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Posted Date: 10 February 2026

doi: 10.20944/preprints202602.0784.v1

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Article

Protective Row Covers for Management of Flea Beetles in Organic Eggplant Production

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Abstract

Organic eggplant production in the United States is challenged by flea beetles, which stunt eggplant growth and reduce yield. Across four experiments between 2019 and 2024, we compared the effects of various pest management strategies on flea beetle abundance, damage, and marketable yield in eggplant production, removing strategies that were ineffective in suppressing flea beetles from later years of the study. Low flea beetle pressure was observed in 2019 and 2020; consequently, experiments were moved to fields with a legacy of higher flea beetle pressure under organic management in 2021 and 2024. Prior to row cover removal, there were significantly more flea beetles in the control than fine-mesh row cover treatments in 2019, 2020, and 2021. Flea beetle feeding damage at flowering was significantly lower in all row cover treatments than the untreated control in 2019, 2021, and 2024 and the organic insecticide treatment in 2019 and 2021. There were no differences in marketable yield between treatments in 2019 and 2020, but marketable yields were significantly higher in fine-mesh row cover treatments than the control and the organic insecticide treatment in 2021 and 2024. These results indicate that fine-mesh row covers may be a viable pest management alternative to organic insecticides in organic eggplant production.

Keywords: eggplant; flea beetles; integrated pest management; organic agriculture; mesotunnels; row covers

1. Introduction

Damage caused by insect pests is one of the top challenges faced by growers of organic specialty crops [1,2]. Pesticides are used to treat over half of the acreage of fruit and vegetable production in the United States [3,4]. While conventional farmers often use effective synthetic insecticides, these products are prohibited in organic agriculture [5]. Furthermore, the National Organic Program crop pest, weed, and disease management practice standard clarifies that organic insecticides may be used only as a last resort, after practicing and documenting preventative cultural and nonchemical pest control measures [5].

The insecticides available to organic specialty crop growers are limited in number and are typically less effective than conventional insecticides, often due to their sensitivity to photodegradation and short residual action [6]. Pyrethrins and spinosad are amongst the most commonly used organic insecticides [7]. A broad-spectrum insecticide derived from Dalmatian chrysanthemum (*Tanacetum cinerariifolium* (Trevir.)), pyrethrins are effective against many pestiferous insects [8]. Pyrethrins degrade rapidly in sunlight, with one study of field-grown

tomatoes (*Lycopersicon esculentum* (Mill.)) and peppers (*Capsicum annuum* (L.)) revealing a half-life of less than two hours [9]. Spinosad, a product derived from the soil actinomycete *Saccharopolyspora spinosa* (Mertz and Yao), is active against a narrower range of target pests, including some Coleopterans [7]. It is susceptible to photolysis, and its efficacy has been documented to drop by more than half within a day of application [10]. Because of the short residual action of these insecticides, crops may quickly become vulnerable to invading pests, necessitating frequent re-applications that raise already-high input costs [7]. One study comparing organic, conventional, and integrated crop management strategies for production of tomatoes, sweet corn (*Zea mays* (L.)), and pumpkin (*Cucurbita pepo* (L.)) revealed that pyrethrins used in the organic system cost 1.2 to 3.6 times more than conventional pesticides used in the other systems [11].

Organic farmers are incentivized to practice preventative pest management strategies before resorting to organic insecticides. Protective row covers, which create a physical barrier between insect pests and crops, are amongst the most promising strategies that can be employed to prevent pest damage in organic systems. Row covers are typically made of a fine nylon mesh or fabric material and are either draped directly over plants (floating row covers) or suspended above the plants using hoops or other structures [12,13]. Mesotunnels are medium-height structures created by affixing row covers over approximately 1-m-tall hoops to create space between the crops and the row cover, mitigating oviposition or feeding by insects through the row cover material and increasing air flow [12]. Fabric row covers trap heat, which can exceed maximum temperatures tolerable for certain crops in warm conditions [14]. Nylon mesh row covers trap less heat than fabric row covers and may be more suitable for warm season production [15]. Row covers have been demonstrated to exclude a variety of insect pests [16–18], including flea beetles (*Phyllotreta* spp.) in brassica crops [19].

One challenge of using row covers in pollinator-dependent crops is that insect exclusion hinders pollination. Strategies to address the problem of pollinator exclusion include removing the row cover at anthesis and either leaving the plants uncovered for the rest of the season (on-off) or replacing the row cover after pollination occurs (on-off-on); leaving the row cover in place for the full season and opening only the ends at anthesis (open-ends); or stocking the sealed row cover with a commercially purchased bee colony (full season) [15,20–22]. Nelson et al [12] found comparable or greater muskmelon (*Cucumis melo* (L.)) yields from a full season treatment compared to an on-off-on row cover treatment, and Pulliam et al [20] found greater acorn squash (*Cucurbita pepo* (L.)) yield from an open-ends treatment compared to both full season and on-off-on treatments. Effects of pollination strategy may vary depending on the crop.

Another organic pest management strategy that has gained popularity in recent years is the use of aromatic essential oils (concentrated plant extracts) or essential oil mixtures as sprays to repel insect pests [23]. Extracts of rosemary (*Salvia rosmarinus* (Spenn.)), lavender (*Lavandula angustifolia* (Mill.)), and rue (*Ruta graveolens* (L.)) show repellent effects against Colorado potato beetle (*Leptinotarsa decemlineata* (Say)) and bean weevil (*Acanthoscelides obtectus* (Say)) adults [24]. In a lab study of eggplant (*Solanum melongena* (L.)), ten different essential oils caused greater than 50% mortality against both aphids (*Aphis gossypii* (Glover)) and whiteflies (*Bemisia tabaci* (Gennadius)), although negative physiological changes due to exposure to several of the essential oil mixtures tested were observed on the plants [25].

Reflective plastic mulches can also be used as a strategy to deter insect pests from attacking crops. Plastic (polyethylene) mulch is commonly used in organic fruit and vegetable production for weed suppression due to the dearth of selective organic herbicides [26] and the positive effects of plastic mulch on crop growth and yield [27]. While black or white plastic mulch is most often used, reflective silver mulch may reflect UV light and repel pests while plants are small [28,29]. Reflective silver plastic mulches reduced populations of Mexican bean beetle (*Epilachna varivestis* (Mulsant)) in green beans (*Phaseolus vulgaris* (L.)) [30] and early season thrips (*Frankliniella occidentalis* (Pergande)) in bell pepper (*Capsicum annuum* (L.)) production [31] compared to black mulch, and shoot and pod borer (*Leucinodes orbonalis* (Guenée)) in eggplant production compared to white mulch [32].

Eggplant is a popular crop that has spread from its native range in India [33] to many parts of the world, including the United States. Demand for eggplant has grown in the United States over the past decades, with per capita availability tripling between 1970 and 2024 [34]. Eggplant is self-fertile and self-compatible, but insect pollination has been shown to enhance eggplant yield by as much as fifty percent [35]. In the United States, eggplant flea beetle, (*Epitrix fuscula* (Crotch) (Coleoptera: Chrysomelidae)) and to a lesser extent tobacco flea beetle (*Epitrix hirtipennis* (Melsheimer) (Coleoptera: Chrysomelidae)) are amongst the most prolific pests of eggplant [36,37]. Colorado potato beetle (*Leptinotarsa decemlineata* (Say)) and false potato beetle (*Leptinotarsa juncta* (Germar) (Coleoptera: Chrysomelidae)) are also significant pests of eggplant in some systems [38,39]. Few studies have focused on the control of eggplant pests using organic compliant practices.

Adult eggplant and tobacco flea beetles feed on the leaves of eggplant and leave many small holes, giving the appearance that the leaf was hit by small pieces of hail or the spray from a shotgun. This damage is often referred to as “shot holes.” Feeding damage on eggplants can cause mortality in young transplants [36], and defoliation from flea beetles has been shown to reduce eggplant yield [37]. Flea beetles are mobile over both short distances due to their enlarged femurs, which enhance their jumping abilities, and over longer distances due to their flying abilities [40], enabling them to rapidly invade fields of host plants.

The objective of this study was to evaluate a variety of organic compliant management techniques for controlling flea beetles (*Epitrix* spp.) in eggplant production with an emphasis on exclusionary row covers. This study took place over four years in 2019, 2020, 2021, and 2024. In the first year of the study, the organic management treatments included a fine-mesh row cover, a fabric row cover, a rotation of organic insecticides, essential oils sprayed on fine-mesh row covers, and reflective silver plastic mulch. These treatments were compared to a negative control (no treatment) and a positive control (conventional insecticides). In subsequent years of the study, some of the organic pest management treatments were removed based on low efficacy in controlling insect pests or detrimental effects on plant growth. These included reflective plastic mulch (excluded after the first year) and essential oils (removed after the second year of the study). The goal of this research was to inform organic eggplant producers about the efficacy of different organic-compliant methods of controlling flea beetles.

2. Materials and Methods

2.1. Site

Field studies were conducted during the summers of 2019, 2020, 2021, and 2024 at the University of Kentucky’s Horticulture Research Farm, located in Lexington, Kentucky (37°58’25.92”N, 84°32’5.85”W). This 40-hectare farm is within USDA plant hardiness zone 7a [41]. The farm is split into organic and conventional sections and includes a diverse arrangement of horticultural crops, including but not limited to annual crops such as leafy greens, cucurbits, and solanaceous crops; perennial fruits such as strawberries, cane berries, and blueberries; tree fruits such as apples; cut flowers; and assorted cover crops. The organic section of the farm contains a working farm that more frequently produces solanaceous crops (tomatoes, peppers, eggplant, and potatoes) and therefore has higher solanaceous pest abundance than the conventional section. In 2019 and 2020, the experiments were conducted in the conventional section of the research farm to allow for the comparison of conventional insecticide treatments as a positive control. However, the 2021 and 2024 experiments were moved to the organic section of the farm to increase pest pressure, while we removed the conventional management treatments from experiments to adhere to organic regulations.

Table 1. Description of the pest management treatments used in the eggplant experiments.

Treatment Name	Abbreviation	Description	Year			
			'19†	'20	'21	'24
Control	CTRL	No spray, no row cover	▪	▪	▪	▪

Organic Insecticide	O-INS	Rotation of spinosad and pyrethrins ¹ sprayed once per week, no row cover	▪	▪	▪	▪
Conventional Insecticide	C-INS	Rotation of pyrethroid and dinotefuran ² sprayed once per week, no row cover	▪	▪		
Agribon Row Cover - On-Off	AGR-OO	Spunbonded fabric row cover ³ – removed at flowering	▪	▪	▪	
ProtekNet Row Cover - On-Off	PNET-OO	25-gram fine-mesh row cover ⁴ – removed at flowering	▪			
ProtekNet Row Cover - On-Off + Rosemary Oil	PNET-OO+R-OIL	25-gram fine-mesh row cover ⁴ - removed at flowering, sprayed with rosemary essential oil ⁵ twice per week until flowering	▪			
ProtekNet Row Cover - On-Off + Eucalyptus Oil	PNET-OO+E-OIL	25-gram fine-mesh row cover ⁴ - removed at flowering, sprayed with eucalyptus essential oil ⁶ twice per week until flowering	▪			
Essentria Essential Oil	ES-OIL	Essentria essential oil ⁷ applied directly onto eggplant twice per week until flowering, no row cover				▪
Neem Oil	N-OIL	Neem oil ⁸ applied directly onto eggplant twice per week until flowering, no row cover				▪
ProtekNet Row Cover - Open Ends	PNET-OE	25-gram fine-mesh row cover ⁴ - ends opened at flowering				▪
ExcludeNet Row Cover – On-Off	ENET-OO	85-gram fine-mesh row cover ⁹ - removed at flowering				▪
ExcludeNet Row Cover – Open Ends	ENET-OE	85-gram fine-mesh row cover ⁹ - ends opened at flowering				▪

¹In 2019, all treatments were grown on both silver and black plastic mulch. All treatments were grown on black plastic mulch in 2020 and 2021 and on white plastic mulch in 2024. ¹Pyganic Crop Protection 5.0^{II} (pyrethrins, Valent U.S.A. Corporation, MGK, Minneapolis, MN, USA) and Entrust SC (spinosad, Corteva Agriscience [Dow AgroScience], Indianapolis, IN, USA). ²Mustang Maxx (pyrethroid, Zeta-cypermethrin, FMC Corporation, Philadelphia, PA, USA) and Scorpion 35SL (dinotefuran, Gowan Company, Yuma, AZ, USA). ³(Agribon grade-20, Berry Plastics, Indiana, USA). ⁴(ProtekNet 25-gram fine-mesh row cover, Dubois, Montreal, Quebec, Canada). ⁵ Rosemary (*Rosmarinus officinalis* (L.)) essential oil (Aura Cacia, Frontier Natural Products Co-op, Norway, IA, USA). ⁶Eucalyptus (*Eucalyptus globulus* (Labill.)) essential oil (Aura Cacia, Frontier Natural Products Co-op, Norway, IA, USA). ⁷Rosemary oil, geraniol, and peppermint oil mix (Essentria IC³, Envincio LLC, Cary, NC). ⁸Neem (*Azadirachta indica*) oil (Safer Brand, Woodstream Corporation, Lititz, PA, USA). ⁹(ExcludeNet 85-gram fine-mesh row cover, Tek-Knit Industries, Montreal, Quebec, Canada).

2.2. 2019 Experimental Design and Treatments

The experiment in 2019 was established as a split block design with mulch color as the main factor (N = 4 blocks) and pest management treatments as sub-plots within mulch color treatments. Each block consisted of two paired beds extending the length of the field, one with reflective silver plastic mulch and one with black plastic mulch (Figure S1). Within each plastic bed, we randomized seven different insecticide, essential oil, and row cover treatments (Table 1). No border beds were implemented as the allocated field lacked sufficient area. Within each bed, plots were 3.05-m-long,

separated by buffers of unplanted plastic that extended 1.2-m, and contained a single row of eggplants transplanted 38.1 cm apart. In 2019 and all subsequent years, the beds were 0.9-m wide and were spaced evenly on 2.1-m centers.

Reflective silver mulch was not used in any subsequent years because it reduced yield, plants grown on silver plastic mulch appeared chlorotic compared to those grown on black plastic mulch, and no differences were found for any measurements of flea beetle abundance or damage (Table A1). For this paper, we treated the 2019 experiment as a randomized complete block design and only included data from the bed with black mulch within each plot.

In 2019, the seven pest management treatments (Table 1) were 1) the untreated, uncovered control treatment (CTRL); 2) the organic insecticide treatment (O-INS), a rotation of pyrethrins (Pyganic 5.0 II) and spinosad (Entrust SC), applied once weekly; 3) the conventional insecticide treatment (C-INS), a rotation of zeta-cypermethrin (Mustang Maxx) and dinotefuran (Scorpion 35SL), applied once weekly; 4) the Agribon treatment (AGR-OO), a fabric row cover; 5) the ProtekNet treatment (PNET-OO), a 25-gram nylon mesh row cover; 6) the ProtekNet + eucalyptus oil treatment (PNET-OO+E-OIL), a ProtekNet row cover additionally treated twice a week with eucalyptus (*Eucalyptus globulus* (Labill.)) essential oil; and 7) the ProtekNet + rosemary oil treatment (PNET-OO+R-OIL), a ProtekNet row cover treated twice a week with rosemary (*Rosmarinus officinalis* (L.)) essential oil. All Agribon and ProtekNet row covers fully covered the plot from the time of transplanting until removal when approximately 50% of plants were flowering (on-off strategy). (See extended methods in the Supplementary Materials for rates used and product sources.)

2.3. 2020 Experimental Design and Treatments

In 2020 and each subsequent year, the experiment was established as a randomized complete block design (N = 4 blocks) (Figure S1). In 2020, each block consisted of one raised bed covered in black plastic mulch extending the length of the field, with seven randomized pest management treatments within each bed. Plot dimensions and transplant spacing matched the 2019 experiment.

The 2020 treatments (Table 1) mirrored those in the 2019 trial, except that the PNET-OO+E-OIL and PNET-OO+R-OIL treatments were replaced with two new treatments: 1) the neem (*Azadirachta indica*) treatment (N-OIL), uncovered and treated twice per week with clarified 70% neem extract, and 2), the Essentria IC3 essential oil treatment (ES-OIL), uncovered and treated twice per week with a commercial mix of rosemary oil, geraniol, and peppermint oil. We decided to eliminate the row covers from the essential oil spray treatments in 2020 due to concerns about the feasibility of farmers using both pest management practices simultaneously. (See extended methods in the Supplementary Materials for product use rates.)

2.4. 2021 Experimental Design and Treatments

In 2021, four raised plastic beds were incorporated into the field, with the two outer beds acting as border beds to minimize edge effects, the two interior beds acting as experimental beds, and each of the four blocks covering half the length of an experimental bed (Figure S1). Within each bed, 6.1-m-long plots were separated by buffers of unplanted plastic that extended 1.5-m.

In 2021, two of the four treatments (Table 1) were the same as in 2019-2020: 1) the control (CTRL) and 2) the Agribon treatment (AGR-OO). Two other treatments incorporated ProtekNet and organic insecticide, but these were managed differently than in previous years. The ProtekNet treatment (PNET-OE) consisted of the same fine-mesh row cover material as in past years, but rather than removing the row cover at flowering, the ends were secured open for the remainder of the season (open-ends). The organic insecticide treatment (O-INS) included the same products and frequency of application as previous years, but products were applied at lower rates that were considered more realistic for farmers. (See extended methods in the Supplementary Materials for product use rates.)

2.5. 2024 Experimental Design and Treatments

In 2024, six raised plastic beds were incorporated into the field (Figure S1). These were divided into two sets of one experimental bed surrounded by two border beds. Within each bed, plots were separated by buffers of unplanted plastic that extended 0.9-m. The experimental unit was a 9.1-m-long plot consisting of three raised beds covered with white plastic mulch. The center (experimental) bed in each plot contained a double row of eggplant transplants planted 45.7 cm apart, while border beds contained a single row of eggplant transplanted at the same spacing.

In 2024, the same control and organic insecticide treatments were included as in 2021 (Table 1). As in 2021, the experiment included on-off and open-ends row cover strategies. Instead of Agribon and ProtekNet, both treatments in 2024 used an 85-gram fine-mesh row cover (ExcludeNet) that was thought to be more durable than the ProtekNet material used for fine-mesh row cover treatments in previous years. Both row cover treatments were kept sealed until approximately 50% of the plants had open flowers, at which time 1) the on-off ExcludeNet row cover treatment (ENET-OO) was removed and 2) the ends of the open-ends ExcludeNet row cover treatment (ENET-OE) were opened and secured with clips. (See extended methods in the Supplementary Materials for product use rates and sources.)

Table 2. Dates of field preparation and sampling activities during the eggplant trials.

Activity	Field Preparation			
	2019	2020	2021	2024
Field disked	March 19	May 27	--	--
Compost applied	--	June 2	April 20	--
Eggplant seeded in greenhouse	March 19	May 7	April 19	April 3
Flail mowed	--	--	April 19	May 6
Spaded	--	--	April 20	May 6
Field cultivated	April 4, 18; May 1	June 8	May 17-21, May 24-28, June 1	May 13
Eggplant transferred into 50 cell trays	<i>date unknown</i>	June 5	May 25	April 24
Beds formed, fertilizer applied, and plastic mulch and drip tape installed	May 1	June 8	May 5	May 13
Eggplant transplanted and row covers implemented	May 7	June 18	June 16	May 20
Cover crop seeded	--	--	June 16	May 20
Insecticide sprayed	May 14, 23; June 4, 21; July 9	July 7, 15, 21, 30	June 24; July 3, 10, 16, 22, 30; August 5, 12, 18	All treatments sprayed for aphid management in the greenhouse on May 15. O-INS treatment only: May 31; June 6, 14, 19, 28; July 6, 11, 19
Essential oils sprayed	<i>twice a week until row cover</i>	<i>twice a week until row cover</i>	--	--

	removal, dates unknown	removal, dates unknown		
Row covers removed or ends opened	June 11	July 22	July 7	June 24
Fertigated	July 1	July 24	--	--
Lacewing larvae released	--	--	--	May 30, June 20
Sampling				
Activity	2019	2020	2021	2024
Sticky cards placed in field	May 24, July 8	June 13, Aug. 3	June 23, July 15	May 28
Vacuum sample	June 11, July 16	July 22, Aug. 12	July 7	June 24
Visual survey	--	--	--	May 29; June 4, 11, 18, 25; July 2, 9, 16, 24
Shot hole leaf damage survey	June 11	--	July 7	May 29; June 4, 11, 18, 25; July 2, 9, 16, 24
Harvest	June 24, 26, 28; July 1, 3, 7, 10, 12	Aug. 5, 11, 13, 17, 21	July 21, 26, 30; Aug. 3, 6, 10, 13, 17, 20	July 8, 12, 15, 19, 22, 25, 30; Aug. 2, 5, 12

2.6. Field Preparation

‘Galine’ F1 hybrid eggplant was used in all four years of the study. In each year, eggplant seeds were seeded in the greenhouse (in 72-cell trays in the first three years and 128-cell trays in 2024) and repotted into 50-cell trays after three weeks (Table 2). To prepare for planting, the fields were disked in 2019 and 2020 and flail mowed to terminate cover crops and spaded in 2021 and 2024 (Table 2). Cultivation was used for weed suppression prior to transplanting in all four years (Table 2). Compost was applied at a rate of 2.72 metric tons per hectare and incorporated into the soil prior to planting in 2019, 2020, and 2021 (Table 2). Beds were formed with one line of drip tape (15.2 cm emitter spacing) buried per bed under black (2019, 2020, and 2021), silver (2019), and white (2024) plastic mulch. Pre-plant 10-0-8 fertilizer was incorporated during bed formation at a rate of 44.6 kg N per ha in 2019, 2020, and 2024 and 84 kg N per ha in 2021 (Table 2). (See extended methods in the Supplementary Materials for additional product information.)

Eggplant seedlings were transplanted into the field six to eight weeks after seeding using a tractor with a water wheel transplanter (Table 2). After planting, transplant holes were backfilled with compost potting media to reduce weed emergence. Calcium nitrate was incorporated by fertigation once midway through the season in 2019 (0.6 kg) and in 2020 (0.3 kg) (Table 2). Following transplanting in 2021 and 2024, 40.3 kg per hectare of teff (*Eragrostis tef* (Zucc.)) was broadcast-seeded in the furrows between the raised beds for weed control (Table 2). In all years, the weeds in the furrows were managed throughout the season through manual weeding with scuffle hoes. Additionally, the furrows were mowed once using a flail mower six weeks after transplanting in 2024. (See extended methods in the Supplementary Materials for additional product information.)

In 2024, aphids were managed preventatively to better isolate the effects of flea beetles. All seedlings were treated with an application of spinosad (Entrust SC) with an adjuvant, NuFilm P, five days prior to planting due to the presence of aphids in the greenhouse (Table 2). Commercially purchased green lacewing larvae (*Chrysoperla rufilabris* (Burmeister)) were released in all four treatments two and four weeks after transplanting (Table 2). (See extended methods in the Supplementary Materials for application rates and additional product information.)

2.7. Treatment Implementation

2.7.1. Row Covers

Row covers were established on the same day as transplanting in all years. Fabric and fine-mesh row cover treatments were installed over 1-m-tall bent hoops (electrical conduit) in structures hereafter referred to as “mesotunnels” and secured with sandbags placed around the perimeter of the plot and snap-on plastic clamps placed on the outward-facing sides of the hoops (Figure 1). Across all row cover treatments and years, mesotunnels were kept sealed until approximately half of the eggplant plants had open flowers, at which time row covers were, depending on the treatment, either removed (on-off treatment) or their ends secured open with clips (open-ends treatment) for the remainder of the season to allow pollinators access to the plants (Table 1, Figure 1).

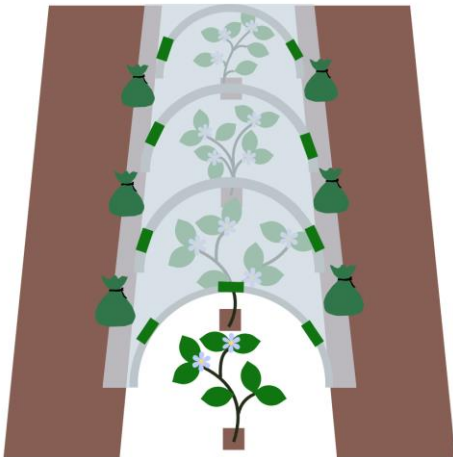


Figure 1. Schematic of a mesotunnel containing a single raised bed covered in white plastic mulch with end of row cover clipped open at flowering.

2.7.2. Insecticide and Essential Oil Treatments

Both insecticides and essential oils were mixed with a spreader sticker adjuvant (Nu-Film® P). Insecticides were applied to corresponding treatments on a weekly basis across all years, beginning about one week after transplanting into the field (Table 2). Following the labels, the maximum allowable rate was used for each insecticide in 2019 and 2020. In 2021 and 2024, lower rates that were considered more realistic for farmers were used. All insecticide sprays were made using an electric-powered backpack sprayer. (See extended methods in the Supplementary Materials for product sources and application rates.)

In 2019 and 2020, essential oils were sprayed twice per week using a spray bottle until row cover removal. We considered the application rate selected in 2019 to be the maximum realistic rate for our field study. In 2020, the application rate we selected was lower as the essential oil mixtures were sprayed directly onto the plant rather than on the larger surface area of a row cover. Additionally, all essential oil sprays were made before 9:00 a.m. when temperatures were low, as previous trials in brassicaceous greens had phytotoxic burns [19]. (See extended methods in the Supplementary Materials for product sources and application rates.)

2.8. Pest and Yield Measurements.

2.8.1. Vacuum Sampling.

We made collections by vacuum sampling with an inverted leaf blower. We modified protocols from Swezey et al [42]. Within each plot, six plants were vacuumed for two seconds each. These

samples were bagged, stored in a -20°C freezer, and later analyzed by a trained technician under magnification to determine the number of individual pest species. In all four years, vacuum sampling was conducted when approximately 50% of the plants in each treatment had flowers, immediately after removing or opening the ends of row covers to allow for pollination (Table 2). Vacuum samples were also collected once after the final harvest in 2019 and 2020 (Table 2).

2.8.2. Sticky traps.

In all four years, flea beetles were quantified using sticky trap sampling. For each plot, one 12.7x17.8-cm, double-sided yellow sticky trap was cut in half and the two halves suspended 0.3 m above the plastic 1-m (2019 through 2021) or 1.5-m (2024) from each end of each plot (Figure S2). In all four years, the traps were placed in the field approximately one week after transplanting and removed seven days later; additionally, sticky traps were placed in the field for one week during harvest in 2019, at the start of harvest in 2020, and one week before the start of harvest in 2021 (Table 2). Following removal from the field, the traps were placed in a freezer and later analyzed by a trained technician to quantify target pest species.

2.8.3. Visual surveys.

In 2024 only, flea beetles were monitored through weekly visual surveys by trained technicians (Table 2, Figure S2). Flags were used to mark 1-m² quadrats centered 1.5, 4.6, and 7.6-m from the south end of each plot. Each week, all six plants in each quadrat were carefully inspected, and the number of observed flea beetles was recorded.

2.8.4. Leaf damage data.

To determine the impact of pest management treatments on flea beetle damage, we measured the number of shot holes per unit leaf area at flowering (removal or opening of the row covers) in three out of four seasons (Figure S2). During the 2019 season, we took two leaves per treatment and counted shot holes within a standard 7.6x12.7-cm section in each leaf (Table 2). During the 2020 season, we did not take flea beetle leaf damage data at flowering. In 2021, we took six leaves per plot on two sampling dates (when the row covers were removed at flowering and midway through harvest), counted the number of shot holes, and measured leaf area using the application LeafByte [43] (Table 2). During the weekly visual surveys in 2024 described above, two plants per quadrat were selected for flea beetle leaf damage measurements using a random number generator and the number of shot holes visible in a square viewing pane placed over the middle vein of the third leaf from the apical bud of each plant was recorded (Table 2). For all three years, we report the number of shot holes per 1-cm² of leaf area in the Results section. For 2024, the averages from the surveys prior to and after flowering (opening or removal of the nets) are presented separately in Table 6, and the data from the survey conducted at flowering only is presented in Figure 2.

2.8.5. Harvest data.

We harvested eggplant two to three times per week during all growing seasons for a total of eight times in 2019, five times in 2020, nine times in 2021, and ten times in 2024 (Table 2, Figure S2). In 2019 and 2020, we followed the three central plants in each plot, while in 2021, we followed the four central plants. In 2024, all eggplant from the center bed of each plot (40 plants) were harvested. Fruits were considered ripe when they reached approximately 12.7-cm in length. All fruits at least 12.7-cm long were harvested, weighed, and graded according to the following USDA guidelines [44]. Fancy, grade-1, and grade-2 fruits were considered marketable. Unmarketable fruits were designated as “culls” due to serious damage from disease, insects, or mechanical injury.

See extended methods in the Supplementary Materials for additional information about sampling equipment, materials, and applications.

2.9. Statistical Analysis.

We conducted analyses for the 2019, 2020, 2021 and 2024 trials separately given the differences in treatments and plot design in each year of the experiments. For each year, the number of levels within the pest management treatment varied given the design of the experiment. Dependent variables compared across pest management treatments included flea beetle abundance variables (vacuum samples, sticky trap samples, and visual observations), flea beetle damage variables (shotholes per 1-cm²), and marketable yield (kg). Because the 2019 experiment included a split plot design with plastic mulch color as a main treatment and pest management as a sub-treatment, we decided to focus the analysis of the pest management treatments on black plastic mulch only because the silver mulch lowered yield. This would make the 2019 data more comparable to the other years. However, we compare the effect of plastic mulch color by aggregating across pest management treatments so that each mulch color maintained four replicates per treatment. All analyses were conducted with R statistical software (v.4.5.1; [45]) using the packages 'lmerTest' [46], 'stats' [45], 'multcomp' [47], 'car' [48], 'FSA' [49], 'lme4' [50], and 'emmeans' [51].

To compare the effect of pest management treatments, we utilized general linear mixed models (GLMM) in the 'lme4' package [50]. For each model, we incorporated pest management treatment as a fixed effect. To nest the randomized block design into the model structure, we incorporated block as a random effect within models. Dependent variables included flea beetle abundance variables (vacuum samples, sticky trap samples, and visual observations), flea beetle damage variables (shotholes per 1-cm²), and marketable yield (kg). In 2019, to compare the effect of plastic mulch color, we averaged across all pest management treatments within each block/plastic mulch bed to maintain a sample size of four replicates per plastic mulch color. We then compared the effect of plastic mulch color (fixed effect) on all dependent variables measured in 2019 using a GLMM with a random effect of block.

We tested all GLMM models for normality using a Shapiro-Wilk test on model residuals. If model residuals were not normally distributed, we transformed independent variables with log or square root transformations to improve the fit to a normal distribution. For all models, we performed Tukey's Post hoc tests to determine pairwise comparisons of different treatment levels if the overall treatment effect was significant.

3. Results

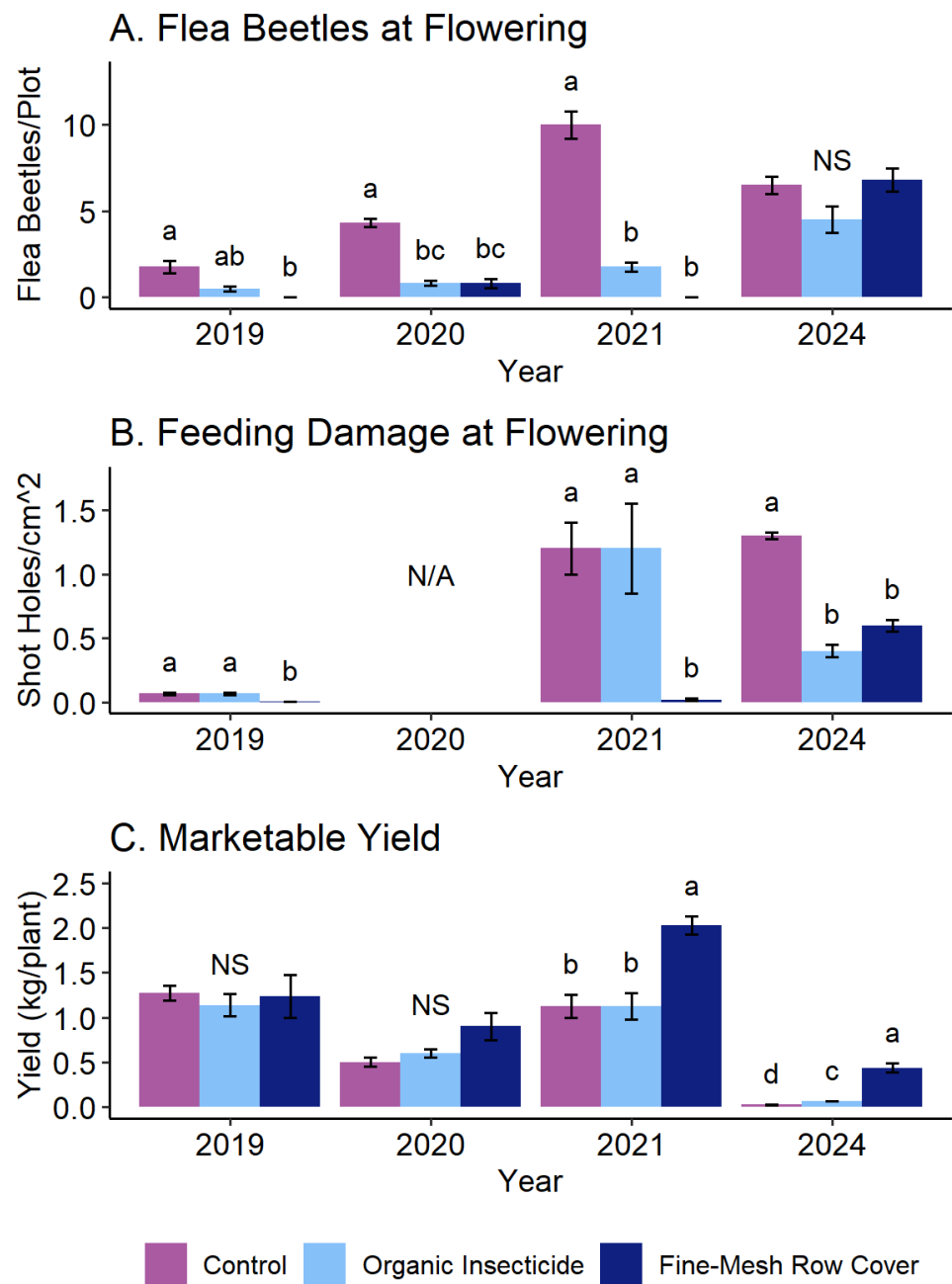


Figure 2. Results shown for a subset of treatments (untreated control - purple, organic insecticide - light blue, and fine-mesh row cover - dark blue) from experiments in 2019, 2020, 2021, and 2024 (Table 3, 4, 5, 6). Data from each experiment were analyzed separately, and the additional treatments were not included in the figure. Letters indicate significant differences ($p < 0.05$) between treatments within a given year assessed with Tukey’s post hoc test. Organic insecticide (O-INS) treatments are a rotation of pyrethrins and spinosad, applied weekly (Table 1). The fine-mesh row cover treatments were PNET-OO in 2019 and 2020, PNET-OE in 2021, and ENET-OE in 2024 (Table 1). (a) Average number of flea beetles collected through vacuum sampling at flowering (removal/opening of row covers). (b) Average number of shot holes from flea beetle feeding damage per 1 cm² of leaf area at flowering (Table 2). Leaf damage was not assessed at flowering in 2020. (c) Average cumulative marketable yield (kg) harvested from each treatment across the entire season, divided by the number of plants harvested per plot. The number of harvest events varied from five to 10 times per season (Table 2).

Flea beetles of different species were combined into a single category for visual surveys due to the difficulty of confidently identifying flea beetles to species in the field, and analysis of sticky traps due to obscurement of identifying characteristics by insects’ position on the cards. Flea beetles were

identified to the species level during vacuum sample processing, although as with visual surveys and sticky traps, we present the total number of flea beetles collected in the following results.

3.1. 2019 Experiment

Table 3. Mean, standard error, and pairwise comparisons for number of flea beetles sampled with vacuum and sticky traps, leaf damage (shot holes per 1-cm²), and marketable yield (kg/plant) for the pest management treatments in 2019. Different letters indicate significant differences (p < 0.05) assessed with Tukey’s post hoc test.

2019 Means						
Treatment ⁱ	FB: Sticky Traps, Early Season ¹	FB: Vacuum Sample at Flowering ^{2, ii}	Shot Holes at Flowering ³	FB: Sticky Traps at Harvest ⁴	FB: Vacuum Sample at Harvest ⁵	Marketable Yield ⁶
CTRL	0.8±0.5	1.8±0.8a	0.07±0.02a	16.8±3.5	7.3±1.6	1.3±0.2
O-INS	0.3±0.1	0.5±0.3ab	0.07±0.02a	15.1±1.2	6.8±1.3	1.1±0.3
C-INS	0.5±0.4	1.0±0.7ab	0.02±0.01ab	9.3±1.4	3.8±1.5	1.3±0.1
AGR-OO	0.3±0.3	0.3±0.3ab	0.003±0.003 b	8.4±1.3	6.0±1.4	0.9±0.2
PNET-OO	0.1±0.1	0.0±0.0b	0.003±0.003 b	7.9±2.0	5.5±1.6	1.2±0.5
PNET-OO+E-OIL	0.0±0.0	0.0±0.0b	0.009±0.006 b	7.9±2.2	10.5±2.5	1.2±0.2
PNET-OO+R-OIL	0.1±0.1	0.0±0.0b	0.003±0.003 b	7.5±2.4	10.8±1.4	1.3±0.3
F	0.9	4.0	7.5	3.2	2.7	0.3
P-value	0.5	0.008	<0.001	0.03	0.05	0.9
2019 - Pairwise Comparisons ⁱⁱⁱ						
CTRL vs AGR-OO	NS	NS	**	NS	NS	NS
CTRL vs PNET-OO		*	**			
CTRL vs PNET-OO+E-OIL		*	*			
CTRL vs PNET-OO+R-OIL		*	**			
O-INS vs AGR-OO		NS	**			
O-INS vs PNET-OO		NS	**			

O-INS vs PNET- OO+E-OIL	NS	*
O-INS vs PNET- OO+R-OIL	NS	*
Significance codes: '***' <0.001 '**' <0.01 '*' <0.05		

ⁱTreatment abbreviations: Control = CTRL, Organic Insecticide = O-INS, Conventional Insecticide = C-INS, Agribon Row Cover - On-Off = AGR-OO, ProtekNet Row Cover - On-Off = PNET-OO, ProtekNet Row Cover + Rosemary Oil - On-Off= PNET-OO+R-OIL, ProtekNet Row Cover + Eucalyptus Oil - On-Off = PNET-OO+E-OIL. ¹Average number of flea beetles per plot collected through sticky traps placed in the field for one week, beginning two weeks after transplanting. ²Average number of flea beetles collected per plot through vacuum sampling at flowering. [#]Square-root transformed to improve fit. ³Shot holes per 1 cm² of leaf area at flowering. ⁴Average number of flea beetles per plot collected through sticky traps placed in the field for one week before the final harvest. ⁵Average number of flea beetles collected per plot through vacuum sampling after the final harvest. ⁶Average marketable grade yield (kg) per plant, summed across harvest events. ⁱⁱⁱOnly pairwise comparisons for which there was a significant difference for at least one model are shown. The following comparisons were omitted from the table because there were no significant differences for any models: CTRL vs O-INS, CTRL vs C-INS, O-INS vs C-INS, C-INS vs AGR-OO, C-INS vs PNET-OO, C-INS vs PNET-OO+E-OIL, C-INS vs PNET-OO+R-OIL, AGR-OO vs PNET-OO, AGR-OO vs PNET-OO+E-OIL, AGR-OO vs PNET-OO+R-OIL, PNET-OO vs PNET-OO+E-OIL, PNET-OO vs PNET-OO+R-OIL, and PNET-OO+E-OIL vs PNET-OO+R-OIL.

3.1.1. Flea Beetle Abundance (2019)

There was a significant effect of pest management treatment on the number of flea beetles found in vacuum samples at flowering (Table 3). The CTRL treatment had a statistically higher number of flea beetles than the PNET-OO and PNET-OO+R-OIL and PNET-OO+E-OIL. There was a significant effect of pest management treatment on the number of flea beetles found on sticky traps deployed for one week at harvest; however, there were no significant pairwise differences between treatments (Table 3). Similarly, there was a significant effect of pest management treatment on the number of flea beetles collected through through vacuum samples at harvest, but there were no significant pairwise differences.

There was no effect of pest management treatment on the number of flea beetles found on sticky traps deployed at transplant (Table 3). Finally, there was no effect of mulch color treatment on the number of flea beetles in vacuum samples (at flowering and at harvest) nor on sticky traps (at transplant and at flowering) (Table A1).

3.1.2. Flea beetle Damage (2019)

There was a significant effect of pest management treatment on the number of shot holes caused by flea beetles at flowering in 2019 (Table 3). A Tukey post hoc test revealed the CTRL and O-INS treatments had significantly more shot holes than the row cover treatments (AGR-OO, PNET-OO, PNET-OO+E-OIL, and PNET-OO+R-OIL). There was no effect of the plastic mulch treatment (Table A1).

3.1.3. Marketable Yield (2019)

Yield did not differ among pest management treatments in 2019 (Table 3). The marketable yield from the black mulch treatment was significantly higher than the silver mulch treatment (Table A1).

3.2. 2020 Experiment

Table 4. Mean, standard error, and pairwise comparisons for number of flea beetles caught by vacuum and sticky traps, and marketable yield for the pest management treatments during the 2020 eggplant trial. Different letters indicate significant differences ($p < 0.05$) assessed with Tukey’s post hoc test.

2020 Means					
Treatment ⁱ	FB: Sticky Traps, Transplant ^{1, ii}	FB: Vacuum Sample, Flowering ²	FB: Sticky Traps, Harvest ³	FB: Vacuum Sample, Harvest ^{4, ii}	Marketable Yield ⁵
CTRL	6.8±0.6	4.3±0.5a	114.5±25.6	30.5±7.3	0.5±0.1
O-INS	3.3±1.0	0.8±0.3bc	87.8±16.3	29±8.8	0.6±0.1
C-INS	19.3±9.7	0.00±0.0c	38.8±6.8	45.3±19.4	1.0±0.1
AGR-OO	3.0±1.7	1.0±0.7bc	122.3±15.2	50.8±30.8	0.7±0.2
PNET-OO	10.3±5.7	0.8±0.5bc	73.8±25.8	40.8±8.6	0.9±0.3
N-OIL	7.3±3.2	0.5±0.3bc	96.0±24.6	40.3±17.9	0.3±0.1
ES-OIL	7.3±2.4	2.3±0.6ab	93.5±13.1	11.8±1.5	0.2±0.0
F	1.8	10.5	2.0	1.3	3.3
P-value	0.1	<0.001	0.1	0.3	0.02
2020 - Pairwise Comparisons ⁱⁱⁱ					
CTRL vs O-INS		***			
CTRL vs C-INS		***			
CTRL vs AGR-OO		**			
CTRL vs PNET-OO	NS	***	NS	NS	NS
CTRL vs N-OIL		***			
C-INS vs ES-OIL		*			
Significance codes: ‘***’ <0.001 ‘**’ <0.01 ‘*’ <0.05					

ⁱTreatment abbreviations: Control = CTRL, Organic Insecticide = O-INS, Conventional Insecticide = C-INS, Agribon Row Cover -On-Off = AGR-OO, ProtekNet Row Cover -On-Off = PNET-OO, Essentria Essential Oil = ES-OIL, Neem Oil = N-OIL. ¹Average number of flea beetles per plot collected through sticky traps placed in the field for one week after transplanting. ⁱⁱLog transformed to improve fit. ²Average number of flea beetles collected per plot through vacuum sampling at flowering. ³Average number of flea beetles per plot collected through sticky traps placed in the field for one week after the final harvest. ⁴Average number of flea beetles collected per plot through vacuum sampling at harvest. ⁵Average marketable grade yield (kg) per plant, summed across harvest events. ⁱⁱⁱOnly pairwise comparisons for which there was a significant difference for at least one model are shown. The following comparisons were omitted from the table because there were no significant differences for any models: CTRL vs ES-OIL, O-INS vs C-INS, O-INS vs AGR-OO, O-INS vs PNET-OO, O-INS vs N-OIL,

O-INS vs ES-OIL, C-INS vs AGR-OO, C-INS vs PNET-OO, C-INS vs N-OIL, AGR-OO vs PNET-OO, AGR-OO vs N-OIL, AGR-OO vs ES-OIL, PNET-OO vs N-OIL, PNET-OO vs ES-OIL, and N-OIL vs ES-OIL.

3.2.1. Flea Beetle Abundance (2020)

There was a significant effect of pest management treatment on the number of flea beetles found by vacuuming when row covers were removed at flowering in 2020 (Table 4). The CTRL treatment had significantly more flea beetles than the O-INS, C-INS, AGR-OO, PNET-OO, and N-OIL treatments. The ES-OIL treatment had significantly more flea beetles than the C-INS treatment. No treatment effects on flea beetle numbers were detected through vacuum sampling after the last harvest, early-season sticky traps, or late-season sticky traps in 2020 (Table 4).

3.2.2. Marketable Yield (2020)

There was a significant effect of pest management treatment on marketable yield in 2020, but a Tukey post hoc test revealed no significant differences between treatments (Table 4).

3.3. 2021 Experiment

Table 5. Mean, standard error, and pairwise comparisons for number of flea beetles caught by vacuum and sticky traps, leaf damage (shot holes per 1-cm²), and marketable yield for the pest management treatments during the 2021 eggplant trial. Different letters indicate significant differences (p < 0.05) assessed with Tukey’s post hoc test.

2021 – Means					
Treatment ⁱ	FB: Sticky Traps, Transplant ¹	FB: Vacuum Sample, Flowering ²	Shot Holes at Flowering ^{3,ii}	FB: Sticky Traps, Harvest ⁴	Marketable Yield ⁵
CTRL	0.5±0.4	10±1.6a	1.2±0.4a	15.0±2.7	1.125±0.25b
O-INS	0.3±0.3	1.75±0.5b	1.2±0.7a	16.6±3.3	1.125±0.3b
AGR-OO	0.0±0.0	0.5±0.5b	0.02±0.03b	7.9±3.0	1.575±0.25ab
PNET-OE	0.0±0.0	0±0b	0.02±0.02b	15.5±3.0	2.025±0.2a
F	1.7	29.4	51.1	2.2	4.7
P-value	0.2	<0.001	<0.001	0.2	0.03
2021 - Pairwise Comparisons					
CTRL vs O-INS	NS	***	NS	NS	NS
CTRL vs AGR-OO		***	***		NS
CTRL vs PNET-OE		***	***		*
O-INS vs AGR-OO		NS	***		NS
O-INS vs PNET-OE		NS	***		*

PNET-OE vs			
AGR-OO	NS	NS	NS

Significance codes: '***' <0.001 '**' <0.01 '*' <0.05

ⁱTreatment abbreviations: Control = CTRL, Organic Insecticide = O-INS, Agribon Row Cover - On-Off = AGR-OO, ProtekNet Row Cover – Open Ends = PNET-OE. ¹Average number of flea beetles per plot collected through sticky traps placed in the field for one week at transplanting. ²Average number of flea beetles collected per plot through vacuum sampling at flowering. ³Shot holes per 1 cm² of leaf area at flowering. ⁱⁱLog tranformed to improve fit. ⁴Average number of flea beetles per plot collected through sticky traps placed in the field for one week before the first harvest. ⁵Average marketable grade yield (kg) per plant, summed across harvest events.

3.3.1. Flea Beetle Abundance (2021)

There was a significant effect of pest management treatment on flea beetles collected through vacuum sampling at flowering in 2021 (Table 5). A Tukey post hoc test revealed there were significantly more flea beetles collected from the CTRL treatment than the O-INS, AGR-OO, and PNET-OE treatments. No flea beetles were collected from any of the PNET-OE plots prior to opening of the mesotunnel ends at flowering. There was no significant effect of pest management treatment on the number of flea beetles collected in sticky traps, either in the week following transplant or in the week preceding the first harvest (Table 5).

3.3.2. Flea Beetle Damage (2021)

There was a significant effect of treatment on the number of shot holes at flowering (Table 5). A Tukey post hoc test revealed there were significantly more shot holes in the samples from the uncovered treatments than in those from the row cover treatments.

3.3.3. Marketable Yield (2021)

There was a significant effect of pest management treatment on marketable yield at harvest time. The marketable yield was significantly higher from the PNET-OE treatment than CTRL and O-INS treatments.

3.4. 2024 Experiment

Table 6. Mean, standard error, and pairwise comparisons for number of flea beetles observed in visual surveys and caught by vacuum and sticky traps, leaf damage (shot holes per 1-cm²), and marketable yield for the pest management treatments during the 2024 eggplant trial. Different letters indicate significant differences (p < 0.05) assessed with Tukey’s post hoc test.

2024 Means						
Treatment ⁱ	FB: Surveys, Entire Season ¹	FB: Sticky Traps, Transplant ²	Shot Holes, Early Season ³	FB: Vacuum Sample, Flowering ⁴	Shot Holes, Late Season ⁵	Marketable Yield ^{6,ii}
CTRL	16.5±1.6a	15.9±4.2	1.8±0.1a	6.5±1.0	2.4±0.4a	0.03±0.008d
O-INS	7.3±1.4b	9.1±2.3	1.6±0.2ab	4.5±1.5	0.9±0.2c	0.07±0.005c
ENET-OO	10.7±1.3b	6.1±0.9	1.1±0.1bc	10.3±4.8	2.4±0.6ab	0.2±0.003b
ENET-OE	8.3±0.7b	8.8±2.8	1.0±0.06c	6.8±1.3	1.4±0.2bc	0.4±0.1a
F	22.3	3.3	9.5	0.8	10.0	60.6
P-value	0.0002	0.07	0.002	0.5	0.003	<0.0001

2024 - Pairwise Comparisons							
CTRL vs O-INS		***	NS	NS	NS	**	*
CTRL vs ENET-OO		**			*	NS	***
CTRL vs ENET-OE		***			**	*	***
O-INS vs ENET-OO		NS			NS	**	**
O-INS vs ENET-OE		NS			*	NS	***
ENET-OO vs ENET-OE		NS			NS	NS	*
Significance codes: '***' <0.001 '**' <0.01 '*' <0.05							

ⁱTreatment abbreviations: Control = CTRL, Organic Insecticide = O-INS, ExcludeNet Row Cover – On-Off = ENET-OO, ExcludeNet Row Cover – Open Ends = ENET-OE. ¹Average number of adult flea beetles counted per 18 plants per plot, averaged across weekly visual surveys. ²Average number of flea beetles per plot collected through sticky traps placed in the field for one week at transplanting. ³Shot holes per 1 cm² of leaf area, averaged across four weekly visual surveys prior to opening/removal of row covers. ⁴Average number of flea beetles collected per plot through vacuum sampling at flowering. ⁵Shot holes per 1 cm² of leaf area, averaged across five weekly visual surveys following opening/removal of row covers. ⁶Average marketable grade yield (kg) per plant, summed across harvest events. ⁱⁱLog tranformed to improve fit.

3.4.1. Flea Beetle Abundance (2024)

There was a significant effect of pest management treatment on the number of flea beetles observed in weekly visual surveys in 2024, averaged across the season (Table 6). A Tukey post hoc test revealed there were significantly more flea beetles in the CTRL treatment than in the ENET-OO, ENET-OE, and the O-INS treatments. The number of flea beetles in the CTRL treatment was double the number in the O-INS treatment and in the ENET-OE treatment. There was no significant effect of pest management treatment on the number of flea beetles collected through sticky traps placed in the field for the week following transplanting or through vacuum sampling at flowering in 2024 (Table 6).

3.4.2. Flea Beetle Damage (2024)

There was a significant effect of pest management treatment on the number of shot holes per 1-cm² of leaf area averaged across the first four, pre-flowering weekly visual surveys, prior to the opening or removal of row covers (Table 6). A Tukey post hoc test revealed there were more shot holes in the CTRL treatment than in the ENET-OO and ENET-OE treatments, and more shot holes in the O-INS treatment than in the ENET-OE treatment.

There was also a significant effect of pest management treatment on the number of shot holes per 1-cm² of leaf area averaged across the last five weekly visual surveys, following the opening or removal of row covers (Table 6). A Tukey post hoc test revealed there were more shot holes in the CTRL treatment than in the O-INS and ENET-OE treatments, and more shot holes in the ENET-OO treatment than the O-INS treatment.

3.4.3. Marketable Yield (2024)

There was a significant effect of pest management treatment on marketable yield in 2024 (Table 6). Marketable yield from the ENET-OE treatment was over 17 times greater than the CTRL treatment, over 6 times greater than the O-INS treatment, and over 2 times greater than the ENET-OO treatment.

4. Discussion

Our study found that row covers were an effective pest management strategy for organic eggplant production, especially when flea beetle pressure was high. Within both the growing seasons of 2019 and 2020, flea beetle pressure was low; for example, control plots averaged 5 times more flea beetles in 2021 and 2024 than in 2019 and 2020. Therefore, results from the first two years reflect the efficacy of these treatments in a lower pest pressure environment. Nonetheless, this study found that row covers are an effective strategy for controlling flea beetles within eggplant cropping systems. Both types of fine-mesh row cover (ProtekNet and ExcludeNet) and the spunbonded row cover (Agribon) provided statistically equivalent or better control of flea beetles than all other treatments across seasons, including conventional insecticides in 2019 and 2020. At the time of row cover removal, the row cover treatments reduced flea beetles and their associated damage significantly below the control treatments in three out of four years (Table 3, Table 4, Table 5, Table 6, Figure 1). Row covers have been found to decrease insect abundance compared to uncovered controls in studies of lepidopteran pests and harlequin bug (*Murgantia histrionica* (Hahn)) in brussels sprouts (*Brassica oleracea*) [16], flea beetles (*Phyllotreta* spp.) in komatsuna (*Brassica rapa* var. *perviridis*) [17], and squash bug (*Anasa tristis* (De Geer)) in acorn squash (*Cucurbita pepo* (L.)) [18].

Fine-mesh row cover treatments had significantly higher yields than both the CTRL and O-INS treatments in 2021 and 2024. These results are consistent with previous field studies that found higher yields from fine-mesh row cover treatments compared to an uncovered control in acorn squash [13], arugula (*Eruca sativa*) and Mizuna mustard greens (*Brassica juncea*) [19]; blackberries (*Rubus* spp.) [52], Chinese cabbage (*Brassica rapa*) [53], and muskmelon (*Cucumis melo* (L.)) [12]. The yield increases we found in fine-mesh row cover treatments may have been attributable to a combination of pest exclusion and microclimate effects. In 2024, yield from the ENET-OE treatment was more than double that of the ENET-OO treatment. ExcludeNet has a larger weave than the ProtekNet row cover used in the first three years (0.95 mm x 0.95 mm, compared to 0.35mm x 0.35mm), and it was less effective at excluding flea beetles. In fact, 2024 was the only year in which the number of flea beetles collected through vacuum sampling when row covers were opened or removed at flowering was not significantly lower in the fine-mesh row cover treatments compared to the CTRL (Figure 2). Weekly surveys revealed that the ENET-OE treatment also had higher (although not statistically significant) damage from flea beetles than the O-INS treatment after flowering, yet the marketable yield from the ENET-OE treatment was almost seven times higher than the O-INS treatment. These results may indicate that a microclimate effect from the ENET-OE treatment provided a benefit to yield on top of the positive effects of pest damage reduction. Spunbonded fabric row covers have been shown to reduce evapotranspiration [54], increase the rate of plant growth [54,55], and increase mean daily air and soil temperatures [55] compared to an uncovered control. Increased temperatures may benefit plant growth, but prolonged exposure to excessively high temperatures may be harmful and lead to yield reductions [56]. Fine-mesh row covers have more moderate effects on microclimate than polypropylene fabric row covers. In field studies, fine-mesh row covers raised air temperatures [12] and soil temperatures and soil moisture [57] compared to an uncovered control, but less than spunbonded fabric row covers.

Maintaining a row cover on a crop for the full season, rather than removing it after flowering, can present additional challenges, including increased labor requirements, the opportunity cost of additional time when the row cover cannot be used on another crop, and potential exclusion of pollinators and natural enemies that might otherwise control secondary pests. In a study of acorn squash, Pulliam et al [20] found no significant difference in either bee activity or seeds per fruit in an open-ends ExcludeNet mesotunnel treatment compared to an uncovered treatment, indicating comparable levels of pollination. However, effects on pollination could vary in mesotunnels of

different sizes and configurations. Böckmann [53] found higher aphid abundance and lower natural enemy abundance in plots covered with fine-mesh row covers compared to open field conditions. Further research comparing on-off and open-ends row cover strategies is needed to provide informed management recommendations for growers.

The reflective mulch, essential oils, and organic insecticide treatments were generally less effective than row covers at reducing flea beetle abundance and damage. During the 2019 season, the mulch treatments did not differ in flea beetle abundance or damage (Table A1). Despite evidence from laboratory studies of essential oils [24,58,59] and studies involving the intercropping of eggplant and culinary herbs [60,61], this study did not find positive effects from the spraying of plant essential oils or commercial essential oil concentrates. We did not see any benefit from spraying rosemary and eucalyptus essential oils on ProtekNet in the PNET-OO+R-OIL and PNET-OO+E-OIL treatments in 2019 compared to the PNET-OO treatment alone. The commercial essential oil mixture and neem oil did not perform well in 2020, as these treatments had lower yields than both the PNET-OO treatment and the conventional insecticide regime (Table 4). We believe this drop in yield may have been due to minor phytotoxic burns that the essential oils caused when sprayed directly on the crop. In a previous study, spraying rosemary essential oil and the commercial neem concentrate directly on brassicaceous leafy greens caused phytotoxicity burns [19].

The O-INS treatment rarely differed from the control in 2019, 2020, and 2021. In 2024, the O-INS treatment had fewer flea beetles, lower flea beetle damage, and higher yield than the CTRL, but the ENET-OE treatment outperformed the O-INS treatment across these metrics. Our results are consistent with previous studies where treatments of pyrethrins and spinosad did not differ from an untreated control in flea beetle abundance in organic-compliant production of leafy greens [19] or eggplant [62]. However, our results contrast with field studies where eggplant flea beetles were effectively controlled by treatments of pyrethrins [7] and spinosad [7,10,63]. In our study, the organic insecticides may have caused insect mortality upon application, but reinvasion by flea beetles between weekly applications after the residual toxicity disappeared could have diminished the overall effectiveness of the treatment. We applied organic insecticides between four and nine times per season, representing a considerable investment of labor and material costs. In a two-year study of acorn squash, a treatment of common organic insecticides, applied weekly, had double the labor and input costs of an untreated control and, in one year, was half as profitable as the control [13]. Considering the high cost of organic insecticides, our results underscore the need for effective, organic-compliant flea beetle management options for eggplant growers.

In all four years of this study, the experimental sites were located on the same research farm. Flea beetle abundance was greater in the last two years of the study, when the field sites were in the organic section of the research farm, which had a history of more frequent cultivation of solanaceous crops compared to the conventional section of the farm. This pattern indicates that flea beetle abundance and effects of pest management strategies are likely to vary in different growing sites, and the efficacy and profitability of different pest management strategies are likely to differ based on insect pest pressure.

5. Conclusions

We found that row covers were an effective strategy for managing flea beetles in organic eggplant production, especially under high flea beetle pressure. In our study, row covers usually provided equivalent or better control of flea beetles and equivalent or higher marketable yield than the control and the organic insecticide treatments. The population of flea beetles can vary greatly from location to location, and knowledge of this should inform management decisions. In areas and times where flea beetle pressure is high, row covers may provide organic producers with an effective management tactic that is compatible with organic certification requirements.

Row covers were more effective at reducing flea beetle abundance and damage and increasing marketable yield than the other organic-compliant pest management strategies we tested. The essential oil treatments in 2019 and 2020 rarely differed from the other treatments, and they never

had statistically lower flea beetle abundance and damage or higher yield than a fine-mesh ProtekNet treatment alone. We found that silver reflective mulch did not have statistically significant effects on pest pressure and was associated with a significant reduction in yield. Furthermore, both the essential oils and silver mulch treatment produced phytotoxic effects on the eggplant leaves. The organic insecticide treatment rarely controlled flea beetles better than the untreated control in this study and always had statistically equivalent or lower yield than row cover treatments.

Our study highlights the potential benefits of deploying row covers with the open-ends strategy on pollinator-dependent crops. There were no significant differences between spunbonded and fine-mesh row covers across any of the metrics we measured in 2019 through 2021, the three years of the study when both row cover types were included. We saw the biggest difference in marketable yield between treatments in 2024, when the open-ends ProtekNet treatment had over seventeen times greater marketable yield than the control and more than double the marketable yield of the on-off ProtekNet treatment. More research is needed to compare open-ends and on-off row cover management strategies to better understand effects on microclimate, pollination, and secondary pest pressure.

Supplementary Materials: The following supporting information can be downloaded at: Preprints.org.

Author Contributions: Conceptualization, E.L., R.D.B., V.H. D.G., R.T.B., and M.W.; methodology, E.L., D.G., R.D.B., V.H., K.P., R.T.B., D.S., M.W., and R.K; software, D.G., E.L. and R.D.B.; formal analysis, D.G., E.L. and R.D.B.; investigation, E.L., R.D.B., V.H., K.P., D.S., and R.K.; resources, D.G.; data curation, E.L., R.D.B., and V.H.; writing—original draft preparation, E.L. and R.D.B.; writing—review and editing, E.L., D.G., R.D.B., V.H., K.P., R.T.B., D.S., M.W., and R.K; visualization, E.L.; supervision, D.G.; project administration, E.L., R.D.B., V.H, D.G., and K.P.; funding acquisition, D.G, R.T.B., and M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Institute of Food and Agriculture, U.S. Department of Agriculture Hatch Grant (KY008079), the Kentucky Department of Agriculture Specialty Crop Block Grant (PON2 035 1900003060 AM180100XXXXG007), and the National Institute of Food and Agriculture, U.S. Department of Agriculture Organic Agriculture Research and Extension Initiative Grant (2023-51300-40855).

Data Availability Statement:

The data presented in this study are available on request from the corresponding author: emlo232@uky.edu.

Acknowledgments: We would like to thank Daniel Potter for commenting on project design and for reviewing this manuscript. We would like to thank Steve Diver, Neil Wilson, Aaron German, and Jay Tucker at the University of Kentucky’s Horticulture Research Farm for all their assistance and guidance with plot setup, planting, and maintenance. We would also like to thank Kyla O’Hearn, Kendall Archer, Simon Aaronson, Briana Bazile, Yuuki Cherian, Sarah Clark, Ryan Depp, Alexis Gauger, Kylie Ryan, Turner Siddens, and Kantima Thongjued for their assistance with harvesting and fieldwork.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CTRL	Control
O-INS	Organic Insecticide
C-INS	Conventional Insecticide
AGR-OO	Agribon Row Cover - On-Off
PNET-OO	ProtekNet Row Cover - On-Off
PNET-OO+R-OIL	ProtekNet Row Cover + Rosemary Oil - On-Off

PNET-OO+E-OIL	ProtekNet Row Cover + Eucalyptus Oil - On-Off
ES-OIL	Essentria Essential Oil
N-OIL	Neem Oil
PNET-OE	ProtekNet Row Cover - Open Ends
ENET-OO	ExcludeNet Row Cover – On-Off
ENET-OE	ExcludeNet Row Cover – Open Ends

Appendix A

Appendix A.1

Table A1. Means and standard errors for number of flea beetles sampled with vacuum and sticky traps, leaf damage (shot holes per 1-cm²), and marketable yield (kg/plant) for the plastic mulch treatments in 2019.

Treatment	FB: Sticky Traps, Early Season ¹	FB: Vacuum Sample at Flowering ^{2,i}	Shot Holes at Flowering ³	FB: Sticky Traps at Harvest ⁴	FB: Vacuum Sample at Harvest ⁵	Marketable Yield ⁶
Black Plastic	0.3±0.06	0.5±0.04	0.02±0.006	10.4±0.5	7.2±0.8	8.2±0.5
Silver Plastic	0.2±0.05	0.4±0.2	0.02±0.006	8.6±1.6	6.5±1.1	6.4±0.5
F	2.9	0.6	0.2	2.3	0.3	6.7
P-value	0.1	0.5	0.7	0.2	0.6	0.04

¹Average number of flea beetles per plot collected through sticky traps placed in the field for one week, beginning two weeks after transplanting. ²Average number of flea beetles collected per plot through vacuum sampling at flowering. ³Shot holes per 1 cm² of leaf area at flowering. ⁴Average number of flea beetles per plot collected through sticky traps placed in the field for one week before the final harvest. ⁵Average number of flea beetles collected per plot through vacuum sampling after the final harvest. ⁶Average marketable grade yield (kg) per plant, summed across harvest events. ⁱSquare-root transformed to improve fit.

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