The Effects of Plastic Mulch Choice on Hemipteran Populations, Soil Temperature, and Productivity of Lavender (*Lavandula* × *intermedia*) in an Ohio Brownfield: A Participatory Approach

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ABSTRACT. Lavender has shown promise as a specialty crop in the Rust Belt cities of the midwestern United States; however, production in these regions can be challenging due to harsh winter conditions, cosmetic damage and disease transmission from hemipteran pests, and a lack of information on best management practices in urban settings. This study uses a participatory research approach to address soil and pest management issues at a small-acreage lavender operation in Ohio. A 2-year field experiment was designed collaboratively with land managers to compare the performance of current mulch practices (black landscape fabric) with the use of silver, dark, and embossed dark plastic mulches on hemipteran insect populations, soil temperature, and leaf area of lavender plants. This experiment used a combination of sticky trap sampling, soil temperature data loggers, and leaf area index sampling. While mulch effects varied by year, silver mulch had significantly lower hemipteran populations in the first year and soil temperatures were significantly higher in blue mulch during both years. Lavender leaf area was significantly greater in red mulch relative to blue mulch but neither mulch treatment showed a significant difference in leaf area compared to the control (black landscape fabric). Finally, there was no evidence of indirect effects of soil temperature on plant growth. These results indicate that the effects of plastic mulch on soil properties, hemipteran insect populations, and lavender development vary by color and texture. Thus, the selection of plastic mulch should be based on specific management issues.

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INTRODUCTION

A member of the mint family (Lamiaceae), lavender (genus *Lavandula*) is a group of perennial aromatic shrubs with over 30 described species and more than 400 cultivars (Vijulie et al. 2022; Crișan et al. 2023). The native distribution of lavender extends from South Asia to Europe, North Africa, the Canary Islands, and Cape Verde. Lavender is a versatile herb that has culinary, beekeeping, and medicinal applications, but is primarily valued for its essential oils. Lavender essential oils, which contain the monoterpenoids linalool and linalyl acetate, are used in many industries, including the food and beverage industry, aromatherapy, perfumery, cosmetics, and pharmaceuticals (Denner 2009; Zheljazkov et al. 2012; Koulivand et al. 2013; Shahdadi et al. 2017). Most large-scale lavender production and essential oil distillation occurs in areas near the Mediterranean basin, with more than two-thirds coming from France and Bulgaria alone (Stanev et al. 2016).

Lavender Cultivation

In the United States, lavender is mainly cultivated as a specialty or niche crop in small-acreage operations, 10 acres or fewer in size (Charles et al. 2002; Quick Stats Database 2025). Lavender production can provide small-scale growers with a viable avenue for direct market sales of lavender plants, soaps, lotions, essential oils, and other value-added products (Adam 2006; Giray et al. 2019). Furthermore, many small-scale producers of lavender in the United States have found alternative marketing strategies that center around agricultural tourism activities (herein referred to as agritourism), including pick-your-own (U-pick) operations, on-farm farmers' markets, and garden tours.

In urban and peri-urban areas, lavender farms also provide an opportunity for ecological restoration of brownfields, defined as former industrial and commercial properties with actual or perceived levels

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of environmental contamination (Greenstein and Sungu-Eryilmaz 2004). The process of cultivating plants that can tolerate and potentially improve contaminated soils, known as phytoremediation, is potentially an environmentally sustainable, low cost, low risk approach to brownfield redevelopment (Ma et al. 2001; Angelova et al. 2015). Lavender has long been recognized as a plant species that thrives in poor quality and marginal soils, and recent evidence indicates that it can be grown in soils that are contaminated with heavy metals (Zheljazkov et al. 2006). Findings from Angelova et al. (2015) indicate that lavender excels in its ability to uptake, translocate, and accumulate lead and cadmium in its aboveground tissues, and that the quality of essential oils are not compromised—even when grown in heavily polluted soils. Given its ornamental value and ability to be grown in contaminated soils, yet processed into contaminant-free products, lavender can be an ideal choice for phytoremediation and redevelopment of brownfields into sites for agritourism (Abu-Darwish 2009). In the Rust Belt cities of the midwestern United States, lavender-based agritourism has grown in popularity in recent years (Hilmarsdóttir 2019). This is in part driven by the long history of industrial development (and more recently, abandonment) in the region. Additionally, several varieties of English lavender (*Lavandula angustifolia*) and hybrid lavender, or lavandin (*Lavandula* × *intermedia*), can tolerate the cold, harsh winters and wet, hot summers characteristic of the region (Adam 2006).

Despite its promise, brownfield-based lavender production in the midwestern United States is particularly challenging for multiple reasons. Several species of insects in the order Hemiptera, including the four-lined plant bug (*Poecilocapsus lineatus*, family Miridae), garden fleahopper (*Microtechnites bractatus*, family Miridae), green peach aphid (*Myzus persicae*, Hemiptera: Aphididae), and tarnished plant bug (*Lygus lineolaris*, family Miridae) can transmit alfalfa mosaic virus (AMV) (genus *Alfamovirus*, family Bromoviridae) (Judge et al. 1970; Nakova 2011; Vasileva 2015; Chilosi et al. 2017; Chuche et al. 2018). Infection with AMV can lead to stunting in lavender plants and, importantly, reduce the quality of processed essential oils (Bruni et al. 2006). Other hemipteran insects such as meadow spittlebug (*Philaenus spumarius*, family Aphrophoridae) secrete foamy masses on flowers and stems that can substantially reduce cosmetic appeal and marketability of U-pick lavender (J. Duxbury, personal communication, 2021).

In addition to their potential susceptibility to pests, many lavender varieties are poorly adapted to the predominantly silty clay loam soils of the Midwest. This requires growers to amend their soils to more closely resemble the slightly alkaline, porous, rocky soils that lavender prefers (Adam 2006). Climate change-related fluctuations in temperature and precipitation levels have also complicated lavender production. Warmer, wetter winters combined with late frosts are a primary driver of root rot, which can lead to early crop failure (Stanev et al. 2016). Soil temperatures between 27 °C to 30 °C tend to promote lavender stem length, leaf growth, and flower production, particularly in the spring and early summer (Maganga 2004; Mitreva and Pankov 2018; Ghaderi-Far et al. 2021).

Plastic Mulch

Plastic mulching has shown promise in creating favorable conditions for crop production on lands with poor soils and constraining environmental factors. First developed in the United States in the 1950s, plastic mulching involves covering the soil with a durable, low-density polyethylene film and planting crops in small holes or perforations in the film (Lamont 2017). While plastic mulches present an effective physical barrier that can reduce weed populations (Johnson and Fennimore 2005; Rajablariani et al. 2012), their role in soil and insect pest management—and ultimately the benefits they impart on crop production—is largely defined by their color, texture, and associated energy radiation behavior.

Light-colored mulches (including white, pink, and silver mulches) reflect a large proportion of global solar radiation back toward the plant canopy, producing a cooling effect under the soil surface (Ibarra-Jiménez et al. 2011; Amare and Desta 2021). The reflected light from light-colored mulches can disrupt insects' ability to locate host plants and have shown generally positive trends in repelling many hemipteran insects (such as aphids, leafhoppers, and whiteflies), though results vary by region and by crop (Brown and Brown 1992; Summers and Stapleton 2002). Black plastic mulch, the most commonly used color, efficiently absorbs most UV (ultraviolet), visible, and infrared wavelengths of incoming solar radiation. This absorbed solar energy is re-released into the soil surface in the form of thermal radiation, or heat (Gordon et al. 2010; Manickam et al. 2010; Shaw Jahan et al. 2018). Blue, red, green, and brown mulches selectively absorb some regions of the photosynthetically active radiation (PAR) spectrum and vary in their transmission of solar infrared radiation and in their reflectivity (Jones et al. 2021).

While dark-colored mulches (black, blue, red, green, and brown) typically produce higher soil temperatures than light-colored mulches (Al-Karaghouli et al. 1990; Gordon et al. 2010; Amare and Desta 2021), light- and dark-colored mulches produce equivocal results in relation to dissuading hemipteran insects (Brown and Brown 1992). A third category of plastic mulches, embossed mulches, are available in both light and dark colors, but differ in texture compared to conventional low-density polyethylene-based mulches. Embossed mulches are more elastic and have increased contact with the soil surface relative to conventional plastic mulches, which makes embossed mulches more efficient at heating soil due to enhanced thermal conductance (Schonbeck and Evanylo 1998). However, their influence on insects remains unknown (Ibarra-Jiménez et al. 2008). While conventional and embossed plastic mulches have been tested in a variety of cropping systems, there is little research on the effects of these different mulches in lavender systems, let alone lavender cultivated in brownfields. In brownfield settings, growers must face the challenge of producing lavender in contaminated soils with little available information on best management practices for their environmental context.

Participatory Research

Participatory research—providing opportunities for feedback and adjustment of experimental design according to the specific needs of the local community—is one way to help growers overcome challenges to agricultural production in brownfields. Participatory methods allow researchers and growers to collaborate and co-create throughout the research process, including in the development of testable questions, methods, data collection, and in the interpretation and dissemination of findings (Krasny et al. 2014; Matzek et al. 2014; van De Gevel et al. 2020). By placing greater emphasis on local contextual factors and knowledge, participatory methods help researchers uncover solutions specific to unique environments, like brownfields, that are more likely to be adopted by stakeholders (Johnson et al. 2004; Ceccarelli and Grando 2007). Indeed, previous studies on brownfield redevelopment initiatives have indicated that stakeholder involvement is a necessary strategy for improving social acceptability (Cappuyns and Kessen 2014; Tendero and Plottu 2019) and promoting environmentally and socially sustainable practices (Kontogianni et al. 2001).

The current study uses a participatory approach to combine knowledge from land managers and researchers to address soil and insect pest management challenges in a brownfield-based lavender operation in northeastern Ohio. Collaboration with land managers led to the development and evaluation of the following research question: *what is the effect of plastic mulch color and texture on hemipteran pest populations, soil temperatures, and lavender growth in a brownfield?* The following hypotheses were tested:

1. Hemipteran insect populations would be significantly lower in silver mulch than in dark-colored conventional (black, blue, red, brown) and embossed mulch (dark green).
2. Soil temperatures would be significantly higher in dark-colored conventional and embossed mulches compared to silver mulch.
3. Plant growth would be significantly higher in dark-colored conventional and embossed mulch compared to silver mulch.

The third hypothesis is based on the rationale that soil temperature is a more important driver of lavender plant growth than the presence of hemipteran insect pests. While insect-borne pathogens such as alfalfa mosaic virus are capable of severely stunting or delaying lavender development, most of the damage in lavender from hemipteran pests is cosmetic and, while still impactful to U-pick sales, does not lead to appreciable differences in yield (Chaisse and Blanc 1990). Soil temperatures, on the other hand, have been shown to influence lavender development and floral production (Ghaderi-Far et al. 2021). The researchers and land managers worked together to develop an experimental design that would test all 3 hypotheses.

METHODS

Study Site

The study was carried out at Lavender Trails, a 1.6-hectare lavender U-pick farm in Orrville, Ohio (Lavender Trails; Wayne County, Ohio; lat 40°51'41"N, long 81°45'15"W). Established in 2018, the farm has more than 1,600 lavender plants, most of which are cultivated varieties of English lavender (*Lavandula angustifolia*), lavandin (*Lavandula* × *intermedia*), and Spanish lavender (*Lavandula stoechas*). On the easternmost side of the farm there is also an apiary and 500 m^2 pollinator garden dominated by a mix of goldenrod species (genus *Solidago*). During the U-pick season (late June to July), Lavender Trails receives approximately 700 to 1,200 visitors each year (J. Duxbury, personal communication, 2021).

Prior to the establishment of the lavender farm, the site was a construction and demolition landfill, which typically contains porous, nutrient-poor soils of crushed concrete, asphalt, and rebar. At Lavender Trails, soils are a mix of Fitchville silt loams and Luray silty clay loam, both of which are poorly draining, easily eroding soils found in valleys on lake and till plains (Web Soil Survey 2022). To improve soil drainage and to make the soil more easily tillable for lavender cultivation, 64 beds of mixed pea gravel, peat moss, compost, and sand were installed at the site in 2018. The areas outside of the lavender beds and pollinator garden are dominated by timothy grass (*Phleum pratense*), fescue (*Festuca* sp.), and clovers (*Trifolium* sp.). The local region experiences a humid continental climate with 4 distinct seasons, punctuated by cold and harsh winters followed by warm and humid summers. Average rainfall is in the range of 76 to 101 cm a year, with 84 cm of snow and 168 days of sun a year (United States NWS 1999).

Participatory Process

Stakeholder identification of priority areas for research began during a workshop in February 2021 when the land managers of Lavender Trails were asked to determine constraints to lavender production at their brownfield site. Individual responses were grouped into larger themes using an inductive approach (Monaghan et al. 2017). The researchers led an activity designed to identify priority production-based issues that could be potentially addressed via a field study. In the activity, individual land managers were asked to "list the top 3 challenges to growing lavender in a brownfield." Responses were collected and placed on a board, then land managers were asked to work together to rank responses in order of least to most concerning. Following a discussion of the responses led by the researchers, the group selected 2 responses—based on everyone's collective expertise—that were most feasible for experimentation. This meeting identified hemipteran pest pressures and low soil temperatures as salient research topics.

The Lavender Trails land managers were invited to a second workshop in March 2021 to discuss potential practices and technologies to address the previously identified areas of research. A semi-structured interview was used to guide the discussion; land managers were asked about past use of pest and soil management practices, as well as new practices that have been considered but not implemented. Semi-structured interviews are designed to gather information on a set of pre-prepared questions while allowing for exploration of topics and subjects that may go beyond the scope of the planned questions (Chaudhuri and Kendall 2021). Pest and soil management measures used in other studies were also discussed. The second workshop concluded with a ranking of the perceived feasibility and potential effectiveness of all identified practices by land managers and researchers.

Analysis of the data from the 2 workshops, including the ranked lists of perceived feasibility and effectiveness of each potential practice, identified the use of colored conventional and embossed plastic mulches as a testable technology. This assessment was supported by the Lavender Trails land managers' experience using plastic mulch to reduce weed establishment and water infiltration at their lavender farm and their interest in comparing the performance of different colors and textures of plastic mulch. Follow-up contacts with land managers occurred shortly after the second workshop to facilitate the selection of mulch color, texture, and experimental design.

Experimental Design

A randomized complete block design with 6 treatments and 5 replicates was used to test the effects of plastic mulch color and texture on soil temperature, abundance of hemipteran insects, and lavender plant growth. Experimental blocks consisted of 5 individual 1.0 m wide by 15 m long rows containing pea gravel and potting soil mix, with a 1.1-meter space between rows. A total of 6 treatments were established across each experimental block, including 1 light-colored conventional plastic mulch (silver mulch), 3 dark-colored conventional plastic mulches (blue, brown, red), 1 dark-green embossed plastic mulch (embossed), and a black landscape fabric control treatment. A negative control of bare soil was not included to prevent the establishment of weed populations within lavender rows—a particular concern of the land managers. All plastic mulches were made from 0.1 mm thick by 1.2 m wide polyethylene material (Agriculture Solutions LLC, Kingfield, Maine USA), and the black landscape fabric was made from 0.5 mm thick by 1.9 m wide woven polyethylene weed barrier (Gardenport Inc., Corona, California USA). The 6 treatments were randomly assigned to 2.3 m long sections within each experimental block with the control treatment receiving 0.2 mm thick black landscape fabric. In each block, four, 2-year old *L. intermedia* var. Grosso lavender plugs were transplanted into pre-cut holes in the plastic mulch or landscape fabric and spaced approximately 0.5 m apart. Plastic mulch treatments and lavender transplants were established on May 30, 2021.

In 2021 and 2022, data on hemipteran abundance, soil temperature, and plant growth was collected in June and July, corresponding to the floral stage and peak harvest period of lavender in Ohio. In 2021, data on all 3 variables were collected when lavender plants were in bud stage (when approximately <50% of all flowers were opened) on June 15, in full bloom (when approximately >50% of all flowers were opened) on July 6, and early fructification (when flowers are visibly developing into fruits) on July 27. In April 2022, approximately 37% of the lavender plants died due to an early spring freeze (J. Duxbury, personal communication, 2022). These plants were replaced by 3-year-old lavender plants of the same variety (*L. intermedia* var. Grosso) on June 21, 2022. As a result of the re-planting, the initial collection of soil temperature, hemipteran abundance, and plant growth data occurred between June 22 and June 29—during the early part of the full bloom period. The second and third sample collections occurred at another later date in full bloom (July 13), and early fructification (July 25), respectively.

Hemipteran Abundance

The abundance of hemipteran insects in the families Cicadellidae, Aphrophoridae, Miridae, Aleyrodidae, Pseudococcidae, and Aphididae were assessed over time using sticky traps. Many of the major and minor insect pests of lavender in the midwestern and eastern portions of the United States are from these 6 families of Hemiptera. Adults and nymphs of these families are generally phloem feeders, using piercing-sucking mouthparts to puncture leaves and stems and ingest plant juices. In lavender, feeding from these groups can result in discoloration and distortion of leaves and stems (McVicar 2010; Ernst 2017; Pundt and Smith 2023). Several species are also capable of transmitting infectious diseases such as AMV or *Xylella fastidiosa*, a gram-negative bacterium that causes wilting of leaves and flowers (Zia-Ul-Haq et al. 2023).

Individual 15 cm by 20 cm yellow sticky cards (Gustave Inc., Baldwin Park, California USA) were used to assess mean hemipteran abundance across treatments over time. Sticky traps were staked approximately 10 cm above the canopy of the center-most lavender plant in each treatment. Sticky traps were placed on June 9, June 29, and July 21 in 2021, and on June 23, July 7, and July 19 in 2022. Seven days after placement, the sticky traps were collected for processing and identification of specimens (n = 30). All hemipteran adults found on sticky traps were identified to family level, then separated into morphospecies, distinctive groups of taxa that share similar morphological features. This process was aided by comparisons to pictures, a reference collection, and lists of diagnostic characteristics. As more specimens were identified, some initial morphospecies categories were further differentiated while others were combined. All specimens were reviewed after the last sticky trap sampling to finalize morphospecies groupings.

Soil Temperature

In 2021, soil temperature data was collected using a soil moisture and temperature probe (Agratronix™, Streetsboro, Ohio USA). On each sample date, soil temperature probes were placed under the mulch or landscape fabric at 3 randomly selected locations in each block, within the top 6.0 cm of soil. Mean soil temperature per block was calculated for all treatments. Mean soil temperatures were assessed every 30 minutes over a 2-hour period from 10 a.m. to noon on each sample date (4 measures per sample date), and a mean daily soil temperature per treatment per date was calculated (n = 30).

Given that soil temperatures can greatly fluctuate over the course of a day (Sinha et al. 2010; Archontoulis et al. 2014; Franquera and Mabesa 2016) a different approach was used in 2022 to gain greater accuracy in estimating mean daily soil temperatures. On June 22, 2022, three incisions were made at randomly selected locations within the plastic mulch of all experimental blocks. Temperature logging iButton® devices (Analog Devices Inc., Wilmington, Massachusetts USA), or thermochrons, were placed into the incisions within the top 6.0 cm of soil and covered with a strip of plastic mulch. Thermochrons were programmed to measure soil temperature every 10 minutes for 144 consecutive hours (6 days). Every 24 hours during the sampling period, the location of the thermochrons was re-randomized to account for microclimatic differences in soil temperature within the blocks. Mean daily temperatures per treatment were then calculated from June 22 to June 27. Further soil temperature recordings with the thermochrons were not made to protect the integrity of the plastic mulch from further incisions.

Plant Growth

Lavender growth was assessed through differences in mean leaf area index over time. Leaf area index, or LAI, is a measure of 50% of the total leaf area of plants in a block per unit ground surface area; it is expressed as a ratio of actual (LAI) to maximum (LAImax) surface area. Measurements of lavender plant LAI were done using an ACCUPAR LP-80 ceptometer (METER Group Inc., Pullman, Washington USA), where point sensor measurements were made by placing the ceptometer diagonally across the blocks and under the canopy of lavender plants. Four LAI readings were taken at each block, and mean LAI per block was calculated per sample date in 2021 and 2022 (n = 30).

Analysis of Data

All data were analyzed in R (R Core Team 2019). A 2-way analyses of variance (ANOVA) was used to evaluate the influence of mulch treatments and time on daily soil temperatures and hemipteran abundance in 2021 and 2022. Given that measurements of leaf area index were made on the same individual plants, repeated measures of analyses of variance were used in 2021 and 2022 to test for significant differences in LAI across mulch treatments and time—with the experimental block included as a statistical factor. Shapiro-Wilk tests run in R revealed that data for the following variables were not normally distributed: hemipteran abundance data in 2021, LAI data in 2021, and daily soil temperature data in 2021 and 2022. To prevent small variations in these datasets from becoming over-exaggerated using parametric statistical tests such as ANOVA, the following transformations were used: log transformation of 2021 hemipteran abundance and LAI data, and square root transformation of 2021 and 2022 daily soil temperature data. Tukey post-hoc tests were used to evaluate pairwise comparisons of mulch treatment and time on hemipteran abundance, daily soil temperature, and leaf area index in 2021 and 2022.

RESULTS

Insect Data

The effects of mulch type treatment on hemipteran abundance varied by year. In 2021, the 2-way ANOVA showed no significant interactive effects, but significant main effects of sample date and mulch type on log-transformed mean hemipteran abundance (Table 1). Tukey post-hoc tests indicated that silver mulch had significantly fewer mean hemipteran individuals than red ($p = 0.031$) and control ($p = 0.28$) mulch treatments but was not significantly different from any other mulch type (Fig. 1A). There were significantly fewer hemipteran insects found in sticky traps during early fructification on July 27th, relative to late bud stage on June 15th ($p = 0.001$) and full bloom on July 6th ($p = 0.002$), with no significant difference in hemipteran abundance on any other date (Fig. 1B). A total of 9,301 adults from 6 hemipteran families were sampled over the 3 sampling dates in 2021, mostly consisting of Aphididae (7,936 individuals across 4 morphospecies), followed by Cicadellidae (1,084 individuals across 5 morphospecies), Aleyrodidae (96 individuals across 2 morphospecies), Miridae (88 individuals across 3 morphospecies), Pseudococcidae (56 individuals across 1 morphospecies), and Aphrophoridae (41 individuals across 2 morphospecies).

Table 1
ANOVA table for mulch type and sample date effects on hemipteran abundance [a]

Year	Source of variation	SS	df	MS	F	*p*-value
2021	Mulch type	0.91	5	0.18	2.71	0.02*
	Date	24.61	1	24.61	366.44	<0.001***
	Block	0.01	1	0.01	0.19	0.66
	Mulch type * date	0.42	5	0.08	1.25	0.30
	Error	5.17	77	0.07		
	Total	31.12	89			
2022	Mulch type	106.0	5	21.19	0.66	0.66
	Date	211.4	1	211.38	6.54	0.01*
	Block	1.1	1	1.09	0.03	0.85
	Mulch type* date	103.6	5	20.72	0.64	0.67
	Error	2487.1	77	32.3		
	Total	2902.2	89			

[a] Statistically significant sources of variation are denoted as:
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.
*** Significant at $p < 0.001$.

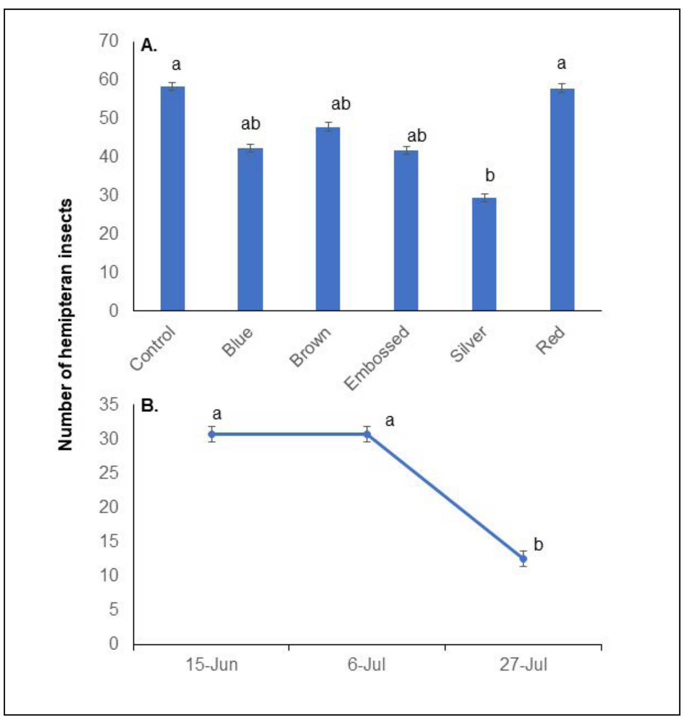

FIGURE 1. Hemipteran abundance in sampled beds (n = 30) in 2021 across A) mulch type treatments and B) sample dates. Error bars represent ±1 SEM. Letters above bars or data points represent significantly different means at α = 0.05, where "a" and "b" are significantly different means and "ab" fall within the boundaries of both statistical means. All means shown are back-transformed logarithmic operations.

For the 2022 sampling period, 2-way ANOVA analysis indicated a significant main effect of sample date, but not of mulch type (Fig. 2A), on hemipteran abundance (Table 1). In 2022, there were significantly more hemipteran insects found in sticky traps during the early stage of full bloom on June 29th relative to July 13th ($p = 0.02$) and early fructification on July 25th ($p = 0.001$), with no difference among the latter 2 dates (Fig. 2B). A total of 960 hemipteran individuals from 6 families were found over 3 sampling dates in 2022, the majority of which were represented by Cicadellidae (460 individuals across 6 morphospecies), followed by Aphididae (320 individuals across 4 morphospecies), Pseudococcidae (76 individuals across 1 morphospecies), Aleyrodidae (68 individuals across 1 morphospecies), Miridae (32 individuals across 5 morphospecies), and Aphrophoridae (4 individuals across 2 morphospecies).

Soil Temperature Data

Two-way ANOVA analyses revealed that mulch type, sample date, and experimental block were all significant main effects of daily soil temperature in 2021, with no significant interactive effects between mulch type and sample date (Table 2). In 2021, mean daily soil temperature under the blue mulch treatment was more than 0.5 °C higher than silver and embossed mulches, a difference that is significant according to Tukey post-hoc tests ($p < 0.01$ for both) (Fig. 3A). However, daily soil temperatures under blue, silver, and embossed mulches were not significantly different from red, brown, or control treatments. Tukey post-hoc tests also showed that daily soil temperatures were significantly lower during bud stage on June 15 compared with full bloom and early fructification stages on July 6 and July 27, respectively ($p < 0.001$ for all) (Fig. 3B). Daily soil temps between the 2 sample dates in July were not significantly different from each other.

While a different approach was used to collect soil temperature data in 2022, the 2-way ANOVA produced similar results to 2021; there was a significant main effect of mulch type, sample date, and experimental block on square root-transformed mean daily soil temperatures, with no evidence of interactive effects (Table 2). Daily soil temperature was significantly higher under blue mulch relative to all other mulch treatments ($p < 0.001$ for all) except red, and red mulch had significantly higher mean daily soil temperature compared to control and embossed mulch treatments ($p < 0.01$) (Fig. 4A). There was also evidence that daily soil

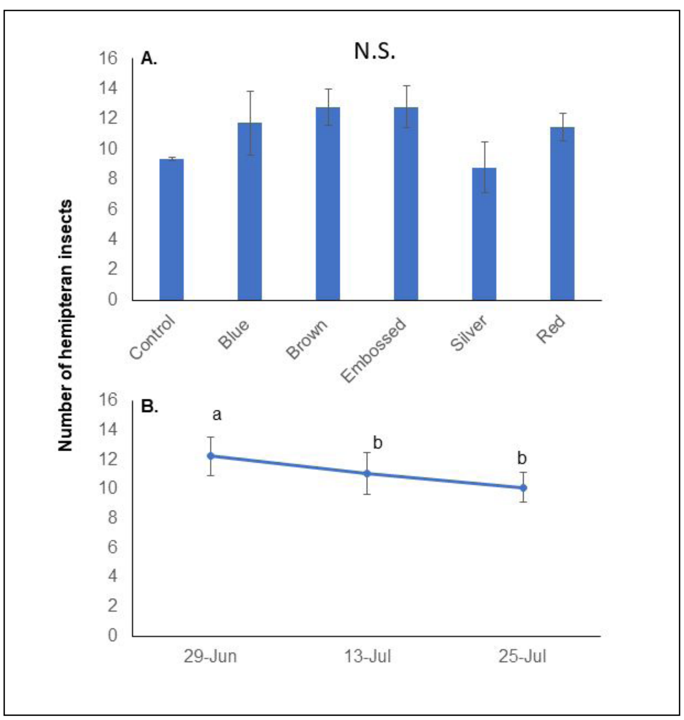

FIGURE 2. Hemipteran abundance (n = 30) in 2022 across A) treatments and B) sample dates. Error bars represent ±1 SEM. Letters above data points represent significantly different means at α = 0.05, where "a" and "b" are significantly different means and "ab" fall within the boundaries of both statistical means. "N.S." stands for nonsignificant.

Table 2
ANOVA table for mulch type and sample date effects on daily soil temperature [a]

Year	Source of variation	SS	df	MS	F	*p*-value
2021	Mulch type	279	5	56	3.71	<0.01**
	Date	7493	1	7493	497.51	<0.001***
	Block	118	1	118	7.86	0.01*
	Mulch type * date	11	5	2	0.15	0.98
	Error	5226	347	15		
	Total	13127	359			
2022	Mulch type	24	5	4.85	7.52	<0.001***
	Date	77	1	15.41	23.9	<0.001***
	Block	130	1	129.76	201.15	<0.001***
	Mulch type * date	8	25	0.33	0.5	0.98
	Error	10009	15515	0.65		
	Total	10248	15547			

[a] Statistically significant sources of variation are denoted as:
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.
*** Significant at $p < 0.001$.

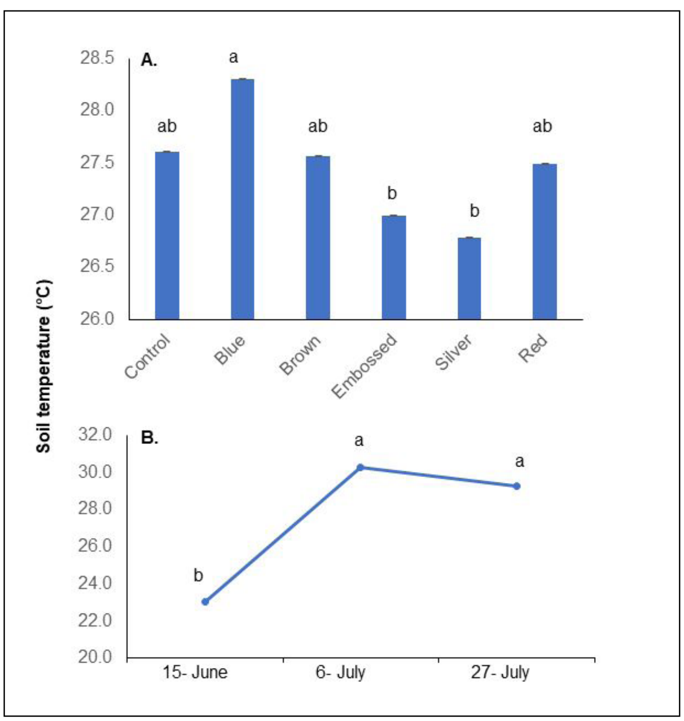

FIGURE 3. Daily soil temperatures in 2021 across A) mulch type treatments and B) sample dates (n = 30). Error bars represent ±1 SEM. Letters above bars or data points represent significantly different means at α = 0.05, where "a" and "b" are significantly different means and "ab" fall within the boundaries of both statistical means.

temperature was significantly higher on June 22 relative to all other sample dates ($p < 0.001$), and that significant differences occurred between all other dates ($p < 0.01$ for all) except between June 23 and June 26, and between June 24, 26, and 27 (Fig. 4B).

Plant Growth Data

There was no evidence of a significant interaction between the main effects of mulch type and sample date on log-transformed LAI in 2021, according to repeated measures of analysis of variance. Simple main effects analysis also shows a lack of significant effects of mulch type, sample date, and experimental block (Table 3) ($\eta^2 = 0.74$). In 2022, there was no significant interactive effect between mulch type and sample date, and no evidence of sample date nor block acting as main effects on leaf area index. Mulch type, however, was a significant main effect of LAI in 2022 (Table 3) ($\eta^2 = 0.43$). Post-hoc tests using the Bonferroni correction indicate LAI was significantly higher in the red mulch treatment compared with blue ($p = 0.005$), but that neither were significantly different from any of the other treatments (Fig. 5).

DISCUSSION

Insects

The findings of the 2-year study only partially support the hypothesis that light-colored, reflective mulches will dissuade hemipteran insects in lavender. Statistical evaluation of hemipteran abundance revealed that mulch effects on hemipteran insects varied by year. In 2021, there were clear differences in the number of hemipteran insects found among different treatments of plastic mulch, with significantly fewer hemipteran insects found in silver plastic mulch relative to red plastic mulch and black landscape fabric. In 2022, however, hemipteran abundance did not significantly differ among mulch treatments.

Family specific responses to mulch type likely played a role in differential treatment effects on hemipteran abundance from one year to the next. In 2021, aphids (Aphididae) were the most abundant family sampled in sticky traps. Multiple species of aphids have been shown to be repelled by short wavelength light reflected from silver mulches in vegetable crops (Brown et al. 1993; Stapleton and Summers 2002; Frank and Liburd 2005). Red mulch has been shown to be preferred by aphids over reflective mulches in other cropping systems

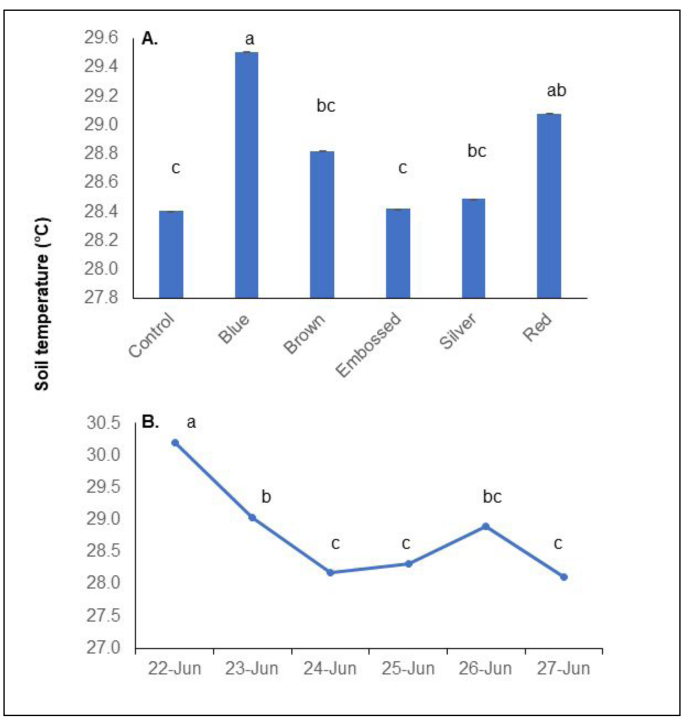

FIGURE 4. Daily soil temperatures in 2022 across A) mulch type treatments and B) sample date (n = 30). Error bars represent ±1 SEM. Letters above bars or data points represent significantly different means at α = 0.05, where "a," "b," and "c" are significantly different means. In cases where there are multiple letters listed ("bc"), the data fall within the boundaries of both means denoted by the included letters. All means shown here are back-transformed square root operations.

Table 3
ANOVA table for mulch type and sample date effects on leaf area index[a]

Year	Source of variation	SS	df	MS	F	*p*-value
2021	Mulch type	0.28	5	0.06	0.92	0.47
	Date	9.38	1	9.38	153.92	0.13
	Block	0.14	5	0.03	0.46	0.81
	Mulch type * date	6.52	107	0.06		
	Error	16.32	118			
	Total	32.64	236			
2022	Mulch type	0.9	5	0.18	3.43	<0.01**
	Date	0.14	1	0.14	2.57	0.11
	Block	0.15	5	0.03	0.56	0.72
	Mulch type * date	4.06	77	0.05		
	Error	5.25	88			
	Total	10.5	176			

[a] Statistically significant sources of variation are denoted as:
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.
*** Significant at $p < 0.001$.

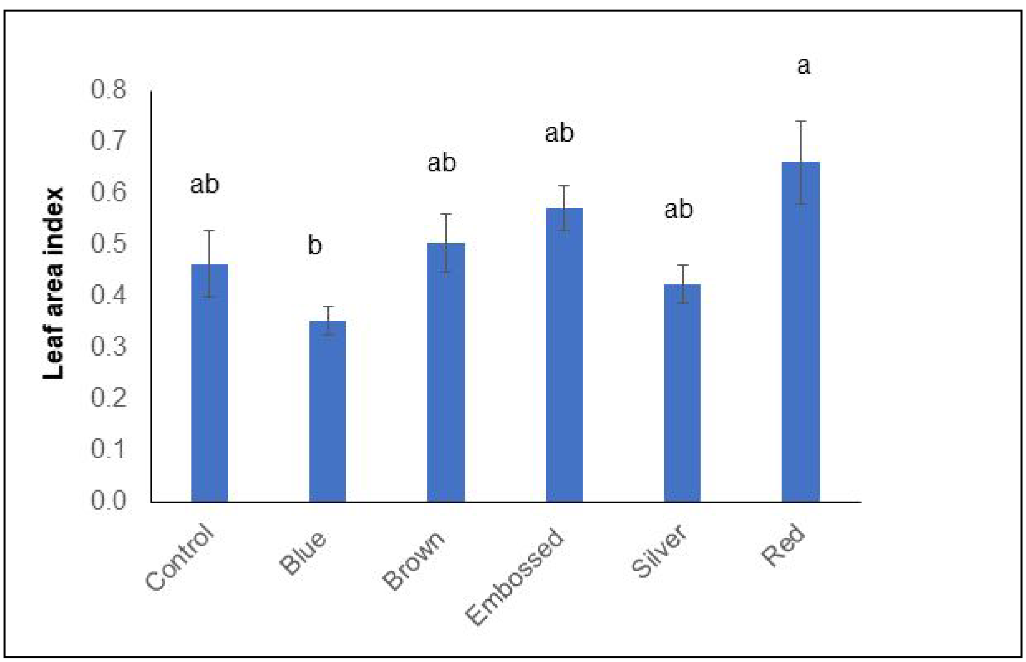

FIGURE 5. Leaf area index in 2022 across mulch type treatments (n = 30). Error bars represent ±1 SEM. Letters above bars represent significantly different means at α = 0.05, where "a" and "b" are significantly different means and "ab" fall within the boundaries of both statistical means. All means shown here are back-transformed square root operations.

(Csizinszky et al. 1995; Greer and Dole 2003). It is therefore likely that the 2021 results were influenced by the relatively high proportion of aphids that year. Studies looking into colored mulch effects on leafhoppers have shown mixed results. Silver and other reflective mulches can be effective at dissuading leafhoppers such as *Macrosteles fascifrons* in oats (Setiawan and Ragsdale 1987) and *Dalbulus maidis* in sweet corn (Summers and Stapleton 2002); however, silver and other reflective mulches have been shown to attract late-season populations of the leafhopper *Empoasca fabae* in common beans (Wells et al. 1984). The influence of mulch color and texture on the behavior of hemipteran insects is likely to be species specific, but the results of this study support the findings that some groups, like aphids, appear to be more affected by mulch color than others.

Soil Temperature

Soil temperatures were higher, to varying degrees, under blue mulch in both years of the study relative to other treatments. In 2021, beds with blue mulch had significantly higher soil temperatures than those with silver mulch. The following year, beds with blue mulch had significantly higher soil temperatures than almost all other mulch treatments, except red. These findings are mostly consistent with what has been reported in other studies: Ibarra-Jiménez et al. (2008) found that maximum soil temperature at 10 cm depth was significantly higher using blue mulch relative to light-colored mulches. In another study, blue mulch was also found to produce higher soil temperatures than white, silver, and red mulch, but not black (Rangarajan and Ingall 2001). Results of the current study partially support the hypothesis that dark mulch colors, such as blue, increase soil temperature due to higher absorption and re-radiation of incoming solar radiation as heat (Jones et al. 2021).

Spatial and temporal factors could partially explain why soil temperatures were not higher under black, brown, red, and embossed mulches relative to silver mulch. Previous work has shown that silver mulch has a greater capacity to insulate soils at night relative to other mulch colors, leading to higher evening soil temperatures (Arancibia and Motsenbocker 2008). Given that evening soil temperatures were factored into daily soil temperature calculations in 2022, it is possible that black, brown, red, and embossed mulches result in significantly higher soil temperatures in the day, but not at night, leading to mean daily soil temperatures that are on par with silver mulch. Furthermore, the soil warming effects of dark and light plastic mulches can be influenced by seasonal differences in sunlight duration and intensity (Díaz-Pérez et al. 2007) as well as by regional differences in climate and soil type (Amare and Desta 2021). Therefore, the apparent difference between the current study's findings and previously published data may also be due in part to the time of year and location in which this study was conducted. Spatio-temporal analyses could be a focus of future studies in order to better ascertain relationships between mulch type, mulch composition, and thermal regimes.

Lavender Growth

Mulch effects on plant growth varied across both years of the study. In 2021, there was no indication that mulch type was a significant factor in plant growth. In 2022, however, beds with red mulch had significantly higher plant growth (as assessed by LAI) than beds with blue. The potential effects of red mulch on plant growth are consistent with previous studies; compared with bare soil or black mulch, red mulch has been shown to increase plant height of red peppers (Decoteau 2008), number of leaves in lettuce (Franquera 2011), and fruit yields in tomatoes (Kasperbauer and Hunt 1998) and strawberries (Kasperbauer 2000). Furthermore, the 2022 data suggest the potential effect of red mulch may not be limited to pre-harvest growth in lavender. While Kasperbauer and Hunt (1998) noted that red mulch effects on tomato plant development only occurred early in the experiment—and that by the middle of the sampling period tomato yield was the same across red and black mulches—the analysis of LAI from the current study revealed that lavender plants were consistently bigger in red mulch relative to blue mulch in 2022, regardless of sampling period.

Red mulches are designed to reflect a higher ratio of far-red to red (FR:R) light back towards plants; plants, in turn, can respond to high FR:R ratios by allocating photosynthate towards elongation of shoots (Hunt et al. 1989). In greenhouse experiments, exposure to high FR:R light has been shown to positively impact growth of basil and other herbs in the mint family (Dou and Niu 2020).

This is the first field study, to the author's knowledge, to demonstrate that lavender plant growth can be enhanced in red mulch relative to blue mulch, potentially through a higher reflection of FR:R light. Further experimentation is needed to better understand the influence of reflected FR:R light on lavender development.

Interestingly, the findings of the current study do not support the hypothesis that dark and embossed mulches promote lavender growth relative to silver mulch, as there was no significant difference in LAI among dark, embossed, or silver mulches in 2021 or 2022. Previous work has shown that the highest yields of other mint family plants, including hyssop, garden thyme, and lemon balm, can be achieved using dark-colored mulches (Aziz et al. 2007). There is also evidence, however, that reflective mulch colors, such as silver or white, can promote an increase in leaf area and number of leaves in onions (Sarkar et al. 2019) and raspberries (McIntosh et al. 2023). The results of the current study provide further evidence that the effects of mulch color and texture on plant development vary by species, and that predictions are hard to make.

Conclusions

The findings of the current study suggest that, while not explicitly tested here, mulch effects on lavender growth are not mediated through temperature changes in the root zone. Had soil temperature been an important driver of plant growth in the current study, leaf area index under blue mulch would have been expected to be significantly greater than embossed mulch, silver mulch, and the black landscape fabric control. It is likely that other factors, potentially including reflection of photosynthetically active radiation and soil moisture retention, resulted in the observed differences in plant growth—particularly for red mulch. Indeed, lavender development is driven by a complicated suite of factors, including light intensity, nutrient availability, soil water content, and salinity, among others (Yasemin et al. 2017; Mitreva and Pankov 2018). Given that plastic mulches have been shown to alter soil properties and nutrient profiles (Manickam et al. 2010), it is important to conduct further evaluation of plastic mulch colors and textures to discern the specific mechanisms influencing lavender development.

The results of the field experiment have several implications for the use of plastic mulches in lavender cultivation. Perhaps the most important implication is that the selection of a plastic mulch color and texture should be guided by specific management goals. If the goal is to make the lavender canopy microclimate less attractive to insect pests such as aphids and leafhoppers, but not at the expense of overall canopy size, then silver mulches could be an appropriate choice. If lavender is being cultivated in a region with cold and wet winters, then a grower's goal might be to increase spring soil temperatures to reduce the chance of freezing conditions in the root zone, making blue mulches an appropriate choice. Although embossed and different colored mulches do not offer any significant increase in leaf area relative to black landscape fabric, these findings indicate that red mulch may be a better choice than blue mulch to promote the overall growth of lavender plants. The results of the current study indicate that the impacts of plastic mulch color and texture are tied to local environmental conditions that may vary from year to year. Thus, when choosing the appropriate mulch type for a particular context, it is important to also consider how yearly differences in soil, crop, and climatic conditions could constrain, neutralize, or enhance the microclimatic changes imparted by colored and embossed plastic mulches.

Participatory Action Research and its Implications

While participatory research is a long term, reflexive, process it can lead to tangible and intangible benefits for all parties involved. This study emphasizes the important role that stakeholders can play in the identification and assessment of technologies that address existing community problems. The empirical knowledge of the stakeholders allowed for in-depth discussion of potential solutions in early meetings. Design activities that drew upon the knowledge of land managers were important in identifying testable solutions that could be easily implemented on the farm, which is an important process in promoting technology adoption among farmers (Wossen et al. 2017; Drewry et al. 2019). By initiating a dialogue and creating spaces for discussion, both researchers and stakeholders can engage in the process of social learning and the co-creation of strategies that address locally relevant problems.

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DECLARATIONS

Ethics approval: Not applicable

Statement of human rights: All research with human subjects in this study was verified as being exempted from review by the Institutional Review Board at The College of Wooster (Protocol #2023/11/26)

Statement of informed consent: Verbal informed consent was obtained prior to semi-structured interviews.

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