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Pepper weevil, Anthonomus eugenii (Coleoptera: Curculionidae) suppression on jalapeño pepper using non-host insect repellent plants

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ABSTRACT

Pepper weevil, *Anthonomus eugenii* Cano is the most harmful insect pest of pepper, *Capsicum annum* L., an important crop in Florida and several other states in the southern region of the United States. All commercially cultivated peppers, including jalapeño peppers, are susceptible to pepper weevil. The use of broad-spectrum insecticides is the primary management tool for controlling pepper weevil. Their continuous use has led to the development of resistance and elimination of natural enemies. Therefore, alternative approaches are needed for effective control. Studies were conducted to evaluate the effectiveness of intercropping non-host insect repellent plants (*Ocimum basilicum* L. (basil), *Tagetes patula* L. (marigold), *Brassica oleracea* L. (cabbage), and *Coriandrum sativum* L. (cilantro)) with jalapeño pepper on pepper weevil population suppression. Each of the four non-host plants consisted of individual treatments and were compared to a jalapeño pepper only (untreated control), or a jalapeño pepper with a standard insecticide regimen of thiamethoxam (positive control). Parameters evaluated include the number of pepper weevil adults on plants, number of infested fallen fruit, and marketable yield. Infested fruit collected from each treatment plot were dissected to evaluate pepper weevil (adult, pupae, and larvae) density. The non-host plant treatments reduced the number of pepper weevil adults found on jalapeño plants, infested fruit, and pepper weevils in infested fruit but not marketable yield when compared with the control treatment. This information is a step forward into finding a sustainable approach for the management of pepper weevil.

1. Introduction

Pepper, *Capsicum annum* L. is one of the five most-cultivated species of the plant genus *Capsicum* in tropical and temperate regions (Dagnoko et al., 2013). Florida is the second-largest producer of bell peppers in the USA. Serrano, jalapeño, guajillo, and poblano are varieties of *C. annuum* cultivated worldwide (Katz, 2009). There are several varieties of hot peppers, including 'habanero', 'ancho', 'poblano', and 'jalapeño' which vary in shape, taste, and in degree of pungency (Kaiser and Ernst, 2018). The demand for hot peppers is increasing due to their increased use in cuisines of many ethnic groups. The increased year-round demand for sweet and hot peppers has created attractive markets for tropical and subtropical production during the winter season when supplies are scarce. Growers have responded by increasing efforts to grow more peppers. The total value of the 2017 crop in Florida was $206 million, 32% of the total US value.

In Florida, peppers are grown in open fields using the raised bed system covered with plastic mulches and drip tubes for irrigation. The raised beds are efficient for holding moisture, fertilization, and fumigants due to low water holding capacity of most Florida soils (Dukes et al., 2003). Pepper is produced using conventional methods where growers depend mainly on broad-spectrum insecticides to manage insect pests. However, the use of insecticides can have undesirable effects on the environment. Some adverse effects of broad-spectrum insecticides include the development of resistance in primary pests, the resurgence of secondary pests, and the elimination of natural enemies (Vasquez et al., 2005; Servin-Villegas et al., 2008). Therefore, the search for alternative strategies for minimizing the use of broad-spectrum insecticides and reducing risks to both the environment and humans has been on the rise in recent decades.

The pepper weevil, *Anthonomus eugenii* Cano (Coleoptera: Curculionidae), is the most harmful insect pest of pepper in Florida and other

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tropical and subtropical regions of North, Central, and South America (Elmore et al., 1934; Riley and Sparks, 1995; Toapanta, 2001). Feeding by adult weevils causes damage to fruits, flowers, and buds, while oviposition and larval feeding reduces marketable fruit production (Rodriguez-Leyva, 2006). All immature life stages develop within fruits, and thus, insecticides sprayed for control of adult pepper weevils do not affect these stages (Elmore et al., 1934; Rodriguez-Leyva, 2006).

To avoid sole reliance on broad-spectrum insecticides, it is important to integrate other control strategies, such as cultural control, biological control, the use of bio-rational insecticides, attract and kill methods using pheromones, and non-host repellent plants to suppress pepper weevil adults. To develop a successful management program, a detailed understanding of the use of different tactics and knowledge about the pest biology and ecology is vital (Pedigo and Rice, 2009).

The use of push-pull tactics can be an efficient technique in reducing pest populations without the use of or limited use of insecticides (Cook et al., 2007). The push-pull strategy involves combining different techniques, such as the use of chemical and visual cues to modify pest behavior and abundance. A push strategy consists of using non-host repellent or deterrent plants by intercropping with the main crop making it difficult for pests to locate plants in the main crop (Cook et al., 2007). In contrast, the pull strategy involves using attractive plants or stimuli or trap crops that distract pests from the main crop, thereby attracting them to where they are eventually killed. By reducing the number of broad-spectrum insecticide sprays on the target crop, this approach can lead to an increase in the number of predators and parasitoids of insect pests, with reduced negative health impacts to humans and the environment (Khan et al., 2006; Cook et al., 2007). It is crucial to understand pest specificity, sensory ability, and mobility to develop a sustainable and reliable push-pull strategy. It is also important to understand the properties and the mechanisms of action of the plants used as intercrop or trap crops (Cook et al., 2007).

Intercropping is a cultural practice usually employed by small-scale farmers in tropical regions to maximize profit by intensively using their farmlands for crop production (Talekar and Shelton, 1993). Intercropping repellent plants with the main crops has been documented to be effective in reducing pest populations (Talekar and Shelton, 1993; Smith and Liburd, 2012). When planted near cabbage (*Brassica oleracea* L.), tropical basil (*Ocimum basilicum* L.) can reduce the damage exerted on cabbage by the webworm (*Hellula undalis* (Fabr.)), diamondback moth (*Plutella xylostella* (L.)), and cotton leafworm (*Spodoptera littoralis* (Bosduval)) (Yarou et al., 2017). Furthermore, basil plants and their essential oil deterred oviposition of the leafminer (*Tuta absoluta* (Meyrick)) on tomato plants (*Solanum lycopersicum* L.) (Yarou et al., 2018). Another plant, marigold (*Tagetes patula* L.) has been reported to have nematicidal properties. It has been intercropped with various crops to suppress nematode populations (Hooks et al., 2010) and other harmful pests, including the carrot rust fly (*Psila rosae* (Fabricius)) (Jankowska et al., 2012). Planting marigolds and other non-hosts of whiteflies (*Trialeurodes vaporariorum* (Westwood)), including basil next to tomato plants, can reduce the population of whiteflies on tomato plants (Conboy et al., 2019).

Intercropping crops with aromatic or repellent plants also has the potential to reduce pest populations and increase the composition and population of potential natural enemies, resulting in the enhancement of biological control of both target and non-target pests (Song et al., 2013). For instance, the number of natural enemies (such as *Chrysoperla sinica* Tjeder, *Chrysoperla formosa* Brauer, *Epistrophe balteata* De Geer, and *Coccinella septempunctata* L.) of the green citrus aphid, *Aphis citricola* van der Goot, was significantly higher in apple orchards in plots intercropped with basil (*Ocimum basilicum* L.) and French marigold (*T. patula*) than in plots with natural vegetation (Song et al., 2013). Natural enemies were high in okra (*Abelmoschus esculentus* L.) plots intercropped with coriander (*Coriandrum sativum* L.), marigold (*Tagetes* spp.), and mint (*Mentha* spp.) (Sujayanand et al., 2016). Consequently, intercropping okra with marigold reduced the whitefly, *Bemisia tabaci* (Gennadius) population, and reduced infestation by the fruit borer, *Earias vittella* (Fab.) (Sujayanand et al., 2016). However, further efforts are needed to incorporate these types of management strategies for pepper weevil control.

Considering the vital role some non-hosts, insect repellents, and aromatic plants play in suppressing some pests in the cropping system, our main objective of the present study was to evaluate various commonly grown non-host plants (basil, marigold, cilantro, and cabbage) in suppressing pepper weevil in host jalapeño crops, using total yield as a measure of non-host crop pest suppression.

2. Materials and methods

2.1. Study area and field preparation

This study was conducted in two field research plots in 2019–2020, one at the Tropical Research and Education Center (TREC), (25.513°N, −80.504°W) and the other in a grower's field (25.543°N, −80.516°W). The first study was initiated in Dec. 2019 (off-station study) and the second in Jan. 2020 (TREC study). The soil type in both studies was in the Rockdale class. The soil type of the plots was a Krome gravelly loam soil classified as a loamy-skeletal, carbonatic hyperthermia lithic rendoll, which consists of 67% limestone pebbles (>2 mm) and 33% finer particles (Noble et al., 1996). The soil was prepared by plowing the field with a moldboard plow (CASE IH agriculture). The field was disked using a disking machine (Athens Plow Co Inc., TN, USA). Raised beds, 91 cm wide and 15 cm high with 1.83 m between centers, were prepared with Kennco superbedders (Kennco Manufacturing Co. Inc., Atoka, OK, USA). Granular fertilizer (N–P–K: 6-12-12) at the rate of 1344 kg/ha was applied at planting as a broadcast and incorporated within four inches of soil surface before placement of plastic mulch. Then, raised beds were covered with white on black plastic mulch (Canslit Inc. Victoriaville, Quebec, Canada, and supplied by IMAFLEX USA Inc.). The polyethylene mulch was placed on the beds using a plastic mulch layer (Kennco micro-combo, Kennco Manufacturing Co. Inc., Atoka, OK, USA). At the time of laying down plastic mulch, two drip tubes (RO-Drip, Rivulis Irrigation Inc., San Diego, CA, USA) with emitters spacing 30 cm apart, one on each side of the plant row at the center, spacing 15 cm, were placed for irrigation.

For planting pepper transplants, holes (7 cm diameter, 5 cm deep) were made manually using a metallic hole-digger. The plot size in both sites was 4.6 m long 1.82 m wide with a 1.5 m non-planted buffer between adjacent plots on the beds. At TREC and off-station sites, jalapeño pepper (variety PS 11435807) transplants were set on the 23rd of January and the 7th of January, respectively, at the center of the beds with 30 cm spacing within the bed and 90 cm spacing between beds.

2.2. Crop management and establishment

Insecticide free jalapeño pepper transplants, 6-weeks old, were provided by Mobley Plant World LLC, Labelle, FL. Pepper plants in all studies were subjected to recommended cultural practices, including irrigation, weeding, and fertilizer application throughout the season (Vegetable Production Handbook of Florida, 2018–2019). Non-host crops used in the present study included cabbage (*Brassica oleracea* var. *capitate*), cilantro santo (*Coriandrum sativum* var. macrocarpum), Italian large leaf basil (*Ocimum basilicum* var. Italian large leaf), and French marigold (*Tagetes patula* var. bonanza bolero). Non-host crops were selected based on local growers' common practice to plant them alongside with peppers (Florida Growers Association, Personal Communication, October 11, 2017). Cilantro and cabbage seeds were obtained from Harris Seeds Company (Rochester, NY) and grown in 128 cell seedling trays in the greenhouse (27 °C and 70% R.H.) at TREC 5 weeks before transplanting them in the field.

Non-host plants were planted in parallel rows on the edge of the bed on both sides 25.4 cm (10 inches) from the central row of the main crop (jalapeño pepper) one week before transplanting pepper. Immediately after transplant, the main crop and the non-host plants were drenched with a starter fertilizer solution (N–P–K: 20:20:20) 6.16 g/l of water (Diamond R Fertilizer Inc. Ft. Pierce, FL.) using a Birchmeier backpack sprayer (15.14-L Backpack Sprayer, model IRIS, Stetten Switzerland) without a nozzle tip. Each plant was drenched with approximately 59.15 ml of the starter fertilizer solution. After setting in the field, plants were irrigated two times daily, delivering 0.64 cm water each time using the already established drip irrigation system (Ro-Drip, USA) to maintain adequate soil moisture. Granular fertilizer (N–P–K: 6:6:6) (Loveland Products Inc., Greely, CO, USA) was applied four weeks after planting and subsequently every two weeks after the first application. The fertilizer was applied 20 cm from and parallel to the transplants row and was incorporated within the top 15 cm of the soil. Weeding was done manually when required. Bravo Weather Stik® (Chlorothalonil, IRAC group M5 fungicide, Syngenta Crop Protection Inc., Greensboro, NC) was applied one, three, and five weeks after transplanting at 1.75 l/ha to reduce the effect of fungal pathogens.

2.3. Experimental design, treatments, and evaluation

The experimental design was a randomized complete block with six treatments and four replications. The non-host plants described above were considered as treatments. Thus, there were six treatments: four non-host plant intercropped treatments (cabbage, basil, cilantro, and marigold), pepper without any intercropped plants sprayed with thiamethoxam (Actara®) and pepper without any intercropped plants and no insecticide spray (control). In the insecticide treatment, thiamethoxam (Actara®, Syngenta USA, IRAC group 4A) was applied weekly by using a Birchmeier backpack sprayer with two flat fan nozzles (TeeJet, R & D Sprayers INC, Louisiana, USA), delivering 280 l/a at 2.11 kg/cm^2. Occasionally, non-host plants were trimmed to avoid overshadowing the main host crop, jalapeño pepper. Insecticides were sprayed seven and five times in the December 2019 and January 2020 studies, respectively.

Plots were carefully scouted at 48 h intervals starting seven days after planting for seven weeks for the presence of pepper weevils and other insects including green peach aphids (*Myzus persicae* (Sulzer)), beet armyworm (*Spodoptera exigua* (Hübner)) and sweetpotato whitefly B–biotype (*Bemisia tabaci* (Gennadius)) (data not shown) on pepper and non-host crops. The efficacy of the non-host plants was evaluated by visually checking five randomly selected jalapeño pepper plants for each treatment plot and recording the number of pepper weevil adults weekly for seven and five times in the December 2019 and January 2020 studies, respectively. When checking plants for adults, pepper weevil infested fallen fruit were collected from those five plants and placed in a transparent plastic cup with lid (283.5 g), which were marked with the date, treatment, and block. Pepper weevil infested fallen fruit were recognized by the presence of yellow calyx, an indication of pepper weevil infestation, which were found at the base of the plants. The infestation was further confirmed by dissecting each fruit and recording the number of pepper weevil larvae, pupae, and adults. Marketable yield was assessed at the end of the season by harvesting all uninfested fruit/plot and recording their number and weight.

2.4. Statistical analysis

Response variables measured were pepper weevil adults on plants, infested fruit counts, number of pepper weevil larvae, pupae, and adult in dissected fruit. Yield data were subjected to a square-root transformation (sqrt (x)) before statistical analysis to meet the assumption of normality and homogeneity of variance. The non-transformed means were reported. Count data were averaged over weeks for the complete season and was treated as a quasi-Poisson. A generalized linear mixed model was used to determine the fixed effect of treatments. To account for the field design (RCBD), block was included as a random effect in models. The Kenward-Roger's method was used to estimate the degrees of freedom (PROC GLIMMIX model, SAS version 9.4, SAS Institute Inc. Cary, NC, 2013). For each response variables, the treatment least square means were separated using Tukey's multiple comparisons procedure. In all cases, the level of statistical significance was set to $\alpha = 0.05$.

3. Results

3.1. Effect of non-host crops on the abundance of pepper weevil

In the present study, we did not observe any pepper weevil on the non-host crops. Insects such as aphids, beet armyworm, leafminers, and whitefly were absent on peppers. We did not observe any other pest infestation at the time of scouting on either intercropped or pepper plants. Four weeks after planting, the cilantro plants had started producing marketable leaves and had reached a height of 30 cm in average, while the cabbage had developed over 6 true leaves and was about 10–12 cm in height. At this point, the pepper plants intercropped with cabbage and cilantro had few leaves and had no fruit, unlike the pepper plants in the rest of the treatments which had started fruiting and were about 30.5 cm tall in average. Eight weeks after transplanting, the cabbage plants had grown wider, developed over 10 true leaves, and started cupping and overshadowing the pepper plants, while the cilantro were about 106.7 m tall in average and started producing flowers. The pepper plants intercropped with cabbage and cilantro were about 36.6 cm tall, had few leaves, and few fruits compared to the pepper plants in all other treatments.

In the TREC study, there were no statistical differences between the mean number of adults observed on pepper plants intercropped with basil, marigold, and the control (Fig. 1). The number of pepper weevil adults observed on plants intercropped with cabbage and cilantro were significantly lower compared to the numbers found on the control plants (Fig. 1). In the off-station study, except for marigold, the number of pepper weevil adults found in all treated plots was statistically fewer than the control (Fig. 2).

3.2. Effect of non-host crops on the number of pepper weevil infested fruit

Pepper weevil infested fallen fruit was not observed on the first two sampling dates, the 26th of February, and the 4th of March at 34 and 40 days after planting (DAP), respectively, in the TREC study. When means were compared across all sampling dates, the mean number of infested fruit observed on pepper plants intercropped with cabbage and cilantro, and the thiamethoxam treated plants were significantly lower compared to the mean number of infested fruit from the control plants (Fig. 3). Results from the plants intercropped with basil and marigold did not differ statistically compared to the control.

No infested fruit was observed in the off-station field on the first sampling date on the 18th of February at 42 days after planting in all treatments and across the sampling dates on the plants intercropped with cabbage (Fig. 4). There were no significant differences between the number of infested fruit recorded on the plants intercropped with marigold and the control. The number of infested fruit on the plants intercropped with cabbage, cilantro, basil, and plants sprayed with thiamethoxam was significantly lower than the numbers found on the control plants.

3.3. Mean number of pepper weevil in dissected fruit

The mean number of pepper weevil (adult + pupae + larva) in dissected fruit was significantly lower in the treatments intercropped with cabbage, cilantro, and plants sprayed with thiamethoxam compared to the control in the TREC study (Fig. 5).

In the off-station study, the infested fruit collected from the thiamethoxam-treated and intercropped plots except for marigold had a significantly lower number of pepper weevil (adult + pupae + larva)

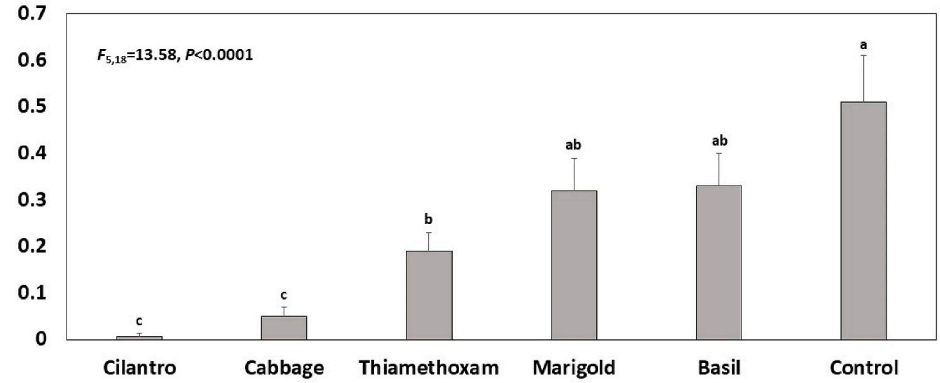

Fig. 1. Mean ± SE number of pepper weevil adults on five random jalapeño pepper plants per treatment plot in the TREC study. Means with the same letter do not differ statistically at P < 0.05 according to Tukey's HSD test.

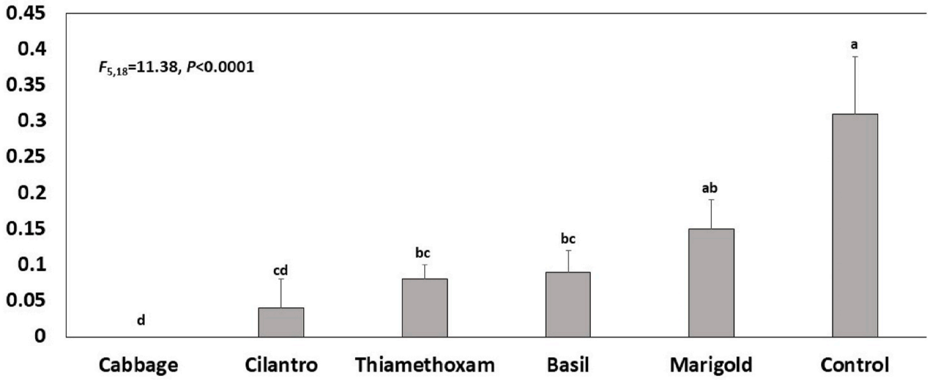

Fig. 2. Mean ± SE number of pepper weevil adults on five random jalapeño pepper plants per treatment plot in the off-station study. Means with the same letter do not differ statistically at P < 0.05 according to Tukey's HSD test.

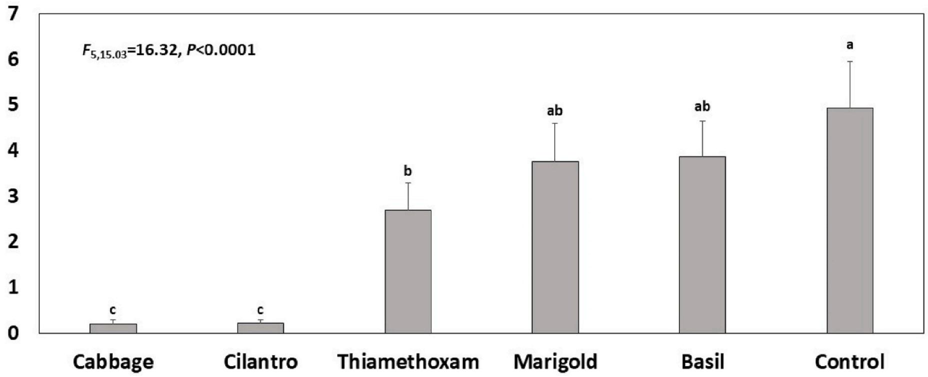

Fig. 3. Mean ± SE number of pepper weevil infested fruits on five random jalapeño pepper plants per treatment plot in the TREC study. Means with the same letter do not differ statistically at P < 0.05 according to Tukey's HSD test.

compared with the control, when means were compared across all sampling dates (Fig. 6).

In summarizing the results, we recorded a reduction in the number of pepper weevil adults by 80, 98, 32, 40 and 60% in TREC study, and 100, 87, 67, 33 and 67% in off-station study when pepper plants were intercropped with cabbage, cilantro, basil, marigold and thiamethoxam, respectively. The reduction in the number of adults reflected in the number of pepper weevil infested fruit, which were recorded as 95.9, 95.9, 20.4, 22.4 and 44.9% in TREC study, and 100, 99, 70, 0 and 70% in the off-station study for cabbage, cilantro, basil, marigold and thiamethoxam, respectively.

Consistent with the above information, we recorded percentage reduction in the number of pepper weevil (larva + pupa + adult) in fallen fruit by 96, 96, 41, 41, and 59.5% in TREC field and 100, 99, 77.7 16.7, and 63% in off-station field for intercropping with cabbage, cilantro, basil, marigold and thiamethoxam, respectively.

3.4. Marketable yield at harvest

In the TREC study, yield in the plots intercropped with basil, marigold, and plants sprayed with thiamethoxam did not differ statistically compared to the yield from the control plots (Fig. 7). Marketable yield

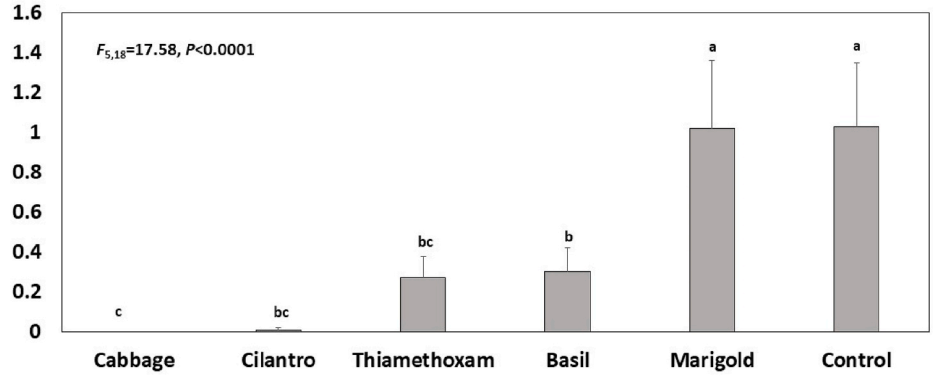

Fig. 4. Mean ± SE number of pepper weevil infested fruits on five random jalapeño pepper plants per treatment plot in the off-station study. Means with the same letter do not differ statistically at P < 0.05 according to Tukey's HSD test.

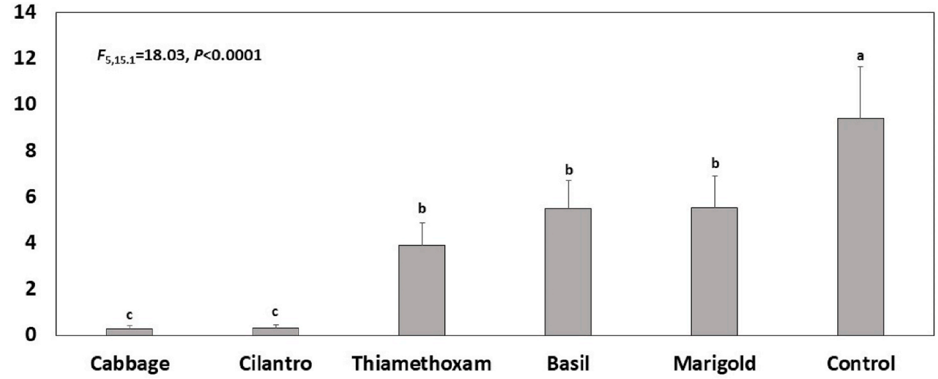

Fig. 5. Mean ± SE number of pepper weevil in dissected fruits collected from five random jalapeño pepper plants per treatment plot in the TREC study. Means with the same letter do not differ statistically at P < 0.05 according to Tukey's HSD test.

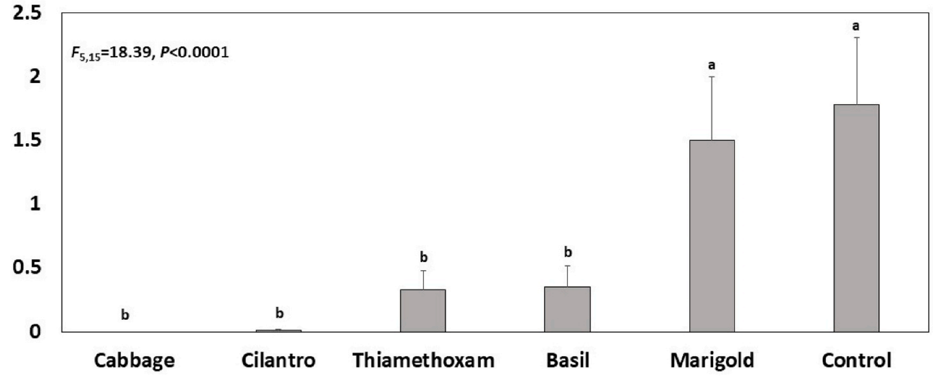

Fig. 6. Mean ± SE number of pepper weevil in dissected fruits collected from five random jalapeño pepper plants per treatment plot in the off-station study. Means with the same letter do not differ statistically at P < 0.05 according to Tukey's HSD test.

from thiamethoxam and Marigold was higher than cabbage and cilantro. Cabbage plots had significantly lower marketable yield than the control. In the off-station study, the plants sprayed with thiamethoxam had a significantly higher yield than the control. Mean marketable yield in the jalapeño pepper plants intercropped with non-host plants did not differ from the control (Fig. 8).

In the TREC study, 25.5%, 40.4%, 12.6%, 17.2%, 35%, and 13.8% of all the total fruit produced in the cabbage, cilantro, basil, marigold, thiamethoxam, and control plots, respectively, were marketable (Table 1). In the off-station study, 74.1%, 69.8%, 15.3%, 9.3%, 33.7%, and 5.4% of all the total fruit produced in the cabbage, cilantro, basil, marigold, thiamethoxam, and control plots, respectively, were marketable (Table 2). We visually rated growth and yield of the non-host crops. The yields of all non-host crops were comparable to the monocrop cultivation suggesting the feasibility of intercropping with pepper in commercial farming.

4. Discussion

Establishing successful strategies for the integrated management of pepper weevil is challenging. Intercropping repellent crops with the primary crop has been relatively successful in reducing the pest population of various crop pests by repelling and delaying infestation and reducing the need for insecticidal tactics (Cook et al., 2007). As stated by

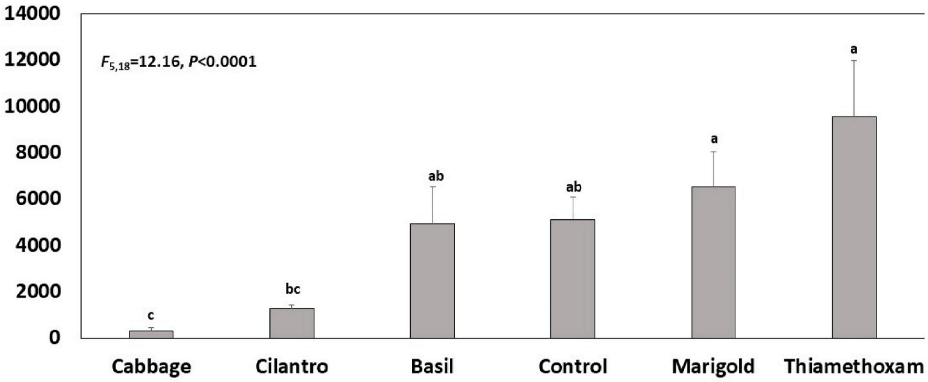

Fig. 7. Mean ± SE marketable yield (kg/ha) of jalapeño fruit per treatment plot in the TREC study. Means with the same letter do not differ statistically at $P < 0.05$ according to Tukey's HSD test.

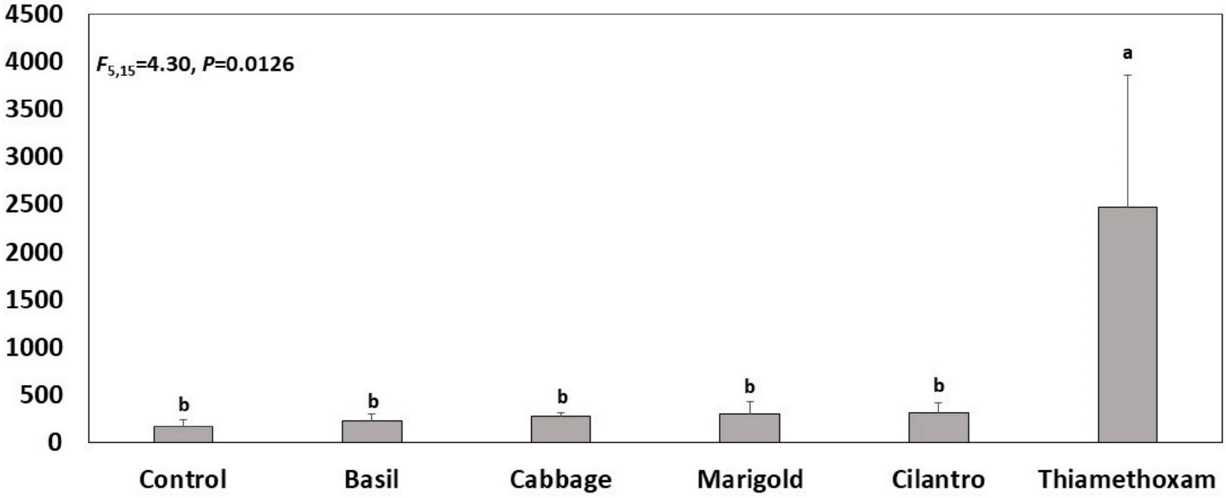

Fig. 8. Mean ± SE marketable yield (kg/ha) of jalapeño fruit per treatment plot in the off-station study. Means with the same letter do not differ statistically at $P < 0.05$ according to Tukey's HSD test.

Table 1
Total jalapeño pepper fruit produced per treatment plot, % infested and % marketable in the TREC field.

Treatment	Total Infested fruit	Marketable fruit	Total fruit produced	% Infested	% Marketable
Cilantro	31	21	52	59.62	40.38
Basil	340.75	49	389.75	87.43	12.57
Thiamethoxam	212.25	114.25	326.5	65.01	34.99
Marigold	344	71.5	415.5	82.79	17.21
Cabbage	18.25	6.25	24.5	74.49	25.51
Control	336	53.75	389.75	86.21	13.80

Table 2
Total jalapeño pepper fruit produced per treatment plot, % infested and % marketable in the off-station field.

Treatment	Total Infested fruit	Marketable fruit	Total fruit produced	% Infested	% Marketable
Cilantro	4	9.25	13.25	30.19	69.81
Cabbage	3.75	10.75	14.5	25.86	74.14
Thiamethoxam	148	75.25	223.25	66.29	33.71
Marigold	183.75	18.75	202.5	90.74	9.26
Basil	96.75	17.5	114.25	84.68	15.32
Control	232.5	13.25	245.75	94.61	5.39

Aiyer (1949), that intercropping reduce pest damage by creating barrier for the pests to find their hosts, because the host plant is more dispersed. They also mentioned that intercropping plants might serve as a trap crop, changing pests' focus for the host crop. Additionally, intercropping plants might cause chemical barrier repelling the pest from the hosts. In our study, a push system was evaluated. We determined the effectiveness of repellent non-host plants against pepper weevil on jalapeño peppers. As a positive control, we used the neonicotinoid thiamethoxam (IRAC, 2020), which is effective when used alone or in combination with other products in reducing the pepper weevil population in field studies (Stansly and Conner, 2003; Seal and Sabines, 2013). Caballero et al. (2015) reported high mortality of pepper weevil adults inflicted by thiamethoxam. Other insect pests of peppers controlled by thiamethoxam include aphids, beetles, leafhoppers, leafminers, thrips, silverleaf whitefly, etc. (Vegetable Handbook, 2018–2019). However, the above-mentioned pests were either absent or at very low densities on pepper in the present study. This allowed us to focus on the primary pest, the pepper weevil.

We observed a reduction in the number of pepper weevil adults and infested fruit on pepper plants intercropped with the non-host repellent crops in both studies (TREC and off-station fields). It is possible that negative cues from the non-host crop, either chemical or behavioral (plant morphology), deter adult females from ovipositing on the pepper fruit. Trenbath (1993) also reported that intercropped plants might render the main crop a less preferred host. He also reported that the intercropped plants might interfere with the regular searching ability of the insect pests. The intercropped plants may also change the environment which favors natural enemies of the pest of the main crop. In our study, we assume that either one or all the above in combination affected pepper weevil's normal searching and oviposition behavior.

In both research sites (TREC and off-station), the pepper plants intercropped with cilantro and cabbage did not grow well due to the fast foliage and root growth of cabbage and cilantro, which likely interfered with nutrient acquisition and access to sunlight. This likely resulted from competition between the main crop (jalapeño pepper) and treatments (cilantro and cabbage) for space, water, nutrient, and sunlight. The distance between the intercropped plants and main crop in our studies could have been one of the reasons why the pepper plants were not able to grow as well as pepper plants did in the non-intercropped plots. Bukovinszky et al. (2004) reported that brussel sprouts plants intercropped with malting barley were smaller when compared to the brussels sprouts monoculture, which could be because of lower photosynthetic activity, drought stress, and competition for nutrients. Due to these adverse factors and other possible interactions, pepper plants intercropped with cabbage and cilantro were small, with reduced fruit production, marketable yield, as well as reduced pest damage resulting in fewer infested fruit. However, Andow (1991) and Kareiva (1983) opined that intercropping results lower quality of plants as compared to the monoculture.

We recorded a dip in the yield of pepper plants intercropped with non-host repellent crops. Intercropped plants compete with the main crops for resources (nutrients and water), which can negatively affect crop yield (Razze et al., 2016). Thus, factors in the intercropping, such as competition might have caused the decline in yield of pepper in the present study. This concern should be addressed in future studies. The effectiveness of intercropping peppers with cabbage and cilantro plants was not properly understood because these two plants grew fast and interfered with the normal growth of pepper plants. This suggests the increase of space between the intercropped (cabbage and cilantro) plants and the pepper plants to provide good air circulation, reduce the effect of their shade on pepper plants, competition for space, nutrients, and sunlight in future studies.

During our study, we observed the presence of bees and other insects, including the pollen beetle, on flowers and plants of basil and cilantro. This is an advantageous strategy to increase the diversity of beneficial insects in the agroecosystem. Brandmeier et al. (2021) observed a higher natural enemy abundance and diversity in wheat (*Triticum aestivum* L.)-faba beans (*Vicia faba* L.) intercropped plots than plots with wheat monoculture. Bee richness and abundance was higher in bell pepper plots intercropped with basil than in the only-pepper plots. This resulted in longer, wider, and heavier fruits in the intercropped plots although these parameters were not measured in our experiment. Furthermore, the presence of floral resources enhances natural enemy conservation and management in agricultural systems (Pereira et al., 2015). Song et al. (2014), observed a higher number of natural enemies in apple orchards intercropped with ageratum (*Ageratum houstonianum* L.), French marigold, and summer savory (Satureja hortensis L.) than in single cropping of apple. In this study, the rate of increase and the density of tortricid pest was lower in intercropped plots compared to only apple plots. The abundance of spirea aphid (*Aphis citricola* Van der Goot) was significantly lower in plots intercropped with ageratum, French marigold, and basil compared with plots with natural vegetation cover. Total number of natural enemies including lady beetle species and green lacewings was higher in basil or French marigold intercropped plots than in natural vegetation plots (Song et al., 2013). We also observed the presence of lady bugs in the intercropped plots but their abundance and effect against insect pests such as aphids and whiteflies were not evaluated in our studies.

We also observed that the basil plants were affected by the fungal diseases, basil downy mildew (*Peronospora belvahrii*) and fusarium wilt (*Fusarium oxysporum* f. sp. *basilicum*), which may have impacted their effectiveness in repelling pepper weevil. The use of basil varieties that are resistant to diseases and, at the same time, exhibit repellent properties could make it more effective in managing pests. Different basil cultivars such as the sweet and sacred basil provided control against the flea beetle, *Phyllotreta sinuata* Steph, and the cabbage webworm, *Hellula undalis* Fabricius when they were planted in association with Chinese kale, *Brassica oleracea* L. (Kianmatee and Ranamukhaarachchi, 2007).

The thiamethoxam treated plants performed better in producing marketable yield and reducing the number of pepper weevil adults and infested fruit. This result was not surprising as thiamethoxam is a standard insecticide effective in managing pepper weevil. However, with respect to the basil plants, it is possible that cultivars that are disease resistant with better repellent properties will end up being even more effective in repelling pepper weevil.

5. Conclusions

All non-host treatments showed trends in reducing the number of pepper weevil adults found on pepper plants, the number of infested fruit, and the number of larvae inside fruit, but not marketable yield when compared to the control. It is essential to identify and successfully establish management plans using non-host crops that delay the establishment of pepper weevil in pepper fields to maintain the pepper weevil population below the threshold level. This will better enhance the parasitoids' presence and provide a better and effective management of pepper weevil.

Olfactometer bioassays and small cage experiments should be carried out to screen a larger number of potential non-host and pepper weevil repellent plants prior to futher field studies. This will help to identify effective non-host plants that exhibit repellent properties to the pepper weevil, thus providing more promising control.

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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