

# Evaluating Pollination and Weed Control Strategies under Mesotunnel Systems for Organic Muskmelon Production in Iowa

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**KEYWORDS.** bacterial wilt, economic analysis, *Erwinia tracheiphila*, living mulch, mesotunnels, Teff (*Eragrostis tef*)

**ABSTRACT.** Bacterial wilt of cucurbits, caused by *Erwinia tracheiphila*, is spread by spotted (*Diabrotica undeimpunctata howardi*) and striped (*Acalymma vittatum*) cucumber beetles and results in major losses for US cucurbit (Cucurbitaceae spp.) growers. Organic growers of muskmelon (*Cucumis melo*) lack reliable control measures against bacterial wilt. During previous field trials in Iowa, USA, a system called mesotunnels, which are 3.5-ft-tall barriers covered with a nylon mesh insect netting, resulted in a higher marketable yield of organic ‘Athena’ muskmelon than low tunnels or noncovered plots. However, satisfactory pollination and weed control are challenging in mesotunnels because the netting covers the crop for most or all of the growing season, and economic feasibility of these systems has not been determined. Consequently, two field trials conducted in Iowa from 2020 to 2022 evaluated strategies to ensure pollination under mesotunnels in commercial-scale plots, assess effectiveness of teff (*Eragrostis tef*) as a living mulch for weed control in mesotunnel systems, and compare the profitability of the treatment options for organic ‘Athena’ muskmelon. The treatments used during the pollination trial were as follows: full season, in which mesotunnels remained sealed all season and bumble bees (*Bombus impatiens*) were added at the start of bloom for pollination; open ends, wherein both ends of the tunnels were opened at the start of bloom then reclosed 2 weeks later; and on-off-on, in which nets were removed at the start of bloom and then reinstalled 2 weeks later. The full-season treatment had significantly higher marketable yield than the other treatments in two of three trial years. Plants with the full season and open ends treatments had a bacterial wilt incidence <2.5% across all three years and similar numbers of cucumber beetles, whereas plants with the on-off-on treatment had an average bacterial wilt incidence of 11.0% and significantly more cucumber beetles. The open ends treatment had fewer bee visits to ‘Athena’ muskmelon flowers than the other treatments. In the 2-year (2021–22) weed management trial, treatments applied to the furrow between plastic-mulched rows were as follows: landscape fabric; teff seeded at 4 lb/acre and mowed 3 weeks after seeding; teff seeded at 4 lb/acre and not mowed; a control with bare ground where weeds were mowed 3 weeks after transplanting; and a bare ground control with no mowing. The landscape fabric and mowed teff treatments had statistically similar marketable yield, and mowing appeared to minimize yield losses compared with nonmowed treatments. The landscape fabric had no weeds, followed by mowed teff, mowed bare ground, and nonmowed teff. Nonmowed bare ground had the highest weed biomass. The partial budget and cost-efficiency ratio analysis indicated that the full-season treatment was the most cost-efficient pollination option for mesotunnel systems. An economic analysis of the weed management strategies showed that using teff as a living mulch in the furrows between organic ‘Athena’ muskmelon rows, coupled with timely mowing to suppress its growth, can generate revenue comparable to that of landscape fabric. Our findings suggest that organic ‘Athena’ muskmelon growers in Iowa may gain the greatest yield and soil quality benefits when mesotunnels are kept closed for the entire season, bumble bees are used for pollination, and teff (mowed 3 weeks after seeding) is used to control weeds in the furrows. Further trials integrating these pollination and weed management strategies would help validate a comprehensive approach to organic ‘Athena’ muskmelon production under mesotunnels.

(Cucurbitaceae spp.) crops such as muskmelon (*Cucumis melo*) lose >\$100 million annually in the eastern half of the United States because of bacterial wilt, which is caused by *Erwinia tracheiphila* (Schroder et al. 2001). The pathogen is spread by spotted (*Diabrotica undeimpunctata howardi*) and striped (*Acalymma vittatum*) cucumber beetles (Brust 1997; Brust and Rane 1995; Hoffmann et al. 2000; Rojas et al. 2015). Organic muskmelon growers are especially vulnerable to bacterial wilt because they lack reliable insect control measures. Inconsistent yields caused by severe pest and disease damage have resulted in customer dissatisfaction and contract defaults, threatening economic sustainability of organic production (Diver and Hinman 2008).

Most conventional (nonorganic) growers manage the cucumber beetle–bacterial wilt complex by applying synthetic chemical insecticides because no muskmelon cultivars have resistance to the pathogen. For organic growers, however, the few available organic insecticides are not very effective against cucumber beetles (Nelson et al. 2023). The organic insecticide pyrethrin (Pyganic) has been outperformed by cultural practice control treatments (Cline et al. 2008). Tank-mixing kaolin clay, pyrethrins, neem oil, and *Bacillus thuringiensis* improved the efficacy of pyrethrins against cucumber beetles (Nelson 2019; Nelson et al. 2023). Organic insecticides degrade rapidly when exposed to sunlight and wash off readily with rainfall, leading to short residual activity periods compared with those of synthetic chemical insecticides (Bond et al. 2017). Additionally, organic insecticides are as toxic as synthetic insecticides to pollinators and other beneficial insects that are critical to the pollination of cucurbit crops (Minter and Bessin 2014). Insufficient pollinator visitation to female flowers resulted in an increased incidence of misshapen and otherwise nonmarketable cucurbit fruit (Chomicki et al. 2020; Choudhary and Pandey 2016).

Perimeter trap cropping, another strategy that is used to control the cucumber beetle–bacterial wilt complex, aims to concentrate pests such as cucumber beetles, which enter the field along the borders, to an attractive crop (called the trap crop) in the perimeter rows, where they can be monitored and controlled by insecticide

Consumer demand for fresh, locally grown fruits and vegetables, especially those that are organically produced, has been growing

steadily across the United States (Dimitri and Oberholtzer 2009; Huang et al. 2022; Peng 2019; Smith et al. 2009). However, organic growers of cucurbit

sprays (Cavanagh et al. 2009). Perimeter trap cropping has resulted in inconclusive outcomes of conventional cucurbit production in the Northeast United States. The reliability of this method depends on the trap crop species and its health because wilting or other failure of the trap crop jeopardizes the main crop (Rojas et al. 2015); moreover, perimeter trap cropping has never been validated using organic insecticides. Cultural methods like intercropping and reflective plastic mulch inconsistently suppress disease in organic systems (Cline et al. 2008; Haber et al. 2023). Similarly, the efficacy and profitability of biochemical lures, delayed planting, and crop rotation (Diver and Hinman 2008) have been inconsistent (Rojas et al. 2011, 2015).

Temporary tunnel systems can block the access of pest insects and the pathogens they carry. In addition to providing pest and disease control, tunnels can enhance the marketable yield by protecting flowers, shoots, and fruit from physical damage by hail and high winds (Nair and Ngouajio 2010). For example, “low tunnels” (1.5-ft-tall tunnels supported by wire hoops covered by spunbond polypropylene fabric) have been trialed extensively, but disease suppression efficacy has been highly variable (Rojas et al. 2011, 2015). Low tunnels typically provide protection only until female flowers begin to bloom, when the covers are removed to allow pollination. They also lack sufficient

space to accommodate subsequent crop growth and are prone to overheating that causes crop damage (Athey et al. 2022; Bruce et al. 2019; Dhakal and Nandwani 2020; Grasswitz 2019; Rojas et al. 2011; Tillman et al. 2015; Wells and Loy 1985). However, in a previous study in Iowa using small triple-row plots (30 × 18 ft), we showed that “mesotunnels” consistently increased the marketable yield of organic ‘Athena’ muskmelon compared with low tunnels and noncovered plots (Nelson et al. 2023). Mesotunnels, which are 3.5-ft-tall barriers covered with a 60-g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>) nylon mesh insect netting, have an intermediate size between low tunnels and high tunnels (Nelson et al. 2023), and they have the potential to protect cucurbit crops during the entire growing season (Athey et al. 2022; Nelson et al. 2023).

Despite the potential value of mesotunnels and considerable interest from organic cucurbit growers, and despite the fact that 40% of more than 300 respondents to a 2022 grower survey performed in Iowa and other parts of the United States expressed interest in adopting mesotunnels (Cheng et al. 2023), they pose several challenges. One is the need to ensure crop pollination, which requires the pollinators to have access to the blooms. Parthenocarpic cultivars, which develop fruit without pollination, have been developed for a few cucurbit crops [e.g., cucumber (*Cucumis sativus*)], but not for other cucurbit crops such as muskmelon (Gou et al. 2022; Pandolfini 2009). Potential solutions for pollination in mesotunnels include introducing purchased bee hives into the tunnels or opening the tunnels temporarily during bloom; however, these options have not yet been evaluated.

Another challenge with mesotunnels is controlling weeds in the soil furrows between plastic-mulched crop rows. Many organic cucurbit growers rely on mechanical cultivation to control weeds in the furrows between plastic mulch because effective organic herbicides are unavailable (Lanini 2018). However, mechanical cultivation is not compatible with full-season, multirow mesotunnels in which the rowcovers stay in place for the whole season because workers and machinery have insufficient space to operate. Apart from its tendency to degrade soil structure and reduce soil

organic matter content, mechanical cultivation is practical only for early-season weed control because cucurbit vines rapidly grow into the furrows between rows (Liebman and Davis 2009). However, living mulches may be a viable option for weed control in the furrows because the seed is relatively inexpensive. These mulches can also potentially enhance soil health by incorporating organic matter and limiting erosion (Bhaskar et al. 2021; Brown 2017; Bruce et al. 2022). Living mulches have been used in cucurbit production under rowcovers (Bruce et al. 2022; Nair et al. 2014). In mesotunnels during an Iowa organic ‘Athena’ muskmelon trial, however, both seeding red clover (*Trifolium pratense*) alone and a mixture of annual ryegrass (*Lolium multiflorum*) plus red clover were ineffective because these mulches were outcompeted by weeds (Nelson 2019).

Growers need to know whether they can benefit economically before they invest in mesotunnel systems. Previous studies of low tunnels in small plots (30-ft-long × 6-ft-wide single rows) by Rojas et al. (2011) found that keeping spunbond polypropylene rowcovers on an ‘Athena’ muskmelon crop for 10 d after female flowers appeared was more economically advantageous than either removing the covers at the start of bloom or not using covers, and that opening rowcover ends during bloom was more cost-effective than inserting bumble bee (*Bombus impatiens*) hives under the tunnels (Rojas et al. 2011). However, trials of small plots (30-ft-long × 18-ft-wide triple row) by Nelson et al. (2023) revealed that full-season mesotunnel systems with a bumble bee hive inserted at bloom were more economically efficient than low tunnels and noncovered plots, but economically equivalent to part-season mesotunnels (covers removed at the start of bloom and reinstalled 2 weeks later) for organic ‘Athena’ muskmelon production. An important limitation of these trials is that the small size of the test plots does not reflect the scale of commercial organic production, which may have skewed the practical applicability of the results (Hanna et al. 2018). Testing mesotunnels using larger plots that approximate the scale of commercial production would be an additional step toward assessing the practical suitability of mesotunnels for organic producers.

Received for publication 22 Dec 2023. Accepted for publication 29 Feb 2024.

Published online 19 Apr 2024.

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The authors thank field research assistants from the Gleason Laboratory and the staff at the Iowa State University Horticulture Research Station for excellent support. This work was funded by the Organic Research and Extension Initiative (OREI) of United States Department of Agriculture-National Institute of Food and Agriculture (USDA-NIFA) (grant 2019-51300-30248).

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<https://doi.org/10.21273/HORTTECH05379-23>

The objectives of our study were to evaluate pollination strategies under mesotunnels in commercial-scale plots, assess the effectiveness of living mulches as an alternative weed control strategy in mesotunnels, and compare the economic efficiency of the strategies within each objective. During the pollination trial, we hypothesized that in plots with an approximate commercial size (150-ft-long), full-season mesotunnels pollinated by a single bumble bee hive would produce higher marketable yields and economic returns than alternatives that depended on ambient pollinators. This hypothesis is based on the findings of Nelson et al. (2023), who performed smaller-scale (30-ft-long subplot) experiments and found that full-season mesotunnels with a bumble bee hive out-yielded noncovered plots. We used larger plots to test whether these results would scale up because pollinator outputs may be affected by the plot size. Using this agroecological approach, we assumed that the spatial scale could impact pollination efficacy and, thus, the potential profitability of the system (Belmin et al. 2022; Drinkwater 2002). During the weed control trial, our goal was to evaluate weed suppression and ecological benefit of teff (*Eragrostis tef*) as a living mulch. In contrast to the pollination trial, we used 30-ft-long plots because we assumed that weed suppression activities would not be influenced by plot size. During this trial, we hypothesized that using landscape fabric as a groundcover would produce higher marketable yields and economic returns than other treatments, but that mowing teff as a groundcover would deliver comparable results.

## Materials and methods

### Field preparation

Trials were conducted annually from 2020 to 2022, at the Iowa State University Horticulture Research Station, Ames, IA, USA (lat. 42° 6'23.748"N, long. 93°35'23.372"W). A soil test was conducted each year before the first plowing to determine nitrogen (N), phosphorus (P), and potassium (K) levels. Organic compost made from dairy cow manure was applied to the soil and incorporated within 24 h of application. A 4N–2.61P–3.32K fertilizer (Sustâne; Natural Fertilizer, Inc., Cannon Falls,

MN, USA) was broadcast in plant rows to meet the 100 lb/acre N per muskmelon crop requirements, and the soil test results were used as a guide (Brandenberger et al. 2021). During a single operation, a 6-ft-wide bed was shaped, drip tape (Dripdepot, White City, OR, USA) was laid, and black plastic mulch was laid on top. During the pollination trial, 4-ft-wide landscape fabric (Nolt's Midwest Produce Supplies, Charles City, IA, USA) was laid in the furrows between black plastic-covered beds for weed control, and 6- × 1-inch, 11-gauge staples (Steel Sod; Nolt's Midwest Produce Supplies) delivered by a 32- × 12- × 2.5-inch staple gun (Staple Wasp; Best Materials® LLC, Phoenix, AZ, USA) were used to hold the fabric to the ground. During the weed management trial, living mulch was seeded in the furrows using a 36-inch drop spreader (Gandy, Owatonna, MN, USA) at the time of crop transplanting.

Muskmelon (cv. Athena) seedlings from nontreated seeds (Johnny's Selected Seeds, Waterville, ME, USA) were sown in an all-purpose organic potting mix (Berger OM6; Hummert International, Topeka, KS, USA) and maintained in an organically certified greenhouse for 2 weeks. After 2 weeks, the seedlings were hardened-off outdoors under 60-g/m<sup>2</sup> nylon mesh insect netting [0.07 × 0.04 inch (0.1778 × 0.1016 cm); ProtekNet; DuBois Agrinovation, Saint-Rémi, QC, Canada] for 5 to 7 d before transplanting.

In 2020 and 2021, organically certified land planted with a mixture of cowpea (*Vigna unguiculata*), sunn hemp (*Crotalaria juncea*), and hybrid sorghum-sudangrass (*Sorghum × drummondii*) during preceding years was used. To meet the crop rotation requirements for organic production in 2022, a noncertified plot that had been planted with broccoli (*Brassica oleracea* var. *italica*), garlic (*Allium sativum*), cauliflower (*Brassica oleracea* var. *botrytis*), and cereal rye (*Secale cereale*) during preceding years was used.

### Experimental design

In each year, there were four replications per treatment with subplots arranged in a randomized complete block design. 'Athena' muskmelon seedlings were transplanted into three-row subplots with 6-ft row centers and

2-ft intrarow plant spacing. A single piece of rowcover fabric covered each three-row subplot. During all three years, mesotunnels were installed on the same day as that when the crop was transplanted. Hoops made from 1-inch-diameter, 10-ft-long galvanized steel conduit were manually bent to a U-shape using a conduit bender (QuickHoops™; Johnny's Selected Seeds, Waterville, ME, USA). In 2020, the hoops were arranged perpendicular to the planting row, whereas in 2021 and 2022, a zig-zag pattern parallel to the rows, except for the last hoop at each end of the tunnel, which was placed perpendicular to the row, was adopted (Gonzalez et al. 2023). A 3.5-ft-tall (1.07-m-tall) tunnel was made by draping the nylon mesh over three rows of conduit hoops, and 14- × 26-inch black plastic sandbags (Nolt's Midwest Produce Supplies) were used to secure the fabric edges to the soil surface. Sandbags were placed every 6 ft along tunnel edges, and five sand bags were placed at each end of a tunnel (Gonzalez et al. 2023).

### Pollination trial

This trial was conducted annually from 2020 to 2022. Subplots had a length of 150 ft and width of 18 ft. Treatments included full season, open ends, and on-off-on. With the full-season treatment, tunnels remained sealed from transplanting until the start of harvest. When the first female flowers appeared (approximately 3 weeks after transplanting), a purchased bumble bee hive (Excel Startup; Koppert Biological Systems, Inc., Howell, MI, USA) was placed on bricks at the center of the subplot with the flight hole facing in the direction of the crop row. A plastic laundry basket was placed over the bee hive to protect it from sunlight and rainfall (Nelson et al. 2023). With the open ends treatment, the netting was opened at both ends for 2 weeks during bloom and then resealed 2 weeks later (Table 1). With the on-off-on treatment, the entire length of the netting on a 150-ft subplot was removed for 2 weeks during bloom and then recovered 2 weeks later. All nets were removed permanently when harvest began.

Scouting for insect pests and disease symptoms was performed twice per week to determine when spray thresholds were met that would trigger

**Table 1. Timeline of field preparation and mesotunnel establishment in 2020, 2021, and 2022 at the Iowa State University Horticulture Research Station, Ames, IA, USA. Dates indicate the completion of each task in both weed control and pollination trials.**

| Operation   | Date   |        |        |
|---|--------|--------|--------|
|   | 2020   | 2021   | 2022   |
| Sampled soil and compost for nutrient recommendations                             | 10 Apr | 7 Apr  | 29 Mar |
| Deep tillage  | 25 Apr | 10 Apr | 18 Apr |
| Applied composted manure and tilled   | 16 May | 10 May | 23 Apr |
| Seeded 'Athena' muskmelon into 48-cell trays                                      | 10 May | 11 May | 19 May |
| Applied fertilizer, installed drip tape and black plastic mulch                   | 28 May | 12 May | 23 May |
| Hardened-off 'Athena' muskmelon seedlings   | 30 May | 22 May | 2 Jun  |
| Installed landscape fabric to furrows   | 5 Jun  | 31 May | 6 Jun  |
| Transplanted seedlings and installed weed control treatments                      | 7 Jun  | 1 Jun  | 8 Jun  |
| Bumble bee boxes installed, rowcovers temporarily removed, and tunnel ends opened | 26 Jun | 15 Jun | 22 Jun |
| Mowing treatments applied   | 1 Jul  | 22 Jun | 2 Jul  |
| Row covers resealed   | 10 Jul | 1 Jul  | 7 Jul  |

the application of a fungicide or insecticide. Copper hydroxide (Champ<sup>®</sup> WG; Nufarm Americas Inc., Burr Ridge, IL, USA) was applied directly through the nylon mesh for the control of foliar fungal diseases. Pyrethrins (Pyganic<sup>®</sup> Crop Protection EC 5.0 ii; MGK Company, Minneapolis, MN, USA), kaolin clay (Surround<sup>™</sup> WP; Tessen-derlo Kerley Inc., Phoenix, AZ, USA), and neem oil (Trilogy<sup>®</sup> 70EC; Certis USA, LLC, Columbia, MD, USA) were tank-mixed and applied for the control of cucumber beetles and squash bugs. Flight holes of bumble bee hives were closed 1 d before spraying pesticides and reopened after the field re-entry period had passed.

#### Weed control trial

This trial was conducted in 2021 and 2022. Subplots had a length of 30 ft and width of 18 ft. The five treatments were as follows: landscape fabric covering the furrows between plastic-mulched rows; noncoated seed of teff (Green Cover, Bladen, NE, USA) sown in the furrow at 4 lb/acre (4.4836 kg·ha<sup>-2</sup>) and mowed 3 weeks after seeding (Table 1); teff seeded at 4 lb/acre with no mowing; bare ground (not seeded), where weeds were mowed 3 weeks after transplanting; and bare ground with no mowing. Mowing was performed to a height of 2 to 4 inches using a trimmer mower (22-inch YARDMAX; Roselle, IL, USA). Two soil moisture sensors (Watermark; Spectrum Technologies Inc., Aurora, IL, USA) were installed at depths of 6 and 12 inches per day after mesotunnels were set to determine irrigation timing. A single bumble bee hive (Excel Startup) was inserted at the center of

each tunnel when the first female flowers opened. Flight holes of the hives were sealed 1 d before opening the nets for mowing or spraying a fungicide. Tunnels were resealed immediately after mowing was completed, and flight holes were reopened after the re-entry period of the fungicide had passed.

#### Field data collection

**BEE ACTIVITY, PEST AND INSECT MONITORING, AND INSECTICIDE APPLICATION.** During the pollination trial, visual observations of bee activity in all treatments were made twice per day, 2 days per week, between 8:00 and 11:00 AM, during the 2-week period when the nets were removed (on-off-on), ends were opened (open ends), and bee hives were installed (full season) (McGrady et al. 2021; Riggs et al. 2003; Shuler et al. 2005; Stoner 2020). Three plants in each of three 6-ft-long sections on the center row of a subplot were used as observation zones; one zone was located at the midpoint of the subplot, and two others were located ~6 ft from the ends of the subplot. Bumble bees and other bees were counted in flowers located in each of these zones during a period of 60 s (Obregon et al. 2022; Stoner 2020). During the subsequent 60 s, striped and spotted cucumber beetles, as well as other insects, were counted in the same aforementioned observation zones. Cucumber beetles and other insects were scouted at the same times; however, these insects were also scouted for an additional 1 week after the nets were resealed and subjected to on-off-on and open ends

treatments. Counts were performed by two individuals standing on opposite sides of the observation zone; the same individuals performed the counts during every observation period. The location of scouting zones was randomized, and count data were averaged from the four subplots in each treatment. Insecticide spray thresholds were one cucumber beetle per zone until 5 weeks after transplanting, and two beetles per zone thereafter (Brust and Foster 1999; Nelson et al. 2023). A tank mix consisting of pyrethrins (Pyganic<sup>®</sup> Crop Protection EC 5.0 ii), kaolin clay (Surround<sup>™</sup> WP), and neem oil (Trilogy<sup>®</sup> 70EC) was sprayed when a threshold was met for either one cucumber beetle species or a total of both species.

**DISEASE RATING AND FUNGICIDE SPRAYING.** During both the pollination and weed control trials, symptoms of Alternaria leaf spot (ALS) caused by the fungus *Alternaria cucumerina* and bacterial wilt were assessed twice weekly in the center row in each subplot. The number of plants with bacterial wilt symptoms per subplot was counted. For Alternaria leaf spot, the number of plants with necrosis comprising >5% of the canopy was counted (James 1971; Patil and Bodhe 2011; Pethybridge and Nelson 2018; Wijekoon et al. 2008). When incidence of Alternaria leaf spot exceeded 10%, copper hydroxide (Champ<sup>®</sup> WG) was sprayed directly through the nylon mesh fabric. After the first spray, additional sprays were applied weekly until 1 week before harvest.

**WEED BIOMASS.** Two days before the first fruit harvest during the weed control trial, weeds were sampled using

2- × 3-ft quadrats. All weeds located inside an arbitrarily located quadrat were harvested at the soil surface (Wortman et al. 2010), oven-dried at 68 °C (154.4 °F) for 72 h, and weighed.

**YIELD.** During the pollination trial, subplots were subdivided into 10 15-ft-long zones. During each harvest, all fruits in each zone of the middle row of the subplot were weighed separately. The yield from all 10 zones was summed to determine the yield per subplot. During the weed management experiment, however, fruits were harvested collectively from the entire 30-ft-long subplot. Harvesting was performed every 2 d; fruit were categorized as marketable or nonmarketable based on a United States Department of Agriculture (USDA) grading scale (US Department of Agriculture, Agricultural Marketing Service 2006). Nonmarketable fruit included those with a combined surface area of damage (i.e., insect, sunscald, or rodent feeding injury) exceeding 5%, damage extending into the fruit flesh (i.e., cracking or bird, insect, or rodent feeding injury), or exhibiting softened rot spots. Fruit weighing less than 3 lb were considered nonmarketable.

### Statistical analysis

An analysis of variance was performed using JMP statistical software (JMP® Pro version 16.2.0; SAS Institute Inc., Cary, NC, USA). Means were separated using Tukey's honestly significant difference multiple comparisons adjustment at  $P < 0.05$ . Data for each year were analyzed separately because homogeneity of variance criteria for pooling the data across years were not met.

### Economic analysis

A partial budget analysis that incorporated revenue and costs of materials and labor (Izaba et al. 2021; Nian et al. 2022; Wei et al. 2020) was performed to compare the relative cost-efficiency of the treatments within each trial. Costs for items that were relatively uniform among treatments included seeds, sandbags, hoops, nylon mesh, purchased beehives, spraying, and weed control. Labor costs were estimated for plot preparation, cutting of the net fabric to the subplot size, sandbag filling, mesotunnel preparation and setup, beehive installation,

pollination-related labor, spraying, mowing, and field cleanup after harvest. Other materials in the treatments were treated as nonreusable items, except for the netting, hoops, and sandbags. An "equivalent annual cost" approach (Rosli et al. 2017) was used to amortize several material expenses: rowcovers were assumed to have a 3-year life expectancy, whereas sandbags were assumed to last for 5 years, and hoops were expected to last for 10 years. Eq. [1] was used to calculate the equivalent annual cost:

$$\frac{\text{Asset Price}}{1 - \frac{1}{(1 + r)^t}} * r, \text{ where } r = 5\% \quad [1]$$

where  $r$  is interest rate and  $t$  is time.

To compare relative cost-efficiency among treatments, the ratio of the change in gross revenue (based on changes in marketable yield and retail or wholesale price per pound in treatment  $x$ ) to the additional cost incurred with that treatment (Polasky et al. 2011; Tan-Torres et al. 2003) was calculated using Eq. 2. The cost-efficiency ratio compared treatments based on how many additional dollars of revenue were generated for each dollar invested in the production cost. A relative cost-efficiency ratio  $>1$  indicates that each dollar invested in the production system of treatment  $x$  would generate  $>\$1$  additional revenue from marketable 'Athena' muskmelon than for the system of treatment  $y$ .

Relative cost efficiency ratio

$$= \frac{\frac{\text{Yield} * \text{Price}}{\text{cost}} \text{ for treatment } x}{\frac{\text{Yield} * \text{Price}}{\text{cost}} \text{ for treatment } y} \quad [2]$$

## Results and discussion

### Pollination trial

**YIELD AND POLLINATOR ACTIVITY.** The full-season treatment had the highest marketable yield during all three years and was significantly ( $p < 0.05$ ) higher than that of the other two treatments in 2020 and 2021 (Table 2). A higher weight of nonmarketable (cull) fruit with the on-off-on treatment than that with the open ends or full-season treatments may have been associated with higher counts of cucumber beetles with the on-off-on treatment. These findings were consistent with a trial performed in Iowa by Nelson et al. (2023) that found that the organic 'Athena' muskmelon marketable yield tended to be higher with full-season treatment than with on-off-on treatment. The current experiment extended the mesotunnel study of Nelson et al. (2023) in two ways: by expanding from subplots with a small size (length, 30 ft) to those with a nearly commercial size (length, 150 ft) and by adding an open ends strategy as a potential way to simplify mesotunnel manipulation to allow pollination during the bloom period. Regarding the open ends strategy in

**Table 2. Effects of pollination strategy on the yield of organic 'Athena' muskmelon under mesotunnels in 150 × 18 ft (45.7 × 5.5 m) plots in Iowa, USA.**

| Yr   | Treatment                 | Marketable yield (lb/acre) <sup>i</sup> | Nonmarketable yield (lb/acre) <sup>i</sup> |
|------|---------------------------|---|--|
| 2020 | Full season <sup>ii</sup> | 40,047 a <sup>v</sup>                   | 5,068 c                                    |
|      | Open ends <sup>iii</sup>  | 33,004 b                                | 9,072 b                                    |
|      | On-off-on <sup>iv</sup>   | 19,317 c                                | 17,072 a                                   |
|      | <i>P</i> value            | <0.0001                                 | <0.0001                                    |
| 2021 | Full season               | 37,412 a                                | 9,885 a                                    |
|      | Open ends                 | 25,437 b                                | 8,224 a                                    |
|      | On-off-on                 | 26,416 b                                | 11,303 a                                   |
|      | <i>P</i> value            | 0.0048                                  | 0.1409                                     |
| 2022 | Full season               | 48,360 a                                | 6,333 a                                    |
|      | Open ends                 | 33,752 b                                | 3,033 b                                    |
|      | On-off-on                 | 46,116 a                                | 7,247 a                                    |
|      | <i>P</i> value            | 0.0002                                  | 0.0013                                     |

<sup>i</sup> Fruit weight: 1 lb/acre = 1.1209 kg·ha<sup>-1</sup>.

<sup>ii</sup> Full season: mesotunnels (covered by nylon mesh fabric) remained closed all season except for when one bumble bee hive was placed at the center of each subplot when female flowers appeared.

<sup>iii</sup> Open ends: both ends of mesotunnels were opened when female flowers appeared; they were reclosed 2 weeks later.

<sup>iv</sup> On-off-on: Mesotunnel covers were removed when female flowers appeared; they were replaced 2 weeks later.

<sup>v</sup> Within each year, means in a column followed by the same letter are not significantly different at  $P < 0.05$  using Tukey's honestly significant difference test.

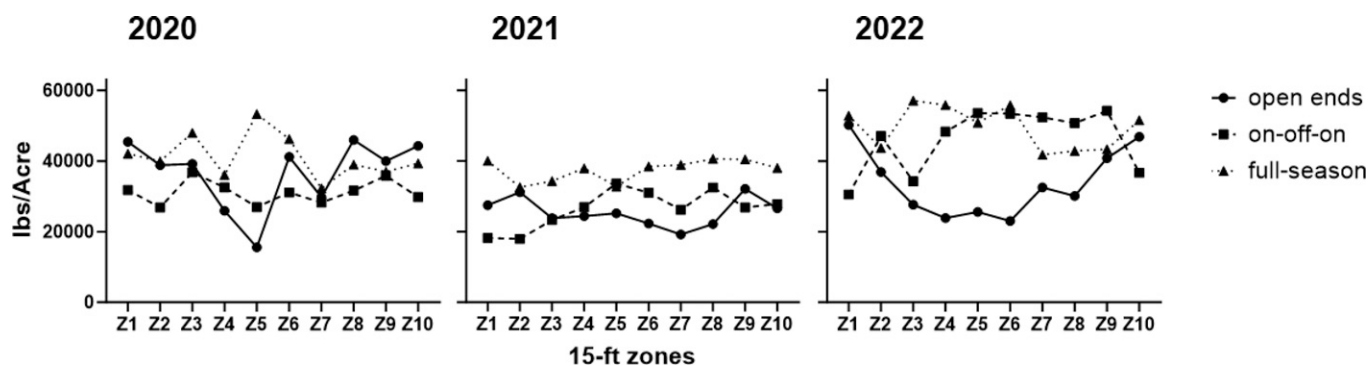


Fig. 1. Mean weight (lb/acre) of marketable ‘Athena’ muskmelon fruit in 15-ft-long zones [90 ft<sup>2</sup> (8.361 m<sup>2</sup>); Z1–Z10] of 150-ft-long subplots of organic ‘Athena’ muskmelon in the pollination trial during 2020, 2021, and 2022. Treatments included open ends (both ends of the mesotunnel were opened when female flowers appeared and then reclosed 2 weeks later), on-off-on [nylon mesh mesotunnel covering 60 g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>) was removed when female flowers appeared and was replaced 2 weeks later], and full season (one bumble bee hive was placed at the center of each subplot when female flowers appeared). The lines represent mean values of marketable ‘Athena’ muskmelon weight in pounds per 90-ft<sup>2</sup> (8.4-m<sup>2</sup>) plot extrapolated to per acre.

2022, we noted lower marketable yield in the harvest zones near the center of the tunnels than that on the ends (Fig. 1); however, this trend was not clear during the other years. Furthermore, the open ends treatment had consistently fewer bee visits to ‘Athena’ muskmelon flowers than the other treatments (Table 3), and it showed a trend of declining bee flower visits from the ends toward the middle of the tunnel in 2022 as well as previous years (data not shown). These spatial effects were not observed with the other two treatments (Fig. 1). Except for 2022, compared to the other treatments, the on-off-on treatment had significantly more bees visiting flowers (Table 3). However, the full-season treatment had the highest number of flower visits by bumble bees each year, which was an expected result, because of the introduction of a purchased hive of bumble bees. These observations suggest that pollinator activity was positively related to ‘Athena’ muskmelon yield because more pollinator activity with the on-off-on and full-season treatments resulted in more marketable yield compared with the open ends treatment.

Our results strengthen the evidence that mesotunnel systems can be a viable management alternative for organic cucurbit growers who are vulnerable to damage from cucumber beetles and bacterial wilt (Nelson et al. 2023). However, outcomes of mesotunnel pollination strategies can differ by geographic region. For example, an organic ‘Athena’ muskmelon field trial in central New York using the same treatments as

those in the present trial found that marketable yield was significantly higher with the on-off-on treatment than with the other two treatments in both years (Sarah Pethybridge, personal communication). This discrepancy in yield between trials performed ~900 miles apart may be attributable to different soil, weather, pollinator activity, and pest-pressure conditions, thus underlining the importance of validating mesotunnel strategies by region over multiple growing seasons.

**CUCUMBER BEETLES AND OTHER INSECT PESTS.** Mesotunnels were highly effective at excluding cucumber beetles

and other insect pests from the ‘Athena’ muskmelon crop with the full-season treatment compared with the other treatments (Table 4). This trend is consistent with observations during mesotunnel trials in Iowa (Nelson et al. 2023) and New York (Sarah Pethybridge, personal communication). During the present study, cucumber beetles, both striped and spotted, were the main insect pests on ‘Athena’ muskmelon plants. The full-season treatment had almost no cucumber beetles, whereas the on-off-on treatment had the highest cucumber beetle counts across the three years of the

Table 3. Mean counts of bees in ‘Athena’ muskmelon flowers in the pollination trial in 150- × 18-ft (45.7 × 5.5-m) plots in Iowa, USA.

| Yr   | Treatment                 | Bumble bees (no./36 ft <sup>2</sup> ) <sup>i</sup> | Other bees (no./36 ft <sup>2</sup> ) <sup>i</sup> | Total bees (no./36 ft <sup>2</sup> ) <sup>i</sup> |
|------|---------------------------|--|---|---|
| 2020 | Full season <sup>ii</sup> | 2.6 a <sup>v</sup>                                 | 0.3 b   | 2.9 b   |
|      | Open ends <sup>iii</sup>  | 1.1 b  | 1.1 b   | 2.2 b   |
|      | On-off-on <sup>iv</sup>   | 2.0 ab   | 2.8 a   | 4.8 a   |
|      | <i>P</i> value            | 0.0207   | <0.0001   | 0.0008  |
| 2021 | Full season               | 1.6 a  | 0.1 c   | 1.7 b   |
|      | Open ends                 | 0.3 c  | 0.8 b   | 1.1 b   |
|      | On-off-on                 | 0.5 b  | 3.1 a   | 3.6 a   |
|      | <i>P</i> value            | <0.0001  | <0.0001   | <0.0001   |
| 2022 | Full season               | 6.6 a  | 0.0 c   | 6.6 a   |
|      | Open ends                 | 0.2 b  | 0.8 b   | 1.0 c   |
|      | On-off-on                 | 0.6 b  | 2.2 a   | 2.8 b   |
|      | <i>P</i> value            | <0.0001  | <0.0001   | <0.0001   |

<sup>i</sup> Number of bees observed in flowers/36-ft<sup>2</sup> (3.3-m<sup>2</sup>) zone per 60-second observation period; one bee/36 ft<sup>2</sup> = 0.3 bee/m<sup>2</sup> (1 ft = 0.3 m). Visual observations of bee activity were performed 2 days per week between 8:00 and 11:00 AM; the numbers shown are means over a 2-week period during bloom.

<sup>ii</sup> Full season: mesotunnel covers [nylon mesh, 60 g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>)] remained in place all season, except when one bumble bee hive was placed at the center of each subplot when female flowers appeared.

<sup>iii</sup> Open ends: both ends of each mesotunnel were opened when female flowers appeared; they were reclosed 2 weeks later.

<sup>iv</sup> On-off-on: mesotunnel covers were removed when female flowers appeared; they were replaced 2 weeks later.

<sup>v</sup> Within each year, means in a column followed by the same letter are not significantly different at *P* < 0.05 using Tukey’s honestly significant difference test.

**Table 4. Mean counts of cucumber beetles and other insects on ‘Athena’ muskmelon plants in each pollination trial treatment in 150- × 18-ft (45.7- × 5.5-m) plots in Iowa, USA.**

| Yr   | Treatment                 | Cucumber beetles (no./36 ft <sup>2</sup> ) <sup>i</sup> | Other insects (no./36 ft <sup>2</sup> ) <sup>i</sup> |
|------|---------------------------|---|--|
| 2020 | Full season <sup>ii</sup> | 0.7 c <sup>v</sup>                                      | 1.2 b  |
|      | Open ends <sup>iii</sup>  | 2.3 b   | 1.7 b  |
|      | On-off-on <sup>iv</sup>   | 6.2 a   | 3.9 a  |
|      | <i>P</i> value            | <0.001  | <0.001   |
| 2021 | Full season               | 0.9 c   | 2.3 b  |
|      | Open ends                 | 2.5 b   | 3.4 ab   |
|      | On-off-on                 | 7.5 a   | 4.1 a  |
|      | <i>P</i> value            | <0.0001   | 0.0063   |
| 2022 | Full season               | 0.0 b   | 0.9 c  |
|      | Open ends                 | 0.2 b   | 2.5 b  |
|      | On-off-on                 | 2.4 a   | 4.9 a  |
|      | <i>P</i> value            | <0.0001   | <0.0001  |

<sup>i</sup> Number of cucumber beetles or other insects observed per 36-ft<sup>2</sup> (3.3444-m<sup>2</sup>) zone during a 60-second period; 1 cucumber beetle or other insect/36 ft<sup>2</sup> = 0.3/m<sup>2</sup>; and 1 ft = 0.3048 m. Insect scouting surveys were conducted 2 d per week from the start of bloom until harvest between 8:00 and 11:00 AM. The numbers shown are averages per 36-ft<sup>2</sup> (3.3444-m<sup>2</sup>) zone for the whole season.

<sup>ii</sup> Full season: mesotunnel covers [nylon mesh, 60 g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>)] remained in place all season, except when one bumble bee hive was placed at the center of each subplot when female flowers appeared.

<sup>iii</sup> Open ends: both ends of each mesotunnel were opened when female flowers appeared; they were reclosed 2 weeks later.

<sup>iv</sup> On-off-on: mesotunnel covers were removed when female flowers appeared; they were replaced 2 weeks later.

<sup>v</sup> Within each year, means in a column followed by the same letter are not significantly different at *P* < 0.05 using Tukey’s honestly significant difference test.

trial (Table 4). The on-off-on treatment also had significantly higher counts of other insect pests than the full-season treatment; however, in 2021, it was statistically similar to the open ends treatment (Table 4). Insect pest counts tripled when the ends of the mesotunnels were opened, and especially when the entire exclusion net was taken off during bloom, thus increasing the risk of crop damage from direct feeding injury and bacterial wilt (Athey et al. 2022; Ingwell and Kaplan 2019; Nelson et al. 2023; Rojas et al. 2011; Volesky and Wagner 2020).

**DISEASES.** Full-season mesotunnels were the most effective at preventing bacterial wilt on ‘Athena’ muskmelon (Table 5), in accordance with previous mesotunnel field trial results (Nelson et al. 2023). Bacterial wilt was the predominant disease of economic importance observed across the three years of our trial. The on-off-on treatment had the highest incidence of bacterial wilt, whereas the full-season mesotunnels had the lowest incidence (Table 5). *Alternaria* leaf spot incidence with the on-off-on treatment also exceeded that in other treatments every year; however, the difference was statistically significant only in 2020. The nylon mesh material does not block the entry of fungal spores, nor

does it substantially alter microclimatic conditions on the crop (Nelson et al. 2023); therefore, mesotunnels may be expected to have little impact on the progress of diseases caused by foliar fungi (e.g., *Alternaria* leaf spot and powdery mildew (*Podosphaera xanthii*))

or oomycetes [e.g., downy mildew (*Pseudoperonospora cubensis*)], as observed during a study performed in New York by Pethybridge et al. (2023). An important practical advantage of the mesh fabric over the spunbonded polypropylene typically used in low tunnels is that pesticide sprays can be applied through the mesh (Nelson et al. 2023).

**ECONOMIC ANALYSIS.** Based on our results, mesotunnel systems for organic ‘Athena’ muskmelon production using the full-season pollination strategy had the highest profit potential (Tables 6 and 7). The per-subplot cost of the mesotunnel system was somewhat higher for the full-season treatment than for the other treatments, mainly because of the added cost of the hives with the full-season treatment (Table 6). Between 55% and 60% of the total costs per subplot were equivalent among all three treatments (e.g., land rental, seeds, irrigation, black plastic, compost, fertilizer, staples, plot setup, machinery, and labor associated with installing and removing the plastic mulches and nylon mesh). Labor costs accounted for up to 20% of the total cost. The full-season treatment required no pesticide sprays and had the least treatment-related labor cost among the three treatments, consistent with results of Nelson et al. (2023).

**Table 5. Incidence (number of symptomatic plants) of bacterial wilt and *Alternaria* leaf spot on ‘Athena’ muskmelon plants in the pollination trial in 150- × 18-ft (45.7- × 5.5-m) plots in Iowa, USA.**

| Yr   | Treatment                 | Bacterial wilt (no./subplot) <sup>i</sup> | ALS (no./subplot) <sup>i</sup> |
|------|---------------------------|---|--------------------------------|
| 2020 | Full season <sup>ii</sup> | 1.1 c <sup>v</sup>                        | 0.2 b                          |
|      | Open ends <sup>iii</sup>  | 3.2 b                                     | 1.1 b                          |
|      | On-off-on <sup>iv</sup>   | 8.4 a                                     | 11.9 a                         |
|      | <i>P</i> value            | <0.0001                                   | <0.0001                        |
| 2021 | Full season               | 0.6 b                                     | 3.0 a                          |
|      | Open ends                 | 1.9 b                                     | 3.4 a                          |
|      | On-off-on                 | 5.7 a                                     | 4.0 a                          |
|      | <i>P</i> value            | <0.0001                                   | 0.8291                         |
| 2022 | Full season               | 0.1 b                                     | 9.1 a                          |
|      | Open ends                 | 2.3 b                                     | 5.5 a                          |
|      | On-off-on                 | 8.1 a                                     | 9.5 a                          |
|      | <i>P</i> value            | <0.0001                                   | 0.2160                         |

<sup>i</sup> Mean number of symptomatic plants per 75 plants scouted in each subplot. Surveys were conducted 2 days per week between 8:00 and 11:00 AM from the start of bloom until harvest; the numbers shown are averages per subplot for the whole season.

<sup>ii</sup> Full season: mesotunnel covers [nylon mesh 60 g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>)] remained in place all season, except when one bumble bee hive was placed at the center of each subplot when female flowers appeared.

<sup>iii</sup> Open ends: both ends of each mesotunnel were opened when female flowers appeared; they were reclosed 2 weeks later.

<sup>iv</sup> On-off-on: mesotunnel covers were removed when female flowers appeared; they were replaced 2 weeks later.

<sup>v</sup> Within each year, means in a column followed by the same letter are not significantly different at *P* < 0.05 using Tukey’s honestly significant difference test.

ALS = *Alternaria* leaf spot.

**Table 6. Comparison of costs (in US dollars) of pollination trial treatments in organic ‘Athena’ muskmelon production under mesotunnel systems in Iowa, USA, from 2020 to 2022 based on a plot size of 2,700 ft<sup>2</sup> (250.8 m<sup>2</sup>).**

| Yr                                     | Treatment                   | Mesotunnel supplies <sup>i</sup> | Sprayer and pesticides <sup>ii</sup> | Bumble bee hives <sup>iii</sup> | Variable labor cost <sup>iv</sup> | Common cost <sup>v</sup> | Total cost <sup>vi</sup> |
|--|-----------------------------|----------------------------------|--------------------------------------|---------------------------------|-----------------------------------|--------------------------|--------------------------|
| Cost (\$) per 2,700 ft <sup>2vii</sup> |                             |                                  |                                      |                                 |                                   |                          |                          |
| 2020                                   | Full season <sup>viii</sup> | 185                              | 0                                    | 135                             | 220                               | 604                      | 1,144                    |
|  | Open ends <sup>ix</sup>     | 185                              | 56                                   | 0                               | 246                               | 604                      | 1,091                    |
|  | On-off-on <sup>x</sup>      | 185                              | 56                                   | 0                               | 243                               | 604                      | 1,088                    |
| 2021                                   | Full season                 | 183                              | 0                                    | 137                             | 163                               | 604                      | 1,087                    |
|  | Open ends                   | 183                              | 27                                   | 0                               | 181                               | 604                      | 995                      |
|  | On-off-on                   | 183                              | 27                                   | 0                               | 179                               | 604                      | 993                      |
| 2022                                   | Full season                 | 183                              | 0                                    | 137                             | 163                               | 599                      | 1,082                    |
|  | Open ends                   | 183                              | 27                                   | 0                               | 178                               | 599                      | 987                      |
|  | On-off-on                   | 183                              | 27                                   | 0                               | 176                               | 599                      | 985                      |

<sup>i</sup> Mesotunnel supplies included nylon mesh, hoop bender, hoops, landscape fabric, and sand bags.

<sup>ii</sup> Cost of pesticides and machinery depreciation.

<sup>iii</sup> Total cost of purchased bumble bee hives including shipping.

<sup>iv</sup> Variable labor costs for tasks specific to each pollination treatment, including opening and closing of tunnels, spraying time, and bumble bee hive installation.

<sup>v</sup> Costs that were equal for each treatment, including land rental, seeds, irrigation, black plastic, compost, fertilizer, staples, plot setup machinery, and labor associated with their use, application, and installation.

<sup>vi</sup> Total cost in US dollars.

<sup>vii</sup> \$1.00/2,700 ft<sup>2</sup> (250.8 m<sup>2</sup>) = \$16.13/acre = \$39.87/ha.

<sup>viii</sup> Full season: mesotunnel covers [nylon mesh, 60 g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>)] remained in place all season, except when one bumble bee hive was placed at the center of each subplot when female flowers appeared.

<sup>ix</sup> Open ends: both ends of each mesotunnel were opened when female flowers appeared; they were reclosed 2 weeks later.

<sup>x</sup> On-off-on: mesotunnel covers were removed when female flowers appeared; they were replaced 2 weeks later.

We assumed that retail and wholesale prices for ‘Athena’ muskmelon in central Iowa from 2020 to 2022 averaged \$2/lb and \$1.5/lb, respectively (Ajay Nair, personal communication). Our analysis indicated that the full-season treatment was the most profitable at both the retail and wholesale prices (Table 7).

Relative cost-efficiency ratio comparisons across treatments indicated

that, on average, the full-season treatment was the most cost-efficient, followed by the on-off-on and open ends treatments. This resulted from substantially higher yields of the full-season treatment compared with those of others across three years. Cost-efficiency ratios between the on-off-on and open ends treatments and between the full-season and on-off-on treatments varied from >1 to <1 among

years, suggesting that the relative economic advantage of one of these treatments over the other may fluctuate depending on the growing season (Fig. 2). However, the cost-efficiency ratio between the open ends and on-off-on treatments was close to 1, on average, suggesting that these two treatments may be comparable for ‘Athena’ muskmelon production (Fig. 2). These results indicate that the full-season

**Table 7. Economic comparison (annual total cost, marketable yield, selling price, revenue, and profit) of treatments in the pollination trial for organic muskmelon in Iowa, USA, based on a plot size of 150 × 18 ft.**

| Yr                                   | Treatment                 | Marketable yield (lb/2,700 ft <sup>2</sup> ) <sup>i</sup> | Total cost <sup>ii</sup> | Retail price (\$2.00/lb)     |                           | Wholesale price (\$1.50/lb)  |                           |
|--------------------------------------|---------------------------|---|--------------------------|------------------------------|---------------------------|------------------------------|---------------------------|
|                                      |                           |   |                          | Gross revenue <sup>iii</sup> | Net revenue <sup>iv</sup> | Gross revenue <sup>iii</sup> | Net revenue <sup>iv</sup> |
| Cost (\$) per 2,700 ft <sup>2v</sup> |                           |   |                          |                              |                           |                              |                           |
| 2020                                 | Full season <sup>vi</sup> | 2,562   | 1,144                    | 5,124                        | 3,980                     | 3,843                        | 2,699                     |
|                                      | Open ends <sup>vii</sup>  | 2,269   | 1,091                    | 4,538                        | 3,447                     | 3,404                        | 2,313                     |
|                                      | On-off-on <sup>viii</sup> | 1,930   | 1,088                    | 3,861                        | 2,773                     | 2,895                        | 1,807                     |
| 2021                                 | Full season               | 2,318   | 1,087                    | 4,638                        | 3,551                     | 3,478                        | 2,391                     |
|                                      | Open ends                 | 1,576   | 995                      | 3,153                        | 2,158                     | 2,365                        | 1,370                     |
|                                      | On-off-on                 | 1,637   | 993                      | 3,275                        | 2,282                     | 2,456                        | 1,463                     |
| 2022                                 | Full season               | 2,997   | 1,082                    | 5,995                        | 4,913                     | 4,496                        | 3,414                     |
|                                      | Open ends                 | 2,092   | 987                      | 4,184                        | 3,197                     | 3,138                        | 2,151                     |
|                                      | On-off-on                 | 2,858   | 985                      | 5,717                        | 4,732                     | 4,288                        | 3,303                     |

<sup>i</sup> Marketable fruit weight: 1 lb/2,700 ft<sup>2</sup> (250.8 m<sup>2</sup>) = 16.1lb/acre = 18.1 kg/ha.

<sup>ii</sup> Total cost of each pollination treatment per 2,700 ft<sup>2</sup> (250.83 m<sup>2</sup>) subplot.

<sup>iii</sup> Gross revenue = marketable yield × selling price; the estimated average retail and wholesale prices in Iowa for ‘Athena’ muskmelon during 2020–2022 were \$2.00/lb and \$1.50/lb, respectively (Nair, personal communication).

<sup>iv</sup> Net revenue = gross revenue – total cost of each treatment.

<sup>v</sup> \$1/2,700 ft<sup>2</sup> (250.83 m<sup>2</sup>) = \$16.13/acre = \$39.87/ha.

<sup>vi</sup> Full season: mesotunnel covers [nylon mesh, 60 g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>)] remained in place all season, except when one bumble bee hive was placed at the center of each subplot when female flowers appeared.

<sup>vii</sup> Open ends: both ends of each mesotunnel were opened when female flowers appeared; they were reclosed 2 weeks later.

<sup>viii</sup> On-off-on: mesotunnel covers were removed when female flowers appeared; they were replaced 2 weeks later.



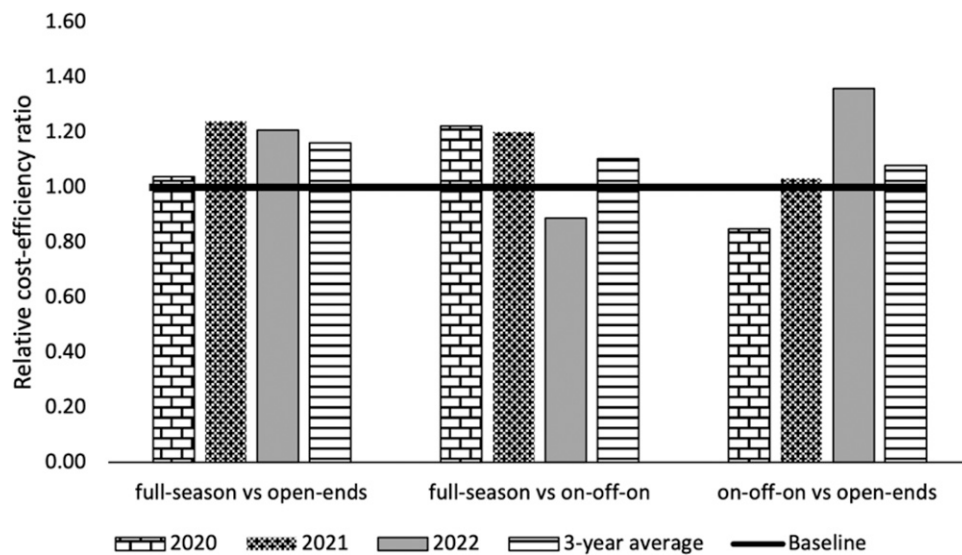


Fig. 2. Relative cost-efficiency ratios comparing mesotunnel treatments during the pollination trial depicting annual comparisons among treatments by year and by the 3-year average (2020–22). The ratio was calculated by dividing cost efficiency of the first-named treatment by the second-named treatment for each comparison of two treatments. Treatments: on-off-on, both ends of nylon mesh [60-g/m<sup>2</sup> (0.197 oz/ft<sup>2</sup>)] covers were opened when the first female flowers opened and reclosed 2 weeks later; open ends, covers were removed entirely for 2 weeks when the first female flowers opened and then were reinstalled; full season, covers remained closed from transplanting until first harvest, and a purchased bumble bee hive was inserted when the first female flowers opened. The solid horizontal line indicates the baseline at which neither treatment had a cost-efficiency advantage; the area above the baseline indicates the first-listed treatment had higher cost-efficiency than the other treatment; and the area below the baseline indicates the first-listed treatment with a lower cost-efficiency ratio than the other treatment. Relative cost-efficiency ratio = (revenue ÷ cost) of the first treatment ÷ (revenue ÷ cost) of the second treatment.

pollination strategy with bumble bees installed at bloom was the most reliable and consistently provided higher net revenue across the three years of the study, thus aligning with the findings in small plots (Nelson et al. 2023).

Actual costs incurred will vary with grower choices. For example, some growers are likely to be unwilling to purchase and handle bumble bees (Diggins 2023). Alternatives to relatively costly purchases of bumble bees include the use of native bees (Gómez et al. 2016; Tschoeke et al. 2015; Winfree et al. 2007), which could be augmented by planting bee-attracting plants alongside the main crop in mesotunnels (Azpiazu et al. 2020; Barbir et al. 2015; Hogg et al. 2010). Alternatively, the open ends strategy might be improved by reducing the continuous length of the tunnel to encourage pollinator visitation in the middle of the mesotunnel. The number of hives that would be needed for longer production-scale tunnels (e.g., 500 ft) that may be used on larger organic farms needs to be assessed, as does the issue of whether the release of purchased bees into the environment after harvest could spread viruses or other bee pests to native bee populations

(Goulson 2003; Goulson and Hughes 2015). These questions point to the need for further field studies to validate mesotunnel pollination strategies.

### Weed control trial

**YIELD.** When mowed 3 weeks after seeding, teff as a living mulch produced marketable yield that was statistically similar to those of the landscape fabric treatment and higher than those of the other treatments (Table 8). In other vegetable crops, mowing of living mulch between crop rows also reduced yield loss observed in nonmowed treatments (Brown 2017; Tarrant et al. 2020). When it emerges, teff grows vigorously, produces an extensive root system, and is exceptionally tolerant to drought. Therefore, we speculated that the suppressive effect of nonmowed teff on ‘Athena’ muskmelon yield was caused by competition for nutrients, light, and water between teff and the crop (Tarrant et al. 2020); similar competitive effects have been observed for annual ryegrass (Puka-Beals and Gramig 2021) and black oats (*Avena strigosa*) (Chase and Mbuya 2008) when used as living mulches between plastic-covered raised beds of various vegetable crops. During our trials, timely

mowing (3 weeks after transplanting) appeared to be critical in managing teff as a living mulch in organic ‘Athena’ muskmelon production, providing durable weed control while minimizing competition with the crop. We also noted that the impact of mowing furrows that were initially left bare but were then colonized by weeds varied substantially by year; mowing had negligible effects on the marketable yield in 2021, but it approximately doubled in 2022 compared with no mowing (Table 8). This outcome suggests that the yield benefit from mowing nonseeded furrows may be inconsistent.

**WEED BIOMASS.** Teff was highly effective at suppressing weeds during both years of the experiment (Table 9), supporting the findings of studies of other crops (MacLaren et al. 2019; Puka-Beals and Gramig 2021; Tarrant et al. 2020). The landscape fabric treatment had no weeds, whereas weed biomass was progressively higher in the mowed teff treatment, mowed bare ground, nonmowed teff, and the nonmowed bare ground control (Table 9). Although the landscape fabric treatment eliminated weeds, mowed teff may confer more sustainability benefits by adding soil

**Table 8. Impact of weed management treatments on yield of organic ‘Athena’ muskmelon under mesotunnels in 30- × 18-ft (45.7- × 5.5-m) plots during 2021 and 2022 in Iowa, USA.**

| Yr   | Treatment                            | Marketable (lb/acre) <sup>i</sup> | Nonmarketable (lb/acre) <sup>i</sup> |
|------|--------------------------------------|-----------------------------------|--------------------------------------|
| 2021 | Landscape fabric <sup>ii</sup>       | 43,354 a <sup>vii</sup>           | 7,199 a                              |
|      | Teff, mowed <sup>iii</sup>           | 39,884 ab                         | 8,972 a                              |
|      | Teff, not mowed <sup>iv</sup>        | 26,794 b                          | 8,433 a                              |
|      | Bare ground, mowed <sup>v</sup>      | 26,613 b                          | 10,902 a                             |
|      | Bare ground, not mowed <sup>vi</sup> | 27,817 b                          | 7,066 a                              |
|      | <i>P</i> value                       | 0.0075                            | 0.6487                               |
| 2022 | Landscape fabric                     | 44,642 a                          | 6,830 a                              |
|      | Teff, mowed                          | 37,449 ab                         | 9,238 a                              |
|      | Teff, not mowed                      | 23,985 c                          | 7,849 a                              |
|      | Bare ground, mowed                   | 36,139 b                          | 6,887 a                              |
|      | Bare ground, not mowed               | 18,379 c                          | 5,012 a                              |
|      | <i>P</i> value                       | <0.0001                           | 0.2230                               |

<sup>i</sup> 1 lb/acre = 1.1209 kg·ha<sup>-1</sup>.

<sup>ii</sup> Landscape fabric was placed between rows just before transplanting.

<sup>iii</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting and mowed 3 weeks later.

<sup>iv</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting.

<sup>v</sup> No mulch was applied and weeds were mowed 3 weeks after transplanting.

<sup>vi</sup> No mulch was applied between rows and no mowing was performed.

<sup>vii</sup> Within each year, means in a column followed by the same letter are not significantly different at *P* < 0.05 using Tukey’s honestly significant difference test.

organic matter, enhancing soil structure with roots, and suppressing erosion (Bhaskar et al. 2021; Brown 2017; Chase and Mbuya, 2008). Teff is also cheaper and less laborious to establish in the field than installing, removing, and storing landscape fabric (Nelson et al. 2023). When compared with the bare ground treatment, mowed teff yield more marketable ‘Athena’

muskmelon (Table 8) and likely contributed to the suppression of the weed seed bank (Liebman et al. 2021; Nichols et al. 2020). Despite the potential advantages of teff for weed control, it requires consistent moisture for germination and emergence (Mphande, unpublished data), which may pose a challenge during dryer postseeding periods for growers lacking irrigation equipment.

**Table 9. Impact of weed management treatments (on weed biomass in organic ‘Athena’ muskmelon under mesotunnels in 30- × 18-ft (9.1- × 5.5-m) plots in Iowa, USA.**

| Yr   | Treatment                            | Broadleaf weeds (g/6 ft <sup>2</sup> ) <sup>i</sup> | Grass weeds (g/6 ft <sup>2</sup> ) <sup>i</sup> | Total weed biomass (g/6 ft <sup>2</sup> ) <sup>i</sup> |
|------|--------------------------------------|---|---|--|
| 2021 | Landscape fabric <sup>ii</sup>       | 0.0 a <sup>vii</sup>                                | 0.0 a   | 0.0 a  |
|      | Teff, mowed <sup>iii</sup>           | 59.0 a  | 86.5 ab   | 145.5 b  |
|      | Teff, not mowed <sup>iv</sup>        | 224.5 b   | 113.3 ab  | 337.8 bc   |
|      | Bare ground, mowed <sup>v</sup>      | 39.3 a  | 247.3 b   | 286.5 b  |
|      | Bare ground, not mowed <sup>vi</sup> | 362.0 c   | 207.3 ab  | 569.3 c  |
|      | <i>P</i> value                       | <0.0001   | 0.0482  | <0.0001  |
| 2022 | Landscape fabric                     | 0.0 a   | 0.0 a   | 0.0 a  |
|      | Teff, mowed                          | 2.5 a   | 5.5 a   | 8.0 a  |
|      | Teff, not mowed                      | 50.8 a  | 67.8 ab   | 118.5 b  |
|      | Bare ground, mowed                   | 4.6 a   | 128.3 bc  | 132.9 b  |
|      | Bare ground, not mowed               | 117.3 a   | 227.8 c   | 345.0 c  |
|      | <i>P</i> value                       | 0.0815  | <0.0001   | <0.0001  |

<sup>i</sup> Biomass (g/quadrat; 6 ft<sup>2</sup> = 0.5574 m<sup>2</sup>) per subplot harvested 2 d before the first muskmelon harvest and weighed after 3 d of oven-drying at 68 °C (154.4 °F); 1 ft<sup>2</sup> = 0.09 m<sup>2</sup> and 1 °C = 33.8 °F.

<sup>ii</sup> Landscape fabric was placed between rows just before transplanting.

<sup>iii</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting and mowed 3 weeks later.

<sup>iv</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting.

<sup>v</sup> No mulch was applied and weeds were mowed 3 weeks after transplanting.

<sup>vi</sup> No mulch was applied between rows.

<sup>vii</sup> Within each year, means in a column followed by the same letter are not significantly different at *P* < 0.05 using Tukey’s honestly significant difference test.

**ECONOMIC ANALYSIS.** We extrapolated the subplot size (540 ft<sup>2</sup>) of the weed control trials to 2700 ft<sup>2</sup> (150-ft-long × 18-ft-wide) under the assumption (based on our 2020 results of the pollination trials) that a single purchased bumble bee hive would meet pollination needs for this larger (150 ft) mesotunnel size (Rojas et al. 2011). Total per-treatment costs ranged from \$995 to \$1019 across all treatments in each year (Table 10). Treatment-specific labor costs (landscape fabric installation and cleanup, teff seeding, and mowing) were highest for landscape fabric (21% of the total), whereas these costs were 5% to 9% for the other treatments. The retail and wholesale prices for organic ‘Athena’ muskmelon were the same as those for the pollination experiment. Our analysis showed that landscape fabric had the highest net revenue, closely followed by mowed teff during both years. At the 2022 wholesale ‘Athena’ muskmelon price, landscape fabric had \$2274 net revenue compared to the cost of \$1877, followed by mowed teff with \$1855 net revenue and \$1633 in costs. Nonmowed bare ground performed the worst in 2022, with only \$154 net revenue on a \$1556 investment (Table 11). Generally, landscape fabric was the most cost-efficient treatment, followed by mowed teff, mowed bare ground, nonmowed teff, and nonmowed bare ground (Fig. 3). Treatment comparisons varied minimally between the two years, suggesting that the cost-efficiency ratios were relatively stable (Fig. 3). The economic analysis indicated that under mesotunnel systems, organic muskmelon growers could lose more than 90% of revenue to weeds if they are left unchecked (Nelson et al. 2023). However, using teff as a living mulch in the furrows between organic ‘Athena’ muskmelon rows can provide revenue comparable to that of landscape fabric, but with far more benefits to soil quality, as long as the growth of teff is suppressed by timely mowing (Brown 2017; Tarrant et al. 2020). Additional studies would be useful to optimize the mowing timing for teff in a range of soils, climates, and cucurbit crops to optimize weed suppression without sacrificing crop yield and ensure even germination and establishment of teff after sowing (Puka-Beals and Gramig

**Table 10. Summary of costs of weed management treatments in organic ‘Athena’ muskmelon production under mesotunnel systems in Iowa, USA, during 2021 and 2022, based on 30- × 18-ft (9.1- × 5.5-m) plots extrapolated to 150 × 18 ft (45.7 × 5.5 m).**

| Yr                                    | Treatment                            | Mesotunnel supplies <sup>i</sup> | Bumble bee hives <sup>ii</sup> | Variable labor cost <sup>iii</sup> | Common cost <sup>iv</sup> | Total cost <sup>v</sup> |
|---------------------------------------|--------------------------------------|----------------------------------|--------------------------------|------------------------------------|---------------------------|-------------------------|
| Cost (\$) per 2,700 ft <sup>2vi</sup> |                                      |                                  |                                |                                    |                           |                         |
| 2021                                  | Landscape fabric <sup>vii</sup>      | 158                              | 137                            | 402                                | 1,180                     | 1,877                   |
|                                       | Bare ground, mowed <sup>viii</sup>   | 158                              | 137                            | 132                                | 1,180                     | 1,607                   |
|                                       | Bare ground, not mowed <sup>ix</sup> | 158                              | 137                            | 81                                 | 1,180                     | 1,556                   |
|                                       | Teff, mowed <sup>x</sup>             | 158                              | 137                            | 158                                | 1,180                     | 1,633                   |
|                                       | Teff, not mowed <sup>xi</sup>        | 158                              | 137                            | 108                                | 1,180                     | 1,583                   |
| 2022                                  | Landscape fabric                     | 158                              | 137                            | 402                                | 1,180                     | 1,877                   |
|                                       | Teff, mowed                          | 158                              | 137                            | 158                                | 1,180                     | 1,633                   |
|                                       | Teff, not mowed                      | 158                              | 137                            | 108                                | 1,180                     | 1,583                   |
|                                       | Bare ground. Mowed                   | 158                              | 137                            | 132                                | 1,180                     | 1,607                   |
|                                       | Bare ground, not mowed               | 158                              | 137                            | 81                                 | 1,180                     | 1,556                   |

<sup>i</sup> Mesotunnel supplies included nylon mesh, hoop bender, hoops, landscape fabric, and sand bags.

<sup>ii</sup> Total cost of purchased bumble bee hives including shipping.

<sup>iii</sup> Labor costs for tasks specific to each weed control treatment, including landscape fabric installation and cleanup, teff seeding, and mowing.

<sup>iv</sup> Cost of land rental, seeds, irrigation, black plastic, compost, fertilizer, staples, plot setup, machinery, and labor associated with their use, application and installation was identical among treatments.

<sup>v</sup> Sum of all costs in US dollars.

<sup>vi</sup> \$1/2,700 ft<sup>2</sup> (250.8 m<sup>2</sup>) = \$16.13/acre = \$39.87/ha.

<sup>vii</sup> Landscape fabric was placed between rows just before transplanting.

<sup>viii</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting and mowed 3 weeks later.

<sup>ix</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting.

<sup>x</sup> No mulch was applied and weeds were mowed 3 weeks after transplanting.

<sup>xi</sup> No mulch was applied between rows.

2021; Tarrant et al. 2020; Walters and Young 2008).

we showed that certain mesotunnel production practices resulted in higher yield and/or net revenue than others. Using a pollination experiment, we showed that keeping mesotunnels closed for the entire growing season and using purchased bumble bees

for pollination resulted in higher net revenue than either opening the tunnel ends or uncovering the tunnels during bloom. Removal of the nylon mesh covers for pollination of ‘Athena’ muskmelon for as little as 2 weeks provided access to insect pests as well as

## Conclusions

Using two separate field studies accompanied by an economic analysis,

**Table 11. Annual total cost, marketable yield, selling price, gross revenue, and net revenue of organic muskmelon for weed control treatments in the weed management trial in Iowa, USA, during 2021 and 2022 on 30- × 18-ft (9.1- × 5.5-m) plots extrapolated to 150 × 18 ft (45.7 × 5.5 m).**

| Yr                                   | Treatment <sup>i</sup>              | Marketable yield (lb/2,700 ft <sup>2</sup> ) <sup>i</sup> | Total cost <sup>ii</sup> | Retail price (\$2.00/lb)     |                           | Wholesale price (\$1.50/lb)  |                           |
|--------------------------------------|-------------------------------------|---|--------------------------|------------------------------|---------------------------|------------------------------|---------------------------|
|                                      |                                     |   |                          | Gross revenue <sup>iii</sup> | Net revenue <sup>iv</sup> | Gross revenue <sup>iii</sup> | Net revenue <sup>vi</sup> |
| Cost (\$) per 2,700 ft <sup>2v</sup> |                                     |   |                          |                              |                           |                              |                           |
| 2021                                 | Landscape fabric <sup>vi</sup>      | 2,687   | 1,877                    | 5,375                        | 3,498                     | 4,031                        | 2,154                     |
|                                      | Teff, mowed <sup>vii</sup>          | 2,472   | 1,633                    | 4,950                        | 3,317                     | 3,713                        | 2,080                     |
|                                      | Teff, not mowed <sup>viii</sup>     | 1,660   | 1,583                    | 3,330                        | 1,747                     | 2,498                        | 915                       |
|                                      | Bare ground, mowed <sup>ix</sup>    | 1,649   | 1,607                    | 3,299                        | 1,692                     | 2,474                        | 867                       |
|                                      | Bare ground, not mowed <sup>x</sup> | 1,724   | 1,556                    | 3,449                        | 1,893                     | 2,586                        | 1,030                     |
| 2022                                 | Landscape fabric                    | 2,767   | 1,877                    | 5,534                        | 3,657                     | 4,151                        | 2,274                     |
|                                      | Teff, mowed                         | 2,321   | 1,633                    | 4,650                        | 3,017                     | 3,488                        | 1,855                     |
|                                      | Teff, not mowed                     | 1,486   | 1,583                    | 2,970                        | 1,387                     | 2,228                        | 645                       |
|                                      | Bare ground, mowed                  | 2,240   | 1,607                    | 4,440                        | 2,833                     | 3,330                        | 1,723                     |
|                                      | Bare ground, not mowed              | 1,139   | 1,556                    | 2,280                        | 724                       | 1,710                        | 154                       |

<sup>i</sup> Weight of marketable fruit based on the 2,700-ft<sup>2</sup> (250.8-m<sup>2</sup>) plot (= 16.1 lb/acre = 18.1 kg/ha).

<sup>ii</sup> Total cost of each weed control treatment on an extrapolated 2,700-ft<sup>2</sup> (250.8-m<sup>2</sup>) subplot.

<sup>iii</sup> Gross revenue = marketable yield × selling price; estimated average retail and wholesale prices for ‘Athena’ muskmelon in Iowa during 2021–22 were \$2.00/lb and \$1.50/lb, respectively (Nair, personal communication).

<sup>iv</sup> Net revenue = gross revenue – total cost of each treatment.

<sup>v</sup> \$1/2,700 ft<sup>2</sup> (250.8 m<sup>2</sup>) = \$16.13/acre = \$39.87/ha.

<sup>vi</sup> Landscape fabric was placed between rows just before transplanting.

<sup>vii</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting and mowed 3 weeks later.

<sup>viii</sup> Teff was seeded at 4 lb/acre (4.5 kg·ha<sup>-1</sup>) between rows just before transplanting.

<sup>ix</sup> No mulch was applied and weeds were mowed 3 weeks after transplanting.

<sup>x</sup> No mulch was applied between rows.

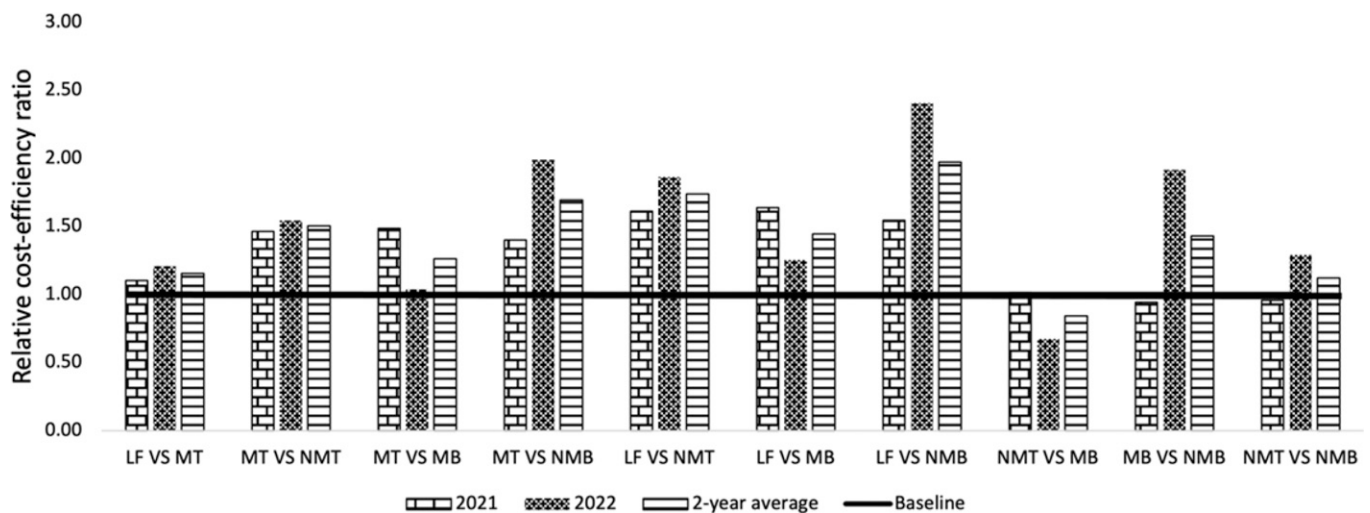


Fig. 3. Cost-efficiency ratios comparing mesotunnel treatments in the weed control trial, showing annual comparisons among treatments by year and by 2-year average (2021–22). The ratio is calculated by dividing cost-efficiency of the first-named treatment by the second-named treatment for each comparison of two treatments. Treatments: nonmowed bare ground (NMB) = bare ground with no mowing; mowed bare ground (MB) = bare ground control where weeds in the furrow were mowed 3 weeks after transplanting; landscape fabric (LF) = furrow was covered with landscape fabric; mowed teff (MT) = teff seeded in the furrow at 4 lb/acre (4.5 kg·ha<sup>-2</sup>) and mowed at 3 weeks after transplanting; nonmowed teff (NMT) = teff seeded in the furrow at 4 lb/acre (4.5 kg·ha<sup>-2</sup>) with no mowing. The solid horizontal line indicates a baseline at which neither treatment had a cost-efficiency advantage. Above the baseline, the first-listed treatment had higher cost-efficiency than the other treatment. Below the baseline, the first-listed treatment had a lower cost-efficiency ratio than the other treatment. Relative cost-efficiency ratio = (revenue ÷ cost) of treatment x ÷ (revenue ÷ cost) of treatment y.

pollinators, and cucumber beetle access increased the risk of crop loss from bacterial wilt. For this study, we used a plot size that was scaled-up from those used during previous studies (Nelson et al. 2023) to evaluate whether the previous results would scale-up to commercial plot size, and they did.

In contrast, our weed management study used a small-scale plot size because we did not anticipate scale impacts on weed management. The weed management trial showed that teff can suppress weeds effectively in the furrows between ‘Athena’ muskmelon beds under mesotunnels, but that mowing 3 weeks after transplanting the crop is essential to avoid yield drag associated with competition between this vigorous living mulch and ‘Athena’ muskmelon. Although landscape fabric effectively eliminated weeds in the furrows and resulted in the highest net returns, it requires considerable labor to install and remove. Furthermore, unlike teff, it provides no benefits for soil quality and can add to the buildup of solid waste in landfills (Flury and Narayan 2021; Zhang et al. 2020, 2022). Growers should evaluate these tradeoffs when selecting a preferred weed management strategy.

We assessed the components of an overall approach for the sustainable use

of mesotunnels in organic ‘Athena’ muskmelon production. Future research could extend our results by combining preferred pollination and weed management strategies to seek an optimized production system in Iowa. Interestingly, concurrent organic ‘Athena’ muskmelon field trials in central New York that used very similar experimental designs obtained results that differed substantially from our Iowa findings (Sarah Pethybridge, personal communication). This outcome emphasizes the need to validate the suitability of these strategies in regions with different soils, climates, and pest–disease complexes.

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