Comparison of Row Cover Systems for Pest Management in Organic Muskmelon in Iowa

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Abstract. Organic growers of cucurbit (Cucurbitaceae) crops in the midwest US have difficulty managing bacterial wilt, a fatal disease whose pathogen (*Erwinia tracheiphila*) is transmitted by striped (*Acalymma vittatum*) and spotted (*Diabrotica undecimpunctata howardi*) cucumber beetles. Registered organic insecticides lack effectiveness and host plant resistance is rare in commercial cultivars of many cucurbit crops. Row covers are widely used as barriers to minimize pest access, but the spunbonded polypropylene fabric covering traditional low tunnels must be removed at bloom to prevent overheating and facilitate pollination, thereby exposing the crop for the rest of the season. "Mesotunnels" – nylon-mesh fabric covering 3.5-ft-high hoops – provide more space than low tunnels and mitigate overheating. In field experiments at Iowa State University (Ames, IA, USA) during 2016-18, two variations of mesotunnels – full-season tunnels [with purchased bumble bees (*Bombus impatiens*) added for pollination] and part-season tunnels (with covers removed for 2 weeks during bloom to provide pollinator access) – were compared with low tunnels and a non-covered treatment for organic 'Athena' muskmelon (*Cucumis melo)* production. Based on scouting results, full-season mesotunnels required no insecticides and part-season mesotunnels averaged 0.6 sprays per season compared to 1.0 and 5.0 sprays per season for the low-tunnel and no-tunnel treatments, respectively. Incidence of pest and disease damage was zero for the full-season mesotunnels, 5% to 22% for the part-season mesotunnels, and 37 to 70% for both of the other treatments. Marketable yield for the full-season mesotunnel treatment significantly exceeded the non-covered treatment in each year and mean marketable yields were numerically higher than for the other treatments. Both mesotunnel treatments had marketable yield that averaged more than twice that of the other treatments in

each year. Economic analysis (partial budget and cost-efficiency ratio) indicated that mesotunnels were likely to be more profitable in Iowa, USA than either low-tunnel or no-tunnel systems, but also that the year-to-year differential among treatments in profitability could be substantial. Additional experiments are needed to evaluate the efficacy of these integrated pest management practices, and their profitability at spatial scales representative of commercial farms.

Introduction

Organic production of muskmelon (*Cucumis melo*) in Iowa, USA is limited by several insect pests and the bacterial pathogens they vector. Important insect pests include striped cucumber beetle (*Acalymma vittatum*), spotted cucumber beetle (*Diabrotica undecimpunctata howardi*) and squash bug (*Anasa tristis*) (Bruton et al., 2003; Saalau Rojas et al., 2015). In addition to causing feeding damage and seedling mortality, cucumber beetles vector the bacterium *Erwinia tracheiphila*, the causal agent of cucurbit bacterial wilt (Brust, 1997; Fleischer et al., 1999; Hoffmann et al., 2000). Squash bug causes feeding damage on muskmelon and vectors the bacterium *Serratia marcescens*, the causal agent of cucurbit yellow vine disease (CYVD) (Bruton et al., 2003; Doughty et al., 2016; Neal, 1993). Both diseases can cause substantial yield losses in Iowa, USA and other production states (Bruton et al., 2003; Saalau Rojas et al., 2015)

Organic insecticides recommended for cucurbit (Cucurbitaceae) pests, including pyrethrins, neem oil, and kaolin clay, have minimal residual activity but are highly toxic to pollinators and other beneficial insects when they get in contact with them (Bond et al., 2012; Doughty et al., 2016; Middleton, 2018; Minter and Bessin, 2014; Perez et al., 2015). Low tunnels can serve as an alternative or supplement to insecticides because they create a physical barrier between plants and pests. Low tunnels typically consist of spunbond polypropylene row cover material suspended above plants on 1.5-ft-tall wire hoops and are deployed immediately after transplanting seedlings. The edges of the row cover are buried in soil or secured by sandbags to prevent insect pests from accessing the plants. However, because muskmelon is exclusively insect-pollinated, row covers in low-tunnel systems must be removed at flowering to allow pollinators to access the female flowers (Hodges and Baxendale, 2007; Minter and Bessin, 2014). Furthermore, these row covers cannot be reapplied after pollination because they can overheat and even kill plants (Arancibia, 2018; Gauger, 2010; Mueller et al., 2006), so their pest and disease deterrence is limited to the early part of the growing season.

A study in Iowa, USA attempted to prolong the pest-protection benefits of spunbond polypropylene row covers by delaying their removal until 10 d after flowering (Saalau Rojas et al., 2015). In one delayed-removal treatment the ends of the tunnels were opened to permit pollinator access after female flowers began to bloom; in another treatment, bumble bee boxes were placed inside the ends of low tunnels when flowering began and removed along with the row covers 10 d later. Both treatments reduced incidence of bacterial wilt compared to the traditional strategy in which row covers were removed at flowering, but delayed removal of the row covers led to a 1-week delay in harvest. Delayed harvest can reduce profitability for growers seeking price premiums for early yield.

On-farm trials in Pennsylvania tested an alternative row cover material – nylon-mesh insect netting – in an effort to prolong the duration of low tunnel protection (Gauger, 2010). The mesh netting was expected to permit full-season protection without overheating plants. Growers deployed modified low tunnels in winter squash (*Cucurbita* sp.) and caterpillar tunnels in cucumber (*Cucumis sativus*), and placed bumble bee boxes inside the tunnels for pollination. The row covers were removed only to harvest crops and were replaced immediately afterward. Growers expressed satisfaction with cucumber yields and fruit quality and found no evidence of beetles passing through the row cover material; however, they were disappointed with low winter squash yields. Furthermore, the large size of the winter squash plants resulted in the plants pressing against the mesh netting. Growers observed squash bugs feeding and laying eggs on the leaves from outside the tunnels, and the squash tendrils wrapped through the netting and created small rips in it.

"Mesotunnels" (Nelson, 2019) have been proposed as a modified barrier system to mitigate limitations of organic pesticides, low tunnels, and spunbond polypropylene row covers, but have not been tested experimentally. Mesotunnels consist of nylon-mesh insect netting suspended on 3.5-ft-tall hoops. A single piece of netting spans three rows of plants and the edges of the netting are held down with plastic bags filled with rocks or sand. The greater interior space in mesotunnels compared to low tunnels facilitates pollinator movement while preventing pest insects from reaching the plants by minimizing plant-to-fabric contact. The mesh row cover fabric facilitates air circulation, which prevents overheating of plants and potentially enabling growers to prolong the covered period later into the season. Pollination in mesotunnel systems can be accomplished by local pollinators or purchased bumble bees. For "full-season" mesotunnels, purchased hives of bumble bees can be inserted under the tunnels when female flowers start to appear. Full-season mesotunnels could provide continuous protection from cucumber beetles and squash bugs from transplanting until harvest. In "part-season" mesotunnels, row covers are removed for 2 weeks when female flowers start to appear in order to allow access by pollinators, then replaced for the rest of the season. During the uncovered period, pest control consists of monitoring pests and applying insecticides when economic thresholds are reached.

The objective of this research was to compare yield, disease management, and cost effectiveness of mesotunnel (full- and part-season), low tunnel, and non-covered systems for organic muskmelon production in Iowa, USA.

Materials and Methods

Field Preparation. The trial was conducted on organic-certified land annually from 2016 through 2018 at the Iowa State University Horticulture Research Station near Gilbert, IA, USA (lat. 42°6’23.748” N, long. 93°35’23.372” W). Organic composted cow and horse manure (Iowa State University Compost Facility, Ames, IA, USA) was applied after rough tillage and incorporated within 24 h of application (Table 1). Compost application was based on pre-plant soil assays for nitrogen (N), phosphorus (P), and potassium (K). To meet remaining N-P-K needs, organic bagged fertilizer was broadcast in plant rows; these included 2N-1.30P-2.49K (Midwestern BioAg, Madison, WI, USA) in 2016, and 4N-2.61P-3.32K (Suståne Natural Fertilizer, Inc., Cannon Falls, MN, USA) in 2017 and 2018. Subsequently, drip tape (The Toro Company, Bloomington, MN, USA) was laid under black plastic mulch on 6-ft row centers. Organic chopped corn (*Zea mays*) stover was applied to the alleys between plastic mulch at a 6-inches depth for weed control.

‘Athena’ muskmelon seedlings were raised from non-treated seeds (Seedway LLC, Hall, NY, USA) in organic potting mix (Mix no. 12; Beautiful Land Products, West Branch, IA, USA) in a greenhouse. 2-week-old seedlings were hardened off in an outdoor shade house under nylon-mesh insect netting (0.07 by 0.04 inch) (ProtekNet; DuBois Agrinovation, Saint-Rémi, QC, Canada) for 1 week before transplant.

Plot locations were rotated so that the same land was not used in consecutive years. Plots were planted to pepper (*Capsicum anuum*) and broccoli (*Brassica oleracea* var. *italica*) prior to year 1 of the trial, cereal rye (*Secale cereale*) prior to year 2, and a mixture of cowpea (*Vigna unguiculata*), sunn hemp (*Crotalaria juncea*) and hybrid sorghum-sudangrass (*Sorghum ×drummondi*) prior to year 3.

Experimental design. Treatments included low tunnels (LT), part-season mesotunnels (PMT), full-season mesotunnels (FMT), and a non-covered control (NC) (Table 2). Treatment subplots were arranged in a randomized complete block with four replications, except in 2017 when treatments were arranged in a Latin square design. Each subplot consisted of three adjacent 30-ft-long rows spaced 6 ft apart; in row-covered treatments, each 3-row subplot was covered by a single piece of fabric.

The LT treatment consisted of spunbond polypropylene row covers (Agribon® AG-30; Berry Global, Evansville, IN, USA) covering 18-inch-high wire hoops (Arancibia, 2018). Row covers on LTs were removed permanently when female flowers began to appear, after which insecticide sprays were applied until harvest based on results of scouting for insect pests (Brust and Foster, 1999; Doughty et al., 2016; Middleton, 2018). PMT subplots had nylon-mesh row covers on 3.5-ft-tall conduit hoops; the covers were removed at flowering to allow pollinator access, then replaced 2 weeks later. Organic insecticides were applied during the uncovered period based on results of scouting. FMT treatment subplots included the same mesh covering and hoop support as PMTs, but the covers remained in place until harvest began. To ensure pollination, a single bumble bee box (Koppert Biological Systems, Inc., Howell, MI, USA) was placed inside each FMT subplot at flowering. The NC control had no row covers; insecticides were applied to this treatment based on scouting thresholds.

Three-week-old muskmelon seedlings were transplanted into plastic mulch with 2-ft in-row spacing (**Table 1**). A water wheel transplanter (1600 series II; Rain-Flo Irrigation, East Earl, PA, USA) was used to transplant seedlings.

All row cover treatments were installed on the same date that seedlings were transplanted. In PMT and FMT, conduit hoops were centered over rows at 6-ft spacing and ends were pushed 6 to 8 inches deep in the soil. Conduit hoops were created by bending 10-ft lengths of 1-inch-diameter galvanized metal conduit pipe with a conduit bender (QuickHoops™ 4 ft ×4 ft Low Tunnel Bender; Johnny's Selected Seeds, Fairfield, ME, USA). After the nylon-mesh row covers (26 ft wide) were cut to 40-ft lengths and draped over three rows of conduit hoops, edges were secured to the soil surface using rock bags. Rock bags were prepared in advance by filling 36-inch lengths of hold-down netting (Berry Hill Irrigation, Inc., Buffalo Junction, VA, USA) with river rock and knotting both ends. In the LT treatment, 1.5-ft-tall hoops made of 9-gauge galvanized steel wire were centered over each 30-ft row at 2.5-ft spacing and ends were inserted approximately 5 inches into the soil. Spunbond polypropylene row covers (26 ft × 40 ft) were draped over each LT subplot and edges were secured to the soil surface using rock bags.

In 2016, an action threshold for row cover removal was reached when 50% of the plants in LT, PMT, and FMT plots had female flowers blooming. In 2017 and 2018, this action threshold was modified to begin at the first appearance of any blooming female flowers, in order to ensure sufficient time for pollination. Row covers in the LT subplots were then removed permanently, and PMT subplots were uncovered and then re-covered 2 weeks later. In the FMT treatment, a bumble bee box (Class C; Koppert Biological Systems, Inc.) was placed on a layer of bricks inside one end of each tunnel. Class C hives were discontinued after 2017, so comparable bumble bee hives (Excel Startup; Koppert Biological Systems, Inc) were used in

2018. Flight holes in the hives were oriented parallel to the crop rows, and ventilated plastic laundry baskets were placed over the tops of the hives to protect against rain and sunlight. Row cover ends were re-closed immediately after bumble bee hives had been installed.

Subplots were hand-weeded during periods when they were not protected by row covers (NC, LT, and PMT treatments) or immediately prior to placement of bumble bee hives (FMT treatment). All treatments were scouted weekly throughout the growing season for disease symptoms and insect injury. Fungicide sprays of copper hydroxide (Champ® WG; Nufarm Americas Inc., Burr Ridge, IL, USA) were applied to uncovered subplots or sprayed directly through the nylon-mesh row covers based on results of monitoring severity of foliar diseases. Insecticides were applied based on insect pest monitoring data collected weekly during periods when plants were not protected by row covers (NC, LT, and PMT treatments). Kaolin clay (Surround™ WP; Tessenderlo Kerley, Inc., Phoenix, AZ, USA), pyrethrins (Pyganic® Crop Protection EC 5.0 ii; MGK Company, Minneapolis, MN, USA), and neem oil (Trilogy® 70EC; Certis USA, L.L.C., Columbia, MD, USA) were tank mixed and applied to a treatment if an economic threshold for cucumber beetle or squash bug was reached. When harvest began, all row covers were permanently removed.

Field Data Collection

Pest-insect monitoring and insecticide applications. Striped and spotted cucumber beetles were scouted in all treatments during noncovered periods twice weekly until plants developed six leaves, and once weekly thereafter. Pest insects were counted in three arbitrarily selected 1.6 × 1.6-ft quadrats in the center row of each subplot and the numbers averaged for each treatment. The spray threshold for both species of cucumber beetles was 0.5 beetles per quadrat until plants developed six leaves, then one beetle per quadrat thereafter (Brust and Foster, 1999). The spray threshold for squash bugs was one egg mass, nymph, or adult per sampling quadrat throughout the season (Doughty et al., 2016). If a threshold was met for either cucumber beetles or squash bugs, a tank mix consisting of at least two insecticides was sprayed (Table 3).

Disease and insect injury monitoring and fungicide applications. Incidence of disease symptoms and insect injury was recorded weekly in the center row of plants in each subplot. A plant was considered to have insect injury if the presence of feeding wounds coincided with a visible decline in plant vigor. The first application of fungicide was based on scouting assessments of the severity of symptoms caused by foliar fungal diseases. Leaf tissue samples of symptomatic plants were submitted to the Iowa State University Plant and Insect Diagnostic Clinic (Ames, IA, USA) for diagnosis. Copper hydroxide was applied to uncovered subplots or sprayed directly through the nylon-mesh row covers.

Yield. Yield data were collected from the center row of each subplot. Ripe fruit were harvested every 2 d and categorized as marketable or nonmarketable, then counted and weighed. Fruit were classed as nonmarketable if the combined surface area of damage (i.e., sunscald, insect or rodent feeding injury) exceeded 5%, if damage extended into the fruit flesh (i.e., cracking or insect, bird, or rodent feeding injury), or if soft spots were present (US Department of Agriculture, Agricultural Marketing Service, 2006). Fruit weighing less than 3 lb were considered nonmarketable.

Temperature. Air temperature was measured hourly beneath row covers from transplanting until row cover removal. One temperature sensor (WatchDog A-150; Spectrum Technologies, Inc., Aurora, IL, USA) was placed 6 inches above the soil surface between two rows of plants in each of three FMT, LT, and NC subplots. Daily maximum temperatures were averaged for each treatment.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using statistical software (RStudio ver. 1.1.383; RStudio, Inc., Boston, MA, USA). Significant ($P < 0.05$) effects were investigated by separation of means with Tukey's honestly significant difference multiple comparisons adjustment. Because homogeneity of variance criteria for pooling the 3 years of data were not met, data for each year were analyzed separately.

Economic Analysis

We conducted a partial budget analysis (Calkins and DiPietre, 1983) to compare cost and economic efficiency of the treatments. As part of this analysis, we used an "equivalent annual cost" (EAC) approach to convert the purchase cost of the nylon-mesh row cover to an annual cost of using this netting material for a 3-year life expectancy, and assumed spunbond polypropylene fabric had a 1-year life expectancy (HM Nelson, unpublished data). Conduit and wire hoops were treated as having a 5-year life expectancy. Additional cost components included sandbags, purchased bumble bee hives, pesticides, and estimated labor cost. Labor costs included setting up and taking down the low tunnels and mesotunnels, and spraying pesticides.

We compared economic efficiency of the treatments using a relative cost-efficiency ratio (Polasky et al., 2011; Tan-Torres Edejer et al., 2003). This ratio expresses the increase in profit (in percentage of marketable muskmelon) for each dollar invested in the per-acre production cost. Using treatments 'X' and 'Y' for comparison as an example, relative cost-efficiency ratio indicated that each dollar invested in the production system of treatment X would yield a higher percentage of marketable muskmelon than for the system of treatment Y if this ratio exceeds 1. Relative cost efficiency ratio for each treatment was calculated using the following equation:

$$\text{Relative cost efficiency ratio} = \frac{\frac{\text{yield}}{\text{cost}} \text{for treatment X}}{\frac{\text{yield}}{\text{cost}} \text{for treatment Y}}$$

Results and Discussion

Insecticide and fungicide applications. Full-season mesotunnels required no insecticide applications (Table 3). In contrast, the NC treatment averaged 5.0 insecticide sprays per season, LT averaged 1.0 sprays per year, and PMT averaged 0.6 sprays per season.

Disease and pest injury. Bacterial wilt was the predominant source of damage to plants, although anthracnose (caused by the fungus *Colletotrichum orbiculare*) and direct insect feeding injury were also noted (data not shown); therefore, disease and pest injury were combined in representing incidence of injury (Table 4). Pest injury was caused primarily by cucumber beetles. Full-season mesotunnels had no disease or pest-injury symptoms in any year (Table 4). In 2016, plants in part-season mesotunnels experienced significantly lower incidence of disease and pest-injury symptoms (13%) than the non-covered control (55%) and low tunnels (51%). In 2017, full-season mesotunnels (0%) had significantly lower incidence of disease and pest injury than low tunnels (55%), and in 2018, both full-season mesotunnels (0%) and part-season mesotunnels (5%) had significantly lower incidence of disease and pest injury than the non-covered control (70%). Tables 3, 4, and 5 indicate that mesotunnels reduced both the need for insecticide sprays and the incidence of disease and pest-associated crop damage compared to the other treatments.

Yield. The full-season mesotunnel treatment yielded significantly ($P < 0.05$) greater weight of marketable fruit than all other treatments in 2016 (Table 5). In 2017 and 2018, full-season mesotunnels, part-season mesotunnels, and low tunnels yielded statistically equal weights of marketable fruit, but only the mesotunnel treatments had significantly higher marketable yield than the non-covered control. Marketable yield in low tunnels was equivalent to the non-covered control in each year. Patterns for number of marketable fruit produced in each treatment were consistent with those of weight of marketable fruit in 2016 and 2018; in 2017, however, no treatment differed statistically from any other treatment. Also noteworthy is the significantly greater weight and number of non-marketable fruit in the non-mesotunnel treatments than the mesotunnel treatments, indicating the impact of the mesotunnels in protecting the fruit. In sum, mesotunnel treatments delivered the highest marketable yields, and the full-season treatment produced marketable yields that were more consistent among years than for the other treatments. These results reflect more consistent protection from cucumber beetles and bacterial wilt in the FMT treatment than in the other treatments.

Air temperature. Average daily maximum temperatures inside FMT plots were within 1.0-7.6 ºF of average ambient daily maximum temperature (NC treatment) in 2016, whereas average daily maximum temperatures beneath spunbond polypropylene row covers (LT treatment) were 22.6-52.6 ºF numerically warmer than ambient temperatures (Fig. 1). The maximum temperature under the FMT treatment was 108.3 ºF, compared to 153.4 ºF under the LT treatment and 101.3 ºF ambient temperature. Numerical temperature differences among treatments were similar in 2017 and 2018 to those recorded in 2016 (Nelson, 2019).

Economic analysis. From 2016 to 2018, the annual costs associated with the mesotunnel system in the 540 ft^2 test plot ranged from \$675 to \$718 for the PMT treatment and \$761 to \$844 for the FMT treatment (Table 6). The cost variations across years for every treatment were closely related to labor cost, including the frequency of insecticide spraying and installation and removal of the row covers. The NC treatment required the most insecticide spraying but had no cost related to installation/disassembling labor. In comparison, all row-cover systems led to less spraying and thus lower chemical costs. In the row-cover tunnel production systems, installation and disassembling labor cost accounted for the majority of production costs. Mesotunnel supplies and bumblebee hives accounted for the majority of non-labor production costs (97-99%). Using a field size large enough to spread the costs could defray these quasi-fixed expenses, and it is possible that per-acre costs for materials would decline as the production scale increased.

Fig. 2 shows relative cost-efficiency ratio for applying three tunnel production systems compared to a non-cover treatment as well as the relative efficiency across the three row-cover systems, respectively. Implementing any row-cover system resulted in lower cost efficiency almost for all 3 years, as the relative cost-efficiency ratios were always lower than 1 except PMT and FMT in 2016. This is due to labor costs related to the installation and disassembling of the row cover structures. Specifically, the cost efficiency of an LT or PMT production system relative to a non-cover system was more stable across years than the FMT production system.

The FMT or PMT production systems were more cost efficient than the LT system in most of the years, and in all the 3-year averages (Fig. 2). Moreover, the FMT cost efficiency is equivalent to the PMT production system, except in 2016. Across all 3 years, the FMT cost efficiencies are significantly higher for 2016 than those for 2017 and 2018. This is because the FMT had much higher marketable yield in 2016 compared to the other three treatments, and the yield difference for the other three treatments was quite similar across years.

Both cucumber beetle populations and bacterial wilt incidence can vary dramatically from year to year, even in the same location (Saalau Rojas et al. 2015), with the result that the extent of the protective advantage provided by tunnels is likely to vary from year to year. It is therefore reasonable to assume that locations with more frequent and serious outbreaks of the pest-disease complex will realize the greatest profit advantage from adopting mesotunnels in organic muskmelon production (Saalau Rojas et al., 2011).

Our plot size was well below the scale of most commercial growers of organic muskmelon. Clearly, assumptions about potential economies of scale need to be tested by larger field experiments to mimic the spatial scales of commercial production.

Conclusions

Our study is the first to evaluate mesotunnels as a production system for organic muskmelon production. In the absence of such physical barriers, organic muskmelon growers in the midwest US struggle to effectively suppress pest insects and the pathogens they vector which frequently decimate plantings. Low tunnels provide early-season protection, but because they must be removed at bloom to avoid overheating the crop they leave the plants exposed for the rest of the season. Mesotunnels can provide an effective barrier for all, or nearly all, of the growing season because of their more breathable mesh covering.

Results of our field trials provided evidence that mesotunnels can effectively safeguard organic muskmelon, resulting in higher and more consistent marketable yield than either low-tunnel or no-tunnel systems. Economic analysis indicated that mesotunnels are likely to be more profitable than either low-tunnel or no-tunnel systems, but also that the differential among treatments in profitability among years may be substantial.

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Table 1. Timeline of field preparation and establishment of row cover experiments for pest exclusion on organic muskmelon in 2016, 2017, and 2018 at the Iowa State University Horticulture Research Station, Ames, Iowa, USA. Entries indicate date of completion of each task.

Operation	**Date**		
	2016	**2017**	**2018**
Soil and compost sampling for nutrient recommendation	15 Mar	31 Mar	29 Mar
Rough tillage	3 May	11 Apr	ND[i]

Applied composted manure and till	16 May	9 May	26 Apr
Seeded muskmelon into 48-cell trays	10 May	11 May	3 May
Applied fertilizer, installed drip tape and black plastic mulch	17 May	15 May	18 May
Applied organic chopped corn stover to alleys	23 May	31 May	18 May
Hardened off muskmelon seedlings	18 May	22 May	18 May
Transplanted seedlings and installed treatments	1 Jun	31 May	23 May
Low tunnel (LT) row covers permanently removed	5 Jul	22 Jun	13 Jun
Part-season mesotunnels (PMT) temporarily removed	22 Jun	22 Jun	13 Jun
Full-season mesotunnel (FMT) bumble bee boxes installed	24 Jun	27 Jun	19 Jun
Part-season mesotunnel (PMT) row covers reapplied	5 Jul	7 Jul	28 Jun

[i] The date of rough tillage was not recorded in 2018.

Table 2. List and description of the row cover treatments applied for pest exclusion on organic muskmelon experiments during 2016, 2017, and 2018 at the Iowa State University Horticulture Research Station, Ames, Iowa, USA.

Treatment	Description[i]
Non-covered	No row covers employed.
Low tunnel	1.5-ft-tall hoops; spunbond polypropylene fabric removed when bloom[ii] began (no reinstallation after).
Part-season mesotunnel	3.5-ft-tall hoops; nylon-mesh fabric removed for 2 weeks during bloom[ii], then reinstalled.
Full-season mesotunnel	3.5-ft-tall hoops; nylon-mesh fabric all season; purchased bumble bee hive inserted when bloom[ii] began.

[i] 1 ft = 0.3048 m.

[ii] First appearance of female flowers.

Table 3. Number of organic insecticide and fungicide applications per treatment in the organic muskmelon trials in 2016, 2017, and 2018 to control insect pests and diseases at the Iowa State University Horticulture research Station, Ames, Iowa, USA.

Treatment	Insecticide applications (no.) [i]			Fungicide applications (no.)		
	2016	2017	2018	2016	2017	2018
Non-covered[ii]	6	6	3	2	2	3
Low tunnel	2	1	0	2	2	2
Part-season mesotunnel	1	1	0	2	2	3
Full-season mesotunnel	0	0	0	2	2	3

[i] In non-covered subplots in 2016, two early-season insecticide tank-mixes for cucumber beetle management substituted spinosad (Entrust®SC Naturalyte®; Dow AgroSciences LLC, Indianapolis, IN, USA) for neem oil. Subsequently, neem oil was substituted for spinosad. Some sprays in 2016 exchanged pyrethrins (Pyganic®; MGK Company, Minneapolis, MN, USA) and/or neem oil (Trilogy®; Certis USA, L.L.C., Columbia, MD, USA) for a mixture of pyrethrins and azadirachtin (Azera; MGK Company, Minneapolis, MN, USA) or azadirachtin only (Aza-Direct; Gowan Company, Yuma, AZ, USA). On 23 Jun 2016, buffalo gourd root powder (Cidetrak® D; Trécé Inc., Adair, OK, USA) was added to the tank-mix with kaolin clay (Surround™ WP Tessenderlo Kerley, Inc., Phoenix, AZ, USA) and azadirachtin, but its use was discontinued thereafter.

[ii] Please refer to Table 2 for descriptions of each treatment.

Table 4. Incidence of combined disease and insect-pest injury on organic muskmelon plants, per treatment in 2016, 2017, and 2018.

Row cover treatment	Percent incidence of disease and insect-pest injury [i]		
	2016	**2017**	**2018**
Non-covered[ii]	55 a[iii]	50 ab	70 a
Low tunnel	51 a	55 a	37 ab
Part-season mesotunnel	13 b	22 ab	5 b
Full-season mesotunnel	0 b	0 b	0 b

[i] Treatment means of percent incidence of disease and pest injury were based on visual assessments of plants in the middle row of each treatment subplot. A plant was considered to be injured if cucumber beetle feeding, bacterial wilt symptoms, or both were severe enough to cause a visible decline in plant vigor.

[ii] Please refer to Table 2 for descriptions of each treatment.

[iii] Within each year, means in a column followed by the same letter do not differ significantly ($P < 0.05$) based on Tukey’s honestly significant difference critical values.

Table 5. Effect of treatments on yield (lb and no. of fruit) on 30-ft-long plots of organic muskmelon in 2016, 2017, and 2018.

Year	Treatment[i]	Mean fruit wt (lb) [ii, iii]		Mean fruit (no.)[i, iii]	
		Marketable	Non-marketable[iv]	Marketable	Non-marketable[iv]
2016	NC	11.5 b	113.9 ab	2.8 b	35.5 b
	LT	22.4 b	168.9 a	5.5 b	53.0 a
	PMT	40.3 b	136.1 ab	9.0 b	37.4 b
	FMT	137.7 a	104.2 b	29.5 a	24.3 b
2017	NC	35.0 b	79.6 ab	7.0 a	26.8 ab
	LT	47.5 ab	110.2 a	10.5 a	31.0 a
	PMT	95.2 a	94.2 a	19.8 a	27.3 ab
	FMT	104.6 a	43.0 b	18.8 a	15.0 b
2018	NC	28.2 b	85.9 a	5.8 b	66.8 a
	LT	59.8 ab	79.7 a	11.5 ab	46.3 ab
	PMT	115.2 a	60.1 a	19.8 a	27.8 b
	FMT	132.3 a	108.6 a	24.3 a	36.5 b

[i] Treatment acronyms correspond to: non-covered (NC), low tunnel (LT), part-season mesotunnel (PMT), and full-season mesotunnel (FMT). Please refer to Table 2 for descriptions of each treatment.

[ii] Within each year, means in a column followed by the same letter do not differ significantly ($P < 0.05$) based on Tukey's honestly significant difference; 1 lb = 0.4536 kg.

[iii] Fruit weight and counts per 30-ft-long (9.14 m) row.

[iv] Includes fruit culled due to any combination of insect damage, disease, poor pollination, small size, sunscald, rodent damage, irregular netting, and other deformities.

Table 6. Summary of the annual cost of row cover treatments applied on organic muskmelon in 2016, 2017, and 2018, based on a plot size of 540 ft^2 (164.59 m^2).

Year	Treatment[i]	Item cost ($)					Total cost ($)
		Insecticides	Fungicides	Row cover supplies[ii]	Bumble bee hives	Labor	
2016	NC	7.13	0.35	0.00	0.00	280.04	287.52
	LT	2.38	0.35	96.96	0.00	561.10	660.79
	PMT	1.19	0.35	136.99	0.00	536.50	675.03
	FMT	0.00	0.35	136.99	125.00	499.38	761.72
2017	NC	7.13	0.35	0.00	0.00	293.55	301.03
	LT	1.19	0.35	96.96	0.00	549.02	647.52
	PMT	1.19	0.35	136.99	0.00	562.38	700.91
	FMT	0.00	0.35	136.99	125.00	523.44	785.78
2018	NC	3.56	0.52	0.00	0.00	216.15	220.23
	LT	0.00	0.35	96.96	0.00	536.43	633.74
	PMT	0.00	0.52	136.99	0.00	581.35	718.86
	FMT	0.00	0.52	136.99	125.00	581.59	844.10

[i] Treatment acronyms correspond to: non-covered (NC), low tunnel (LT), part-season mesotunnel (PMT), and full-season mesotunnel (FMT). Please refer to table 2 for descriptions of each treatment.

[ii] The row cover supplies column includes the cost of the spunbond polypropylene fabric (LT), nylon-mesh fabric (PMT and FMT), wire (LT), conduit hoops (PMT and FMT), and rock bags.

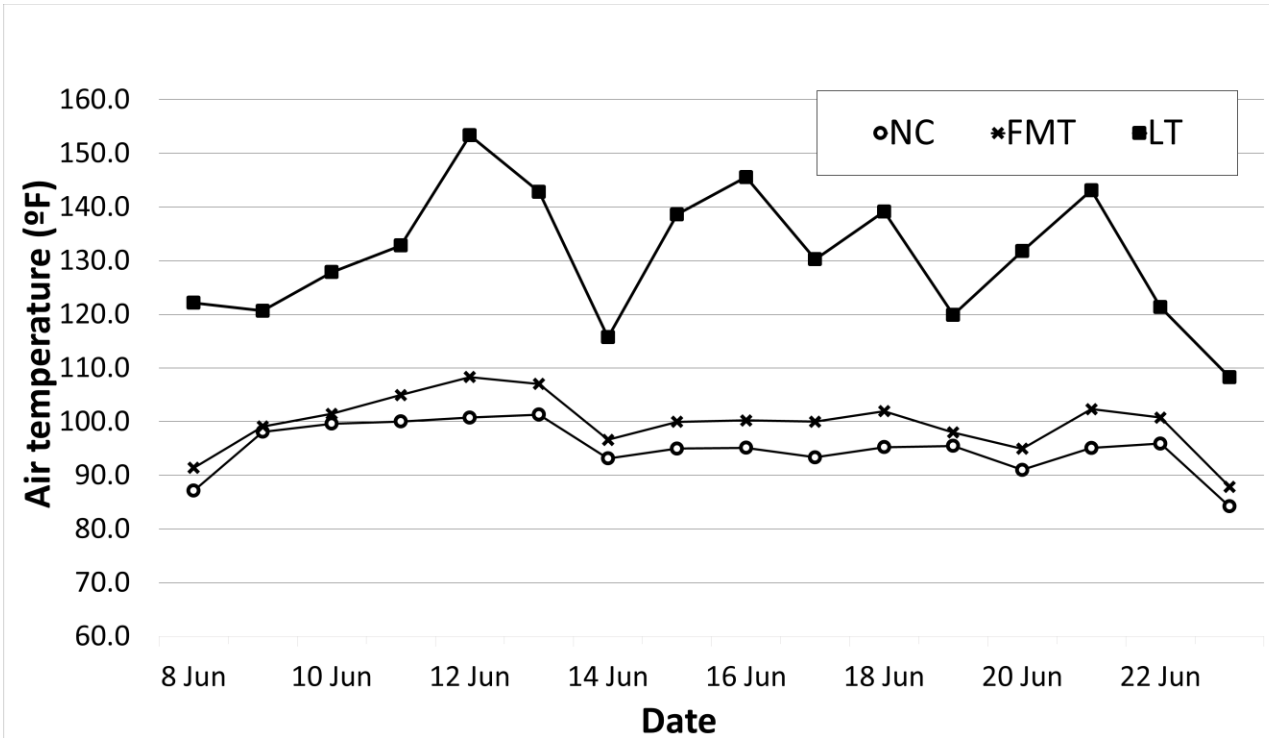

Fig. 1. Daily average maximum air temperature per treatment in 2016 without row cover (NC), inside a low tunnel (LT), and inside a mesotunnel (FMT); ºC = (ºF - 32) ÷ 1.8. Treatment abbreviations: NC= non-covered control treatment; FMT = full-season mesotunnel treatment using a nylon-mesh fabric all season long; LT = low tunnel treatment using a spunbond polypropylene fabric from transplanting through the appearance of the first female flowers.

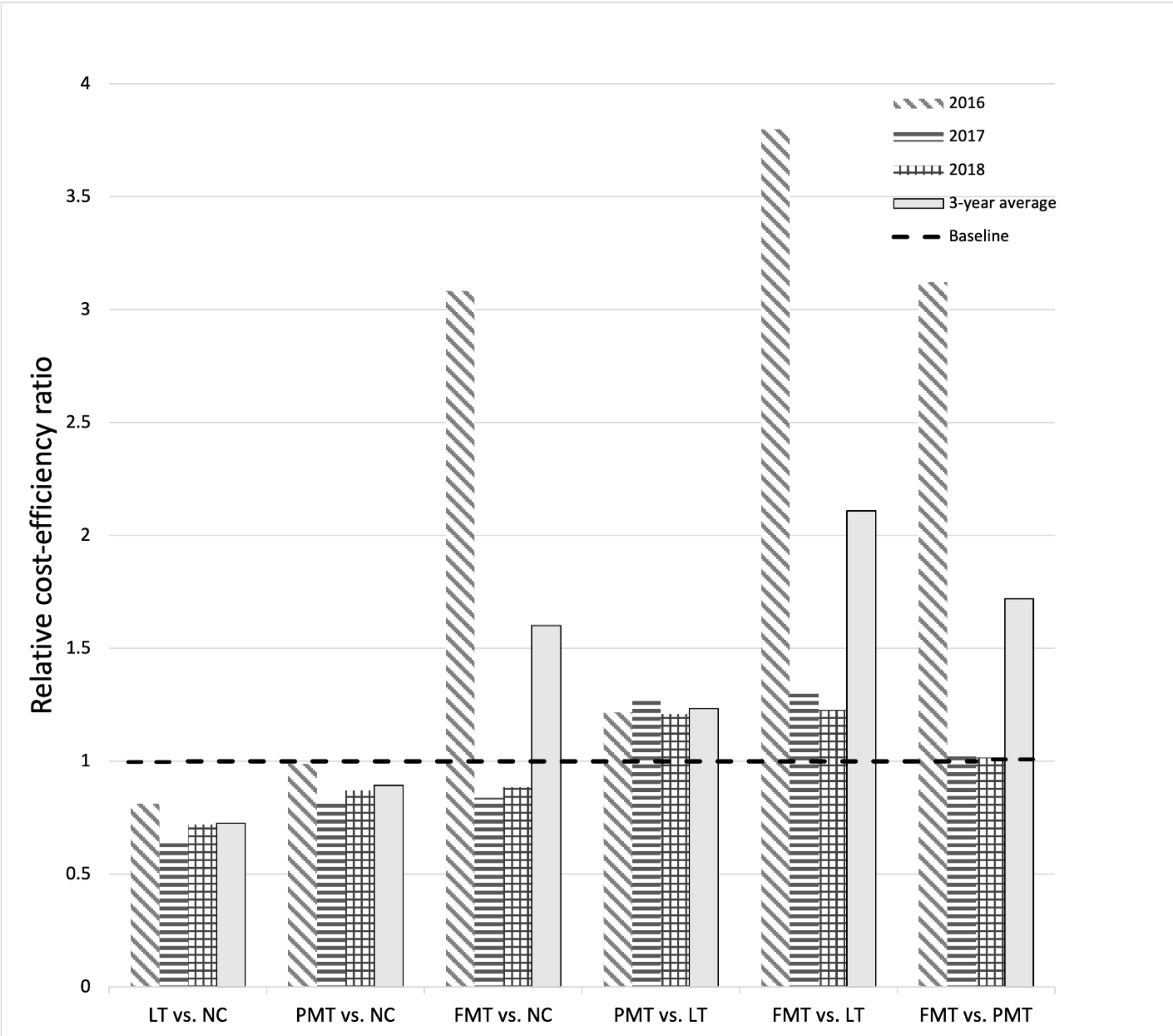

Fig. 2. Yearly and 3-year-average relative cost-efficiency ratio of LT, PMT, and FMT treatments vs. NC treatment (first three clustered sets of bars at left), of PMT and FMT treatments vs. the LT treatment (4th and 5th clusters of bars, respectively, from left to right), and of the FMT treatment vs. the PMT treatment (last cluster of bars at far right) based on the organic muskmelon field trials from 2016 to 2018. Treatment abbreviations: NC= non-covered control treatment; FMT = full-season mesotunnel treatment using a nylon-mesh fabric all season long; LT = low tunnel treatment using a spunbond polypropylene fabric from transplanting through the

appearance of the first female flowers. Relative cost-efficiency ratio = (yield/cost) of treatment X / (yield/cost) of treatment Y.