexico, with up to three harvests across both the rainy and the dry seasons.

The radish fly, *Delia planipalpis* Linnaeus (Diptera: Anthomyiidae), is an emerging pest of broccoli and other brassicaceous crops in Mexico (Lasa *et al*. 2024). The fly oviposits close to the stem of broccoli plants in the early stages of growth, shortly after the seedlings have been transplanted. The larvae feed on the tap root or penetrate the stem, reducing plant growth and causing yellowing, stunting, and plant death. Plants remain susceptible for 3–4 weeks until they reach approximately 30 cm in height.

Each *D. planipalpis* female lays 35–45 eggs in its lifetime. Eggs hatch 2–3 days later, and larvae feed on roots or the stem and pupate in the soil. Under laboratory conditions (~25 °C), the complete lifecycle takes approximately 30 days (Córdova-García *et al*. 2023). In recent years, losses of broccoli seedlings have increased to over 30% in some broccoli producing regions such as Guanajuato State (Comité Estatal de Sanidad Vegetal del Estado de Guanajuato 2014; Meraz-Álvarez *et al*. 2020).

Due to its recent appearance as a nascent pest, no insecticides currently are registered for the management of *D. planipalpis* in Mexico or elsewhere in the world as far as we are aware. When attacks are detected, control strategies mainly involve the application of products that are registered for other pests of broccoli. These include systemic insecticides applied by root irrigation or contact insecticides applied directly to the soil near the plant stem. However, these treatments lack any research-based information on their efficacy or on the duration of their insecticidal activity. As *D. planipalpis* is not a common pest in other countries, no additional information on effective active ingredients is available.

A previous comparison of the efficacy of 29 insecticides performed under laboratory conditions focused on the susceptibility of the cabbage fly, *Delia radicum* Linnaeus, another pest of broccoli (Joseph and Zarate 2015). Other researchers have evaluated the efficacy of a range of conventional and biological insecticides against *D. radicum* and other species of *Delia* pests (Chen *et al*. 2003; Ester *et al*. 2003; Nielsen 2003; Ellis and Scatcherd 2007; Bažok *et al*. 2012; Beck *et al*. 2014; Zhou *et al*. 2016).

The initial screening of insecticides under laboratory conditions allows their selection for subsequent field experiments. Products can be tested against different developmental stages and applied using a range of techniques that consider the biology and behaviour of the pest, the efficacy of insecticides against related species, and the agronomic practices in each crop and region. Given this, the objective of the present study was to assess, under laboratory conditions, the relative efficacy of insecticidal products against different stages of *D. planipalpis*, including adults, eggs, neonate larvae, other larval instars, and pupae. The selection of insecticides was based on their mode of action, their registration for use in broccoli in Mexico, and their reported efficacy against other *Delia* spp. pests.

Material and methods

Insect colony, plants, and insecticides

Experiments were conducted using a laboratory colony of *D. planipalpis* previously established in the Instituto de Ecología AC (Xalapa, Veracruz, Mexico). The colony originated from pupae collected in Guanajuato State, Mexico in 2020 and was subsequently maintained in ventilated acrylic cages (30 × 30 × 30 cm) containing radish plants (*Raphanus sativus* Linnaeus). Radishes (var. Champion) were used because each radish plant supports the development of many *D. planipalpis* larvae, whereas broccoli seedlings become seriously damaged or die when infested by just three or four larvae. The colony was maintained under controlled laboratory conditions at 24 ± 1 °C and 65 % relative humidity with a 12:12-hour (light:darkness) photoperiod. Each radish plant with eggs was placed in a plastic cup with a thin layer of vermiculite for larval development. Pupae were collected weekly and were held separately for adult emergence. Adults of both sexes were segregated into groups at intervals of 1–2 days to produce batches of uniform age for assays. Flies had continuous access to water and food (3:1 ratio of sucrose:hydrolysed protein) before the experiments. The *D. planipalpis* colony is likely to be highly susceptible to insecticides due to the limited application of insecticides against this pest in the field and the period of several generations (> 10 generations) for which it was cultivated under laboratory conditions.

The commercial products used in our experiments are classified as either conventional (synthetic) or organic-approved insecticides (Table 1) and were selected based on their registration in Mexico for use in controlling various species of insect pests of broccoli. The product concentrations tested correspond to the maximal doses recommended to control other pests of broccoli.

Contact toxicity in adults

To assess the mortality of adult flies following contact with dry insecticide residues (World Health Organisation 2022), filter paper rectangles (8.5 × 10 cm) were immersed in insecticide solution at predetermined concentrations or a water control (Table 1). Treated papers were air-dried at room temperature for 24 hours in an extraction hood. Each dry paper was then placed inside a 50-mL centrifuge tube covering nearly the entire internal surface. The tube was sealed with a modified lid perforated with a 10-mm hole to release adults into the tube. A group of 10 adults (five females and five males) aged 1–3 days were introduced into the centrifuge tube, and the hole was sealed with a cotton plug. The flies were confined within the tube for 20 minutes at 24 ± 1 °C and 65% relative humidity. After this period, the adults were collected and transferred to a 475-cm^3 plastic cup containing a piece of cotton moistened with 10% (wt/vol) sucrose solution. The number of knocked-down flies was recorded after 1 hour, and mortality was recorded after 23 hours. Flies that did not respond to the touch of a small paintbrush were considered to be dead. Six replicates were performed for each of the products selected. Given their unique modes of action, *Bacillus thuringiensis* (Bacillaceae) and *Sterneinema feltiae* (Rhabditida: Steinernematidae) were not included in this experiment.

Ovicidal effects and neonate mortality

To assess the ovicidal effects of products, batches of eggs were collected from radish plants in cages with mated *D. planipalpis* females. Eggs were collected from leaf axils at intervals of 48 hours using a fine soft paintbrush. Two rows of five eggs (10 eggs in total) were placed on a dark piece of cotton fabric (20 × 40 mm). Each piece of fabric had previously been immersed in water (control) or insecticide solution (Table 1), allowed to dry for 2 hours at room temperature and placed in the centre of a 9-cm plastic Petri dish containing a piece of cotton wool moistened with distilled water. The moist cotton prevented the desiccation of eggs during the experiment. The Petri dish was then sealed with adhesive paper tape around its border to prevent the escape of neonate larvae. Dishes were incubated at 24 ± 1 °C and 65 % relative humidity in the laboratory for 5 days. After this period, the number of hatched eggs was counted by observation under a stereomicroscope, recognising that the majority of eggs hatch at 72–96 hours after oviposition. Recently hatched larvae were provided with access to food by placing two pieces of *Drosophila* artificial diet (4 × 4 × 20 mm) at opposite edges of the fabric. The diet consisted of sugar, corn flour, yeast, and agar (Dalton *et al*. 2011) and was known to be palatable to neonate *D. planipalpis* (R. Lasa, unpublished data). The mortality of neonate larvae was also registered after 5 days by counting living and dead neonates. Larvae that did not respond to a gentle touch were considered to be dead. Eight replicates were conducted for each insecticide using different batches of eggs.

Mortality of second- and third-instar larvae

Larval mortality on radishes was evaluated using two different methodologies: (1) a conventional foliar spray applied directly to the neck of the plant, and (2) root irrigation. Radishes that were 2.5–4 cm in diameter were prepared by trimming almost all the leaves except for one or two small leaves in the centre of the neck. Radishes were disinfected by immersion in a 0.08% (wt/vol) sodium hypochlorite solution for 10 minutes, rinsed in tap water, and allowed to dry for 2 hours at 24 °C. Radishes then were transplanted into 280-mL cardboard cups (Uline, Monterrey, Mexico) filled with a commercial compost (Happy Flower, Chedraui, Mexico) and were irrigated with tap water. Cups were placed in laboratory cages (30 cups/cage) and illuminated with LED light strips (3500–4000 lux) for 3 days for acclimatisation. On the third day after transplanting, a moist piece of fabric (10 × 10 mm) carrying 10 eggs of *D. planipalpis* (1–2 days old) was placed around the neck of each plant. Radishes remained in the laboratory cages for 6 more days for eggs to hatch and initial larval development to occur within the plant tissue. After this period, larvae had reached the second- and third-instar stages, and radishes were treated either by spraying or root irrigation.

In the spray treatment, each radish was sprayed with 5 mL of water (control) or insecticide solution (Table 1) using a hand sprayer (Glendy Industrial, Jalisco, Mexico) targeted at the neck of the radish plant. In the root irrigation treatment, each radish was irrigated with 30 mL of water (control) or insecticide solution prepared at 50% of the concentration indicated in Table 1. The volumes of spray and irrigation applications were based on conventional practices in broccoli production (typically 250 L/ha for spray applications and 1500 L/ha for irrigation considering a density of 50 000 plants/ha).

Insecticides selected for foliar spray and root irrigation were based on previously reported systemic or translaminar activity (Thompson *et al*. 2000; Shimokawatoko *et al*. 2012; Zhang *et al*. 2023). In this case, the biological insecticides — spinosad, *S. feltiae,* and *B. thuringiensis* — were included in some of the experiments at the request of organic broccoli growers who needed additional biological tools for the control of *D. planipalpis*. Insecticides were applied outdoors to prevent cross-contamination. Radishes were placed into laboratory cages at 1 hour after application and incubated for 5 days under laboratory conditions. Radishes were then carefully dissected, and the number of living and dead larvae recovered from plants was counted to calculate the percentage of mortality. The percentage of radishes that hosted at least one living larva was also recorded. Between 10 and 13 replicates (one radish per replicate) were conducted for each product and its respective control.

Mortality of pupae and adults

Groups of 10 pupae, aged 1– 4 days, were collected from rearing containers and placed in small cups of aluminum foil (10 mm diameter × 5 mm depth) that were crafted in the laboratory. To evaluate the influence of insecticides on adult emergence, a 30-µL volume of water (control) or insecticide solution was applied by micropipette to each small foil cup. Pupae remained in contact with the water or insecticide solution for 20 minutes before being transferred to 475-cm^3 plastic cups containing a 2-mm layer of vermiculite. To promote aeration and prevent fungal growth, the plastic cups were covered with a fine nylon gauze (0.1-mm mesh) and moistened at two-day intervals with 0.3% sodium benzoate solution. Twelve replicates (10 pupae each) were performed for each of the products, except for spirotetramat (10 replicates). Cups were checked daily over a 12-day period to record the number of adults that emerged from pupae. The experiment was performed under controlled laboratory conditions at 24 ± 1 °C and 65% relative humidity with a 12:12-hour (light:darkness) photoperiod. At emergence, adults were transferred to clean 475-cm^3 plastic cups containing water and food (3:1 sugar:hydrolysed protein) and monitored for mortality over a 12-day period. Flies that exhibited no movement upon contact with a small paintbrush were considered to be dead.

Because no adults emerged from pupae treated with Kloster EC (pyriproxyfen) at 0.5 mL/L, a second experiment was performed with an identical methodology except that Kloster EC was applied to pupae at concentrations of 0.1, 0.05, and 0.005 mL/L or a water control. The experiment was replicated using 12 batches of pupae on separate days. The percentage of adult emergence from pupae and adult mortality over 12 days after emergence was evaluated.

Statistical analysis

The percentages of mortality of adults, larvae, and neonates, the percentage of egg hatch, and adult emergence were compared using a nonparametric Kruskal–Wallis test, followed by Dwass–Steel–Critchlow–Fligner (DSCF) pairwise comparisons. The results are reported as medians and interquartile ranges. A Chi-squared test was used to compare the frequencies of radishes hosting at least one living larva across insecticide treatments. All analyses were performed using the R-based package Jamovi, version 2.5 (The Jamovi Project 2024).

Results

Contact toxicity in adults

The two pyrethroid insecticides were the only products that caused knockdown of adult flies 1 hour after treatment. The median (interquartile range; IQR) percentage of knocked-down flies was similar for bifenthrin 100% (100–100%) and lambda-cyhalothrin 80% (73–88%). However, a large fraction of these flies subsequently recovered and were counted as alive in the 23-hour evaluation. The percentage of mortality of flies at 23 hours post-treatment differed markedly among the different products (Kruskal–Wallis: $H = 46.2$, $df = 11$, $P < 0.001$). Flies exposed to bifenthrin residues had the highest mortality, whereas all the other products resulted in mortalities of less than approximately 15%, similar to that of the control (Fig. 1).

Ovicidal effects and neonate mortality

The percentage of egg hatch differed significantly among insecticides (Kruskal–Wallis: $H = 46.0$, $df = 13$, $P < 0.001$). The only insecticide with significant ovicidal activity was the clothianidin-based product (Fig. 2), whereas egg hatch in all the other treatments was similar to that of the control.

The percentage of mortality observed in neonate larvae also differed significantly among the insecticides (Kruskal–Wallis: $H = 117.0$, $df = 13$, $P < 0.001$). Products based on bifenthrin, lambda-cyhalothrin, clothianidin, imidacloprid, thiamethoxam, spinetoram, and spinosad all resulted in neonate mortalities of 80–100%, which were significantly higher than that observed in the control (~15%; Fig. 3). Neonate mortalities in the organic-approved insecticides (*Tagetes* (Asteraceae) extract, *S. feltiae*, and *B. thuringiensis*) and the systemic spirotetramat-based product were similar to that of the control, whereas the neem (Meliaceae) oil– and pyriproxyfen-based products resulted in intermediate percentages of neonates mortality.

Mortality in larvae of the second- and third-instar stages

The percentage of larval mortality at the second- and third-instar stages varied significantly following spray application of products (Kruskal–Wallis: $H = 65.0$, $df = 8$, $P < 0.001$; Fig. 4A). The thiamethoxam- and spinetoram-based products resulted in the highest levels of larval mortality, followed by the clothianidin- and spinosad-based products (Fig. 4A). The imidacloprid-based product and the nematode *S. feltiae* generated intermediate levels of mortality that were similar to those observed in insects treated with the spirotetramat- and *B. thuringiensis*–based products and the control (Fig. 4A).

When insecticides were applied through root irrigation, the percentage of larval mortality also differed significantly among products (Kruskal–Wallis: $H = 65.0$, $df = 8$, $P < 0.001$), and only the systemic neonicotinoid-based products (thiamethoxam, clothianidin, and imidacloprid) resulted in high levels of mortality (75–100%) of second- and third-instar larvae (Fig. 4B).

Radishes were infested with a mean (± standard error) number of larvae that varied between 1.9 ± 0.3 and 3.9 ± 0.5 larvae per radish in the spray application experiment and between 1.3 ± 0.4 and 4.3 ± 1.0 larvae per radish in the root irrigation experiment. Upon inspection at the end of the experiments, 100% of the control radishes contained at least one living larva of *D. planipalpis*. However, the percentage of radishes that contained at least one living larva differed significantly among insecticides following a spray application ($\chi^2 = 55.8$, $df = 8$, $P < 0.001$; percentage values in the box at the top of Fig. 4A) or root irrigation ($\chi^2 = 47.8$, $df = 6$, $P < 0.001$; percentage values in the box at the top of Fig. 4B). The thiamethoxam-based product was the most effective in controlling larvae, with less than 10% of radishes containing a living larva irrespective of the application method.

Adult emergence of treated pupae and subsequent adult mortality

No adults emerged from pupae treated with 0.5 mL/L of the pyriproxyfen-based product, whereas all the other products resulted in adult emergence of 50–70%, similar to that of the control (Kruskal–Wallis: $H = 41.1$, $df = 11$, $P < 0.001$; Fig. 5).

In treatments in which adult flies emerged, a similar but low fly mortality (5–14 %) was observed among products during the 12-day period after emergence, compared to 10% (10–10%; median, IQR) in the control (Kruskal–Wallis: $H = 15.5$, $df = 11$, $P = 0.161$; data not shown).

The percentage of adults that emerged from pupae treated with the pyriproxyfen-based product at different concentrations (0.1, 0.05, and 0.005 mL/L) was significantly lower than that observed for the control pupae (Kruskal–Wallis: $H = 35.3$, $df = 3$, $P < 0.01$; Fig. 6). Even at the lowest product concentration (0.005 mL/L), adult emergence was half that observed for the control.

The median (IQR) mortality of flies at 12 days after emergence also differed markedly between the control 10% (10–10%) and pyriproxyfen-treated insects, which varied from 100% (100–100%) mortality for 0.1 mL/L (n = 3) and 100% (88–100%) for 0.05 mL/L (n = 14), compared to 50% (46–100%) mortality for 0.005 mL/L (n = 22) treated insects (Kruskal–Wallis: $H = 21.3$, $df = 3$, $P < 0.01$).

Discussion

This study evaluated the efficacy of various insecticidal products against each of the developmental stages of *D. planipalpis* through laboratory bioassays. Both females and males of this pest achieve rapid sexual maturation, with females commencing oviposition just 3 days after emergence (Córdova-García *et al*. 2023). This reduces the window for effective fly control and necessitates the use of products that act swiftly against adults. Only the pyrethroid bifenthrin dry residues resulted in moderate adult mortality (median 61%) at 23 hours after exposure. Although the lambda-cyhalothrin residues induced a substantial knockdown effect (median > 80% mortality) on adult flies within 1 hour of exposure to residues, most of these flies recovered, with less than 20% median mortality observed after 23 hours. Under field conditions, knocked-down flies are likely to be susceptible to predation by birds or invertebrate predators while lying on the soil surface during the recovery period, although the magnitude of such predation is difficult to quantify. None of the other insecticidal products tested in the present study produced mortalities significantly higher than that observed for the control.

The clothianidin-based product was the only insecticide that exhibited moderate ovicidal activity. The ovicidal effect of clothianidin, but not of thiamethoxam, has also been documented for the weevil, *Conotrachelus nenuphar* (Hoffmann *et al*. 2008), despite thiamethoxam being a precursor of clothianidin (Nauen *et al*. 2003). These differences in ovicidal activity appear to correlate with the octanol–water partition coefficient of these compounds. The lipid layers of the egg chorion generally serve as a barrier to hydrophilic substances that are characterised by a low octanol–water partition coefficient (Smith and Salkeld 1966). Clothianidin, with a higher partition coefficient, permeates the chorion, whereas thiamethoxam is less likely to reach target sites within the embryo (Hoffmann *et al*. 2008). Kirkpatrick *et al*. (2005) reported similar findings for lepidopteran eggs exposed to acetamiprid (with a higher octanol–water partition coefficient) that demonstrated higher ovicidal activity than the more hydrophilic compounds thiamethoxam and imidacloprid.

Despite the absence of ovicidal activity, products based on bifenthrin, lambda-cyhalothrin, clothianidin, imidacloprid, thiamethoxam, spinetoram, and spinosad were all found to be highly toxic to neonate *D. planipalpis* larvae. Notably, the pyrethroid- and neonicotinoid-based products killed many neonates immediately following eclosion, as dead larvae were observed to have died while trying to cross the treated fabric, whereas larvae in the spinosad and spinetoram treatments were mostly observed to have died after reaching the pieces of diet.

A high prevalence of second- and third-instar larvae developing inside radish plants were killed by the neonicotinoid-based products (thiamethoxam, clothianidin, and imidacloprid) applied through root irrigation. None of the other products showed systemic activity. Neonicotinoids are primarily absorbed by roots and translocated *via* the xylem, providing protection against various pests (Zhang *et al*. 2023). Although some systemic activity of spinosad was previously reported in tomato plants when administered at the base of the stem (Van Leeuwen *et al*. 2006), the low mortality of larvae observed in our experiment after root irrigation suggests that spinosad was not effectively taken up or transported in radish plants.

In contrast to root irrigation, spray application to the neck of the radish plants resulted in larval mortality following treatment with products based on thiamethoxam, clothianidin, spinosad, and spinetoram. However, the imidacloprid-based product was not effective when applied as a spray. Neonicotinoids are absorbed by leaves to a lesser extent than they are through the roots (Zhang *et al*. 2023). Thiamethoxam and clothianidin are considered to be phloem-transported insecticides, whereas imidacloprid is primarily translocated *via* the xylem (Nauen *et al*. 2003; Weichel and Nauen 2004), which could explain the variations in larval mortality observed among these products when applied as a spray. Indeed, the uptake and translocation of neonicotinoids can vary with plant species, environmental conditions, and application method (Zhang *et al*. 2023), which must be considered when extrapolating our results for the control of *D. planipalpis* in broccoli.

Spinosad and spinetoram have low mobility in the soil and do not move within the plant’s vascular system. However, both products exhibit translaminar activity and can penetrate leaf tissue (Thompson *et al*. 2000; Shimokawatoko *et al*. 2012), thereby improving pest control when applied as foliar sprays. The structure of the neck of radish plants, with a crown of leaves that retains some of the spray liquid, may have contributed to the absorption of these active ingredients and their effectiveness against *D. planipalpis* larvae that primarily feed on the radish neck before burrowing into the root. These plant structures and the larval feeding behavior are quite different on broccoli seedlings, where foliar sprays may not be as effective as suggested by our results. In this case, root irrigation remains a potentially viable control option.

We observed intermediate mortality of larvae following application of the nematode *S. feltiae* by root irrigation and foliar sprays that was similar to that of the control. Previous studies on *S. feltiae* for the control of *D. antiqua* and *D. platura* in onions reported that this pathogen needs to be improved or complemented with other control tactics (Chen *et al*. 2003; Ellis and Scatcherd 2007; Beck *et al*. 2014). Our other assays involving neonates or pupae were probably not well suited to the mode of action of this nematode and resulted in consistently low pest mortality.

The emergence of adults from insecticide-treated pupae was similar among all products tested and the control (60–65%), with the exception of the pyriproxyfen-based product that resulted in a reduction in adult emergence that varied with product concentration (Figs. 5 and 6). According to Zhou *et al*. (2016), application of pyriproxyfen (50 mg/kg) to onions infested with *D. antiqua* did not affect larval survival and pupation, but resulted in adult emergence that was approximately 30% lower than the control. Treatment of pupae with pyriproxyfen can also greatly reduce adult emergence in other dipteran pests of agricultural (Casaña-Giner *et al*. 1999; Sánchez-Ramos *et al.* 2024) and veterinary importance (Langley *et al*. 1990; Bull and Meola 1993). The marked reduction in adult emergence and reduced adult longevity makes pyriproxyfen-based products a strong candidate for field testing using a root irrigation approach because *D. planipalpis* pupates in the soil close to the root and the pupal stage lasts approximately two weeks at 24 °C (Córdova-García *et al*. 2023). However, exposure to nonlethal concentrations of this compound has been reported to lead to increased egg production in *D. antiqua* (Zhou *et al*. 2016) and the tephritid *Rhagoletis pomonella* (Duan *et al*. 1995), which would likely have an adverse effect on crop protection and requires consideration in future studies.

Despite its systemic properties, the spirotetramat-based product was ineffective in controlling any stage of *D. planipalpis*. The primary targets of spirotetramat are insects that feed on plant sap, rather than larvae that feed on roots (Fischer and Weiss 2008). The bacterial insecticide Gnatrol, which is based on *B. thuringiensis* var. *israelensis*, and the botanical products based on *Tagetes* extract or neem oil failed to kill significant numbers of larvae, pupae, or adults of *D. planipalpis* in the present study. Insecticides based on *B. thuringiensis* are activated in the gut of phytophagous insects (Pinos *et al*. 2021). Insecticide compounds, including photoactive thiophenes, have been isolated from *Tagetes* spp. and have been found to be biologically active against some dipteran species (Perich *et al*. 1995; Ravikumar 2010) but of limited practical use because of their volatility and poor persistence (Isman 2006). Neem oil exerts its effects through repellency, antifeedant properties, and disruption of the ecdysone hormone that regulates insect moulting (Benelli *et al*. 2017).

Conclusion

We conclude that neonicotinoids, particularly thiamethoxam applied *via* spray or root irrigation, are likely to be the most effective products for controlling *D. planipalpis* in broccoli, whereas clothianidin showed slightly less satisfactory results in the laboratory setting. The imidacloprid-based product was the least effective of the neonicotinoids but remains a potential option *via* root irrigation. The spinetoram-based product was highly effective when applied to the stem oviposition site as a spray. Pyriproxyfen was highly effective in preventing adult emergence and appears promising for root irrigation application. The pyrethroid-based products were not highly active for control of adult flies. Of the other insecticides tested, spinosad and the nematode, *S. feltiae,* had intermediate efficacy as standalone treatments but could complement other control strategies in organic production. Field testing in commercial broccoli production is essential to confirm the efficacy of these insecticides and to provide growers with the most effective tools for *D. planipalpis* management.

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Author contributions. GC, TW and RL conceived research. GC and RL conducted experiments. RL contributed material. TW and RL analysed data and conducted statistical analyses. GC, TW and RL wrote the manuscript. RL secured funding. All authors have read and approved the manuscript.

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Table 1. Insecticides registered in Mexico for the control of different pests of broccoli and tested against *Delia planipalpis*

Active ingredient (a.i.)	Product name (a.i. %)	Concentration tested	Concentration a.i.
Synthetic products			
Bifenthrin (pyrethroid)	Seizer 10 EC (10.87%)	1 mL/L	100 mg/L
Lambda-cyhalothrin (pyrethroid)	Karate Zeon 5 SC (5.15%)	1 mL/L	70 mg/L
Thiamethoxam (neonicotinoid)	Actara 25 WG (25%)	1 g/L	250 mg/L
Clothianidin (neonicotinoid)*	Clutch SC (23.6%)	1 mL/L	257 mg/L
Imidacloprid (neonicotinoid)	Helmfidor SC (30.20%)	1 mL/L	350 mg/L
Spirotetramat (tetramic acid)	Movento 150 OD (15.30%)	1 mL/L	150 mg /L
Spinetoram (spinosoid)	Palgus SC (5.87%)	0.6 mL/L	36 mg/L
Pyriproxyfen (growth regulator)	Kloster EC (11.11%)	0.5 mL/L	51.5 mg/L
Organic-approved products			
Neem oil (botanical)	Neem EC 80 (80.9%)	4 mL/L	3200 mg/L
Tagetes extract (botanical)	Retrix4 EC (90% Tagetes extract)	10 mL/L	9000 mg/L
Spinosad (spinosyns)	Spintor 12 SC (12%)	0.2 mL/L	24 mg/L
Bacillus thuringiensis subsp. *israelensis* (entomopathogen)	Gnatrol (37.4%)	8 g/L	2992 mg/L
Steinernema feltiae (entomopathogen)	Entonem (250 million)	10^7 nematodes/L	10^7 nematodes/L

Product manufacturers: Seizer 10 EC, Aldama Ltd, Mexico City; Karate Zeon 5 SC, Syngenta de México, Mexico City; Actara 25 WG, Syngenta de México, Mexico City; Clutch SC, Valent de México, Zapopan, Mexico; Helmfidor SC, Helm de México, Naucalpan de Juárez, Mexico; Movento 150 OD, Bayer, Mexico City; Palgus SC, Corteva Agriscience, Guadalajara, Mexico; Kloster EC, Proveedor de Insumos Agropecuarios y Servicios, Cualiacán, Mexico; Retrix4 EC, Química Lucava, Celaya, Mexico; Spintor 12 SC, Corteva Agriscience, Guadalajara, Mexico; Gnatrol, Valent de México, Zapopan, Mexico; Entonem, Koppert México, Querétaro, Mexico.

*Clothianidin is currently pending final approval by the Mexican regulatory authorities for use on broccoli.

Figure legends

Figure 1. Box-plot of the percentage mortality of *D. planipalpis* flies after contact with the dry residues of different insecticides. The median (horizontal bar), interquartile range (box), range (vertical whisker), and outliers (dots) are shown. Treatments labelled with different letters differ significantly (DSCF, $P < 0.05$).

Figure 2. Box-plot of the percentage of egg hatch in *D. planipalpis* after contact with the residues of different insecticides. The median (horizontal bar), interquartile range (box), range (vertical whisker), and outliers (dots) are shown. Treatments labelled with different letters differ significantly (DSCF, $P < 0.05$).

Figure 3. Box-plot of the percentage mortality of neonate larvae of *D. planipalpis* after contact with the residues of different insecticides. The median (horizontal bar), interquartile range (box), range (vertical whisker), and outliers (dots) are shown. Bars labelled with different letters differ significantly (DSCF, $P < 0.05$).

Figure 4. Box-plot of the percentage of larval mortality in *D. planipalpis* after the treatment of radish plants with different insecticides by **A**, spray application, and **B**, root irrigation. The median (horizontal bar), interquartile range (box), range (vertical whisker), and outliers (dots) are shown. Values in the box above each figure indicate the percentage of radishes that contained at least one living larva. Treatments or percentage values labelled with different letters differ significantly (DSCF, $P < 0.05$).

Figure 5. Box-plot of the percentage of adult emergence in *D. planipalpis* after the treatment of pupae with different insecticides. The median (horizontal bar), interquartile range (box), range (vertical whisker), and outliers (dots) are shown. Treatments labelled with different letters differ significantly (DSCF, $P < 0.05$).

Figure 6. Box-plot of the percentage of adult emergence in *D. planipalpis* after the treatment of pupae with different concentrations of a pyriproxyfen-based product. The median (horizontal bar), interquartile range (box), range (vertical whisker), and outliers (dots) are shown. Treatments labelled with different letters differ significantly (DSCF, $P < 0.05$).

Fig 1.

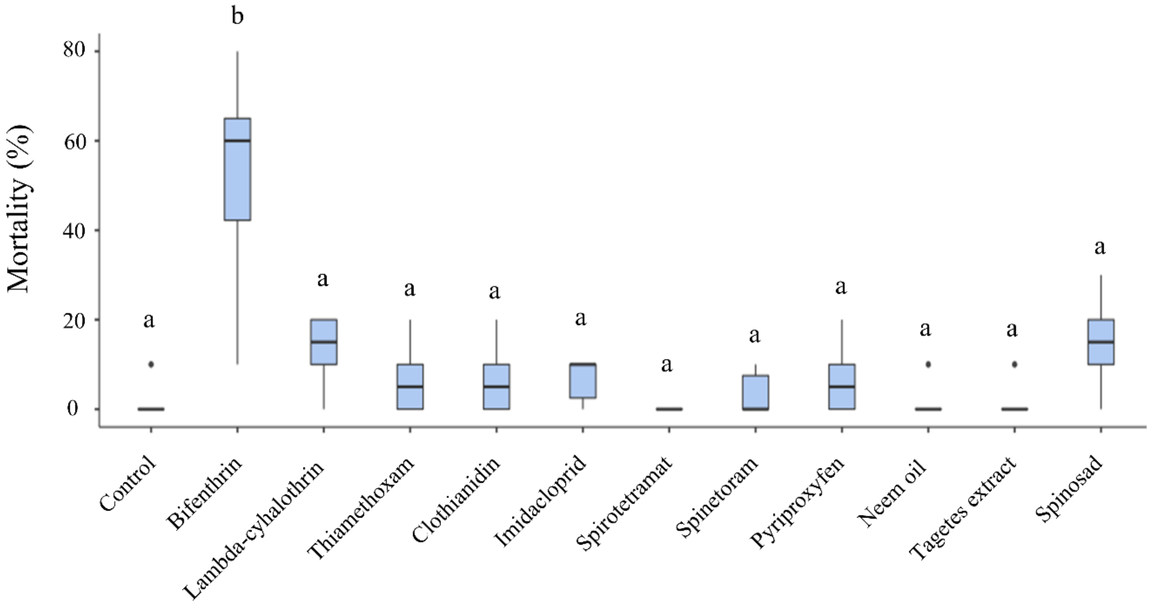
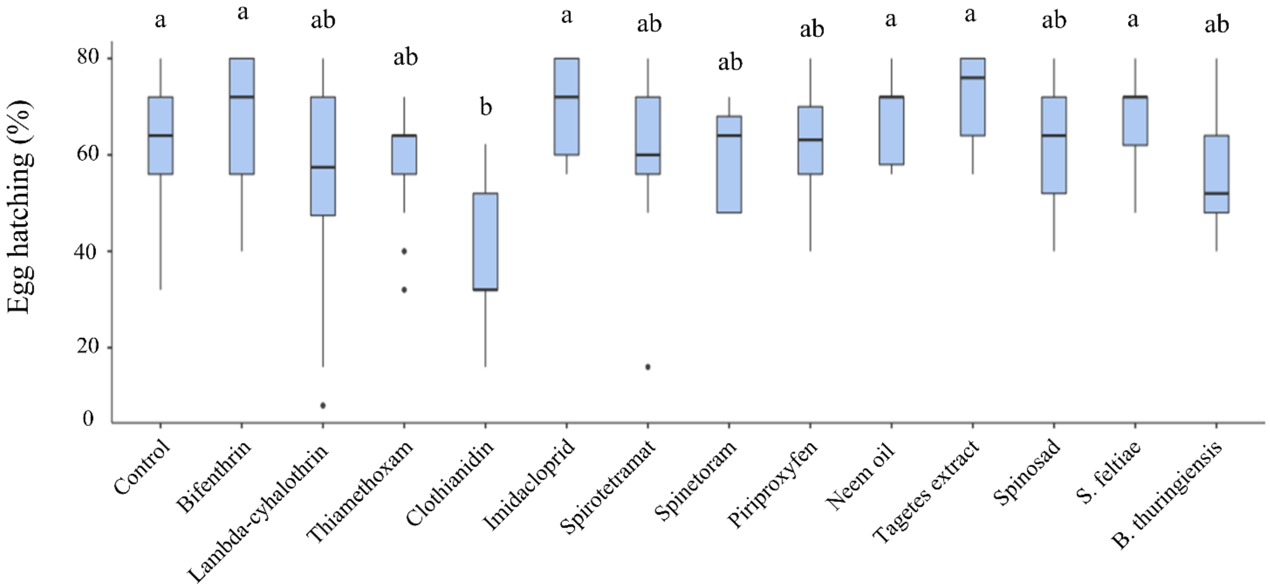
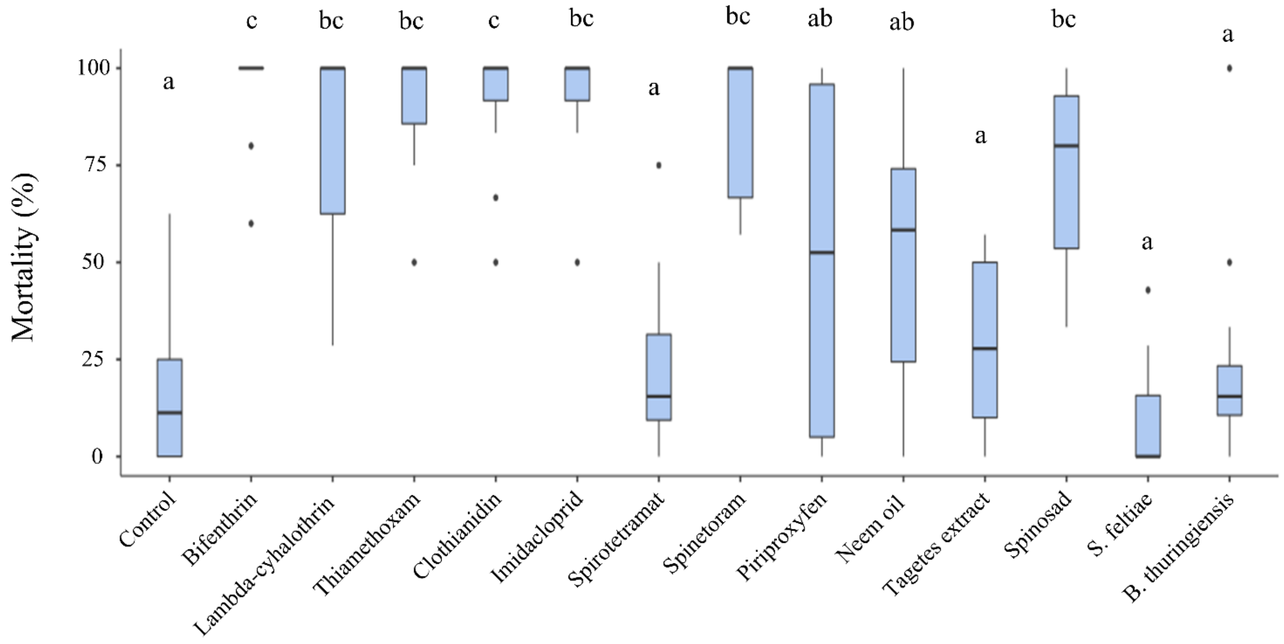

b
a
a
a
a
a
a
a
a
a
a
a
80
60
40
20
0
Mortality (%)
Control
Bifenthrin
Lambda-cyhalothrin
Thiamethoxam
Clothianidin
Imidacloprid
Spirotetramat
Spinetoram
Pyriproxyfen
Neem oil
Tagetes extract
Spinosad

Fig. 2



Egg hatching (%)
0
20
40
60
80
a
a
ab
ab
b
a
ab
ab
ab
a
a
ab
a
ab
Control
Bifenthrin
Lambda-cyhalothrin
Thiamethoxam
Clothianidin
Imidacloprid
Spirotetramat
Spinetoram
Piriproxyfen
Neem oil
Tagetes extract
Spinosad
S. feltiae
B. thuringiensis

Fig. 3



Mortality (%)
0
25
50
75
100
a
c
bc
bc
c
bc
a
bc
ab
ab
a
bc
a
a
Control
Bifenthrin
Lambda-cyhalothrin
Thiamethoxam
Clothianidin
Imidacloprid
Spirotetramat
Spinetoram
Piriproxyfen
Neem oil
Tagetes extract
Spinosad
S. feltiae
B. thuringiensis

Fig 4.

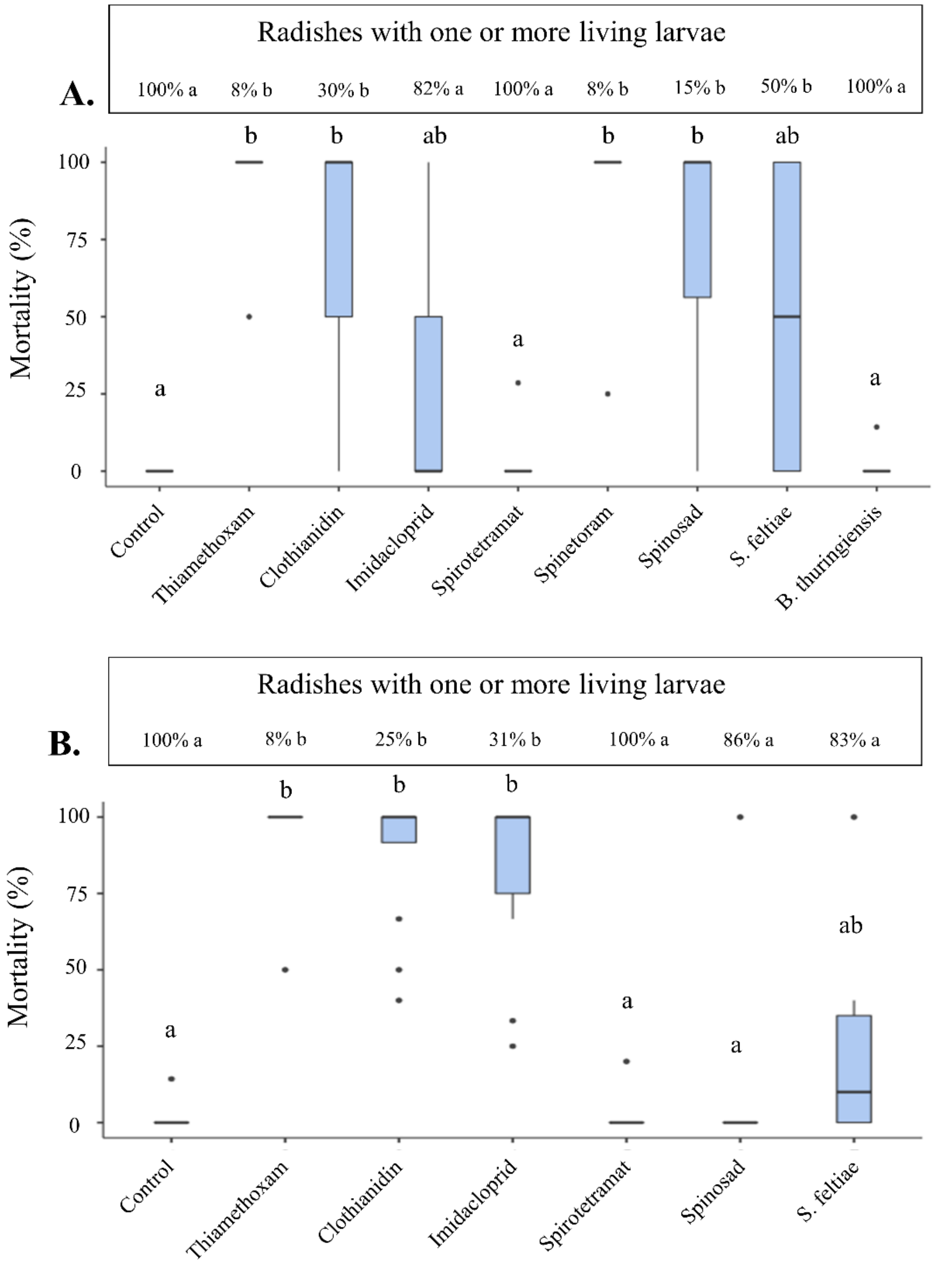

A.
Radishes with one or more living larvae
100% a
8% b
30% b
82% a
100% a
8% b
15% b
50% b
100% a
b
b
ab
b
b
ab
a
a
a
Mortality (%)
100
75
50
25
0
Control
Thiamethoxam
Clothianidin
Imidacloprid
Spirotetramat
Spinetoram
Spinosad
S. feltiae
B. thuringiensis
B.
Radishes with one or more living larvae
100% a
8% b
25% b
31% b
100% a
86% a
83% a
b
b
b
ab
a
a
a
Mortality (%)
100
75
50
25
0
Control
Thiamethoxam
Clothianidin
Imidacloprid
Spirotetranat
Spinosad
S. feltiae

Fig 5.

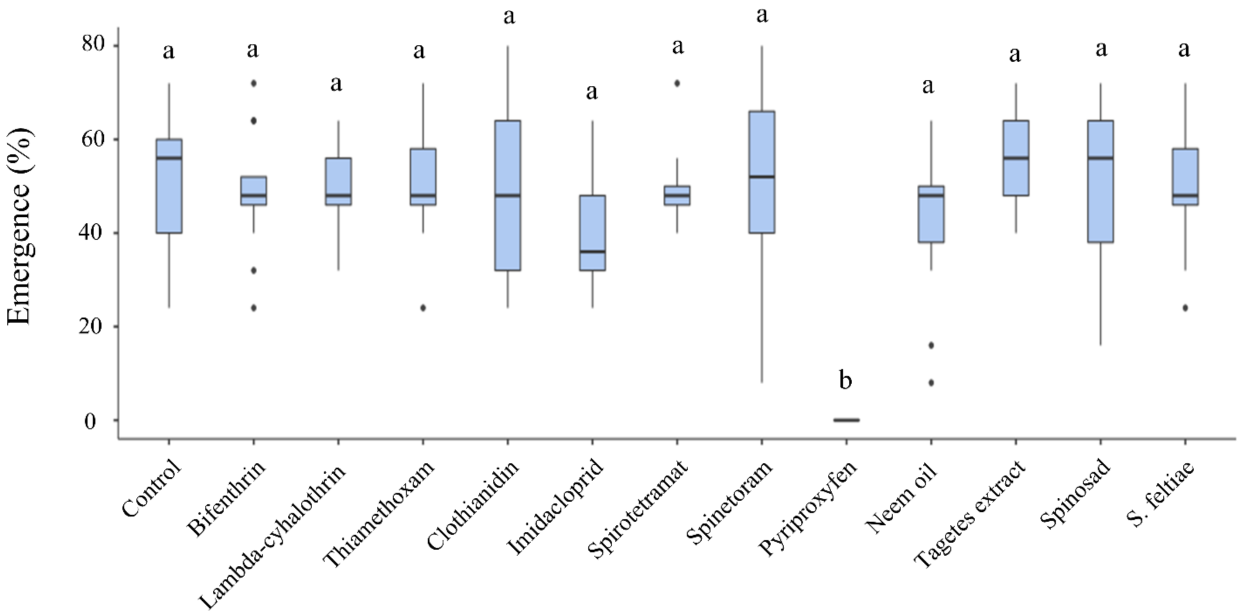
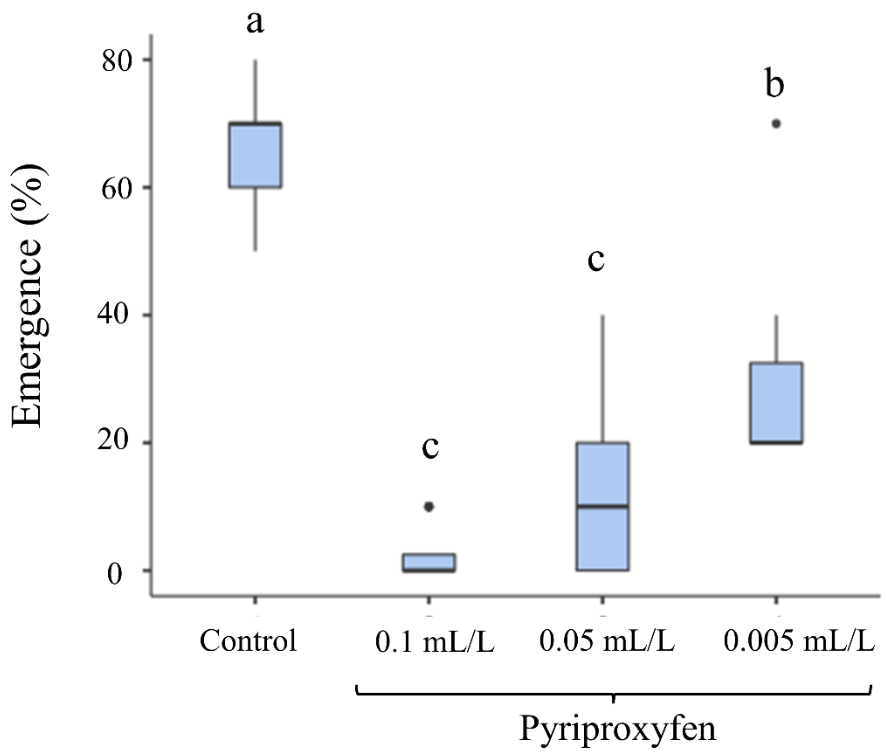

Emergence (%)
0
20
40
60
80
a
a
a
a
a
a
a
a
b
a
a
a
a
Control
Bifenthrin
Lambda-cyhalothrin
Thiamethoxam
Clothianidin
Imidacloprid
Spirotetramat
Spinetoram
Pyriproxyfen
Neem oil
Tagetes extract
Spinosad
S. feltiae

Fig 6.


Emergence (%)
80
60
40
20
0
a
c
c
b
Control
0.1 mL/L
0.05 mL/L
0.005 mL/L
Pyriproxyfen