

Conserving soil moisture with mulches to maintain soil health and improve yield for vegetable production in Kansas

by

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B.S., Kansas State University, 2022

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Horticulture and Natural Resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

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Abstract

Maintaining soil health for open field and high tunnel (HT) production of vegetables has become increasingly prioritized by growers in recent years. High tunnels (HT) are utilized by vegetable growers to extend the growing season and improve the yield and quality of crops. Meanwhile, the use of non-permeable polyethylene tarps has become popular for urban and small-scale vegetable farmers to manage weeds through occultation. Similar tarps could also be used as mulch, but little is known about how this will affect soil and crop productivity compared to other mulch types. This thesis aims to investigate how established and novel mulch types can help growers manage soil temperature, moisture, and health conditions across growing systems and climatic conditions and how these practices may affect the yield and quality of tomato and lettuce. Tomato and lettuce trials were conducted from 2022 to 2024 in HTs and open-field plots to determine the effect of various mulch treatments (bareground, black plastic film, black woven fabric, paper mulch, white silage tarp, and black silage tarp) on soil temperature, moisture, health, crop yield, and crop quality. Soil moisture and temperature were recorded throughout the growing seasons for both crops. Electrical conductivity (EC), bulk density, and respiration data were collected at termination of all trials to assess soil health. For tomato, harvesting occurred weekly to monitor yield. Texture and organoleptic quality were assessed from 3 harvests across the two years. In 2023, lettuce plants were harvested, and yield and quality data were collected.

In the tomato trials, the application of black plastic mulch, fabric mulch, and black silage tarp was associated with higher average soil temperatures (23.7°C-28.9°C), compared to (22.4°C-26.8°C) under white tarp and paper mulch. In the fall lettuce trials, all mulch types retained soil heat in the early season (0.7°C-2.2°C) compared to bareground. The use of silage tarp maintained up to 21% more soil moisture than the bareground treatment for tomato. In the

fall lettuce trials, all mulches were effective at managing moisture loss. Limited effects on soil health criteria were observed, though higher measurements of bulk density and EC may be associated with increases in soil moisture. This study indicates that mulch color and material affect soil temperatures and soil moisture in the summer, whereas in fall all mulches may reduce heat loss in the early period of the growing season and soil moisture (5-7%) in the late season. In the HT tomato trials, mulch had the greatest effects on yield during the early season, and the application of white silage tarp and plastic film mulch increased early marketable fruit yield by 58% compared to the bareground treatment. Mulch type had no significant effect on tomato or lettuce postharvest qualities that were assessed. Our data indicate that silage tarps may be an effective mulch, particularly for HT growers looking to conserve soil moisture and ultimately improve soil health, while maintaining yield. As growers address soil health concerns, it is likely that an integrated approach will need to be adopted that utilizes a combination of practices. The development of regional growing practices that ensure soil health and promote yield will be instrumental in supporting a growing population, and our study indicates that the use of mulches for vegetable production can contribute towards this goal.

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Acknowledgements

This project was truly a team effort, and there are many people to recognize for making this possible, though here I will list a few. First, I would like to sincerely thank my research committee for supporting this project and taking the time to help me learn the ins and outs of the scientific process. Many thanks to Ben and Vicente for the continual technical and logistical assistance this project required. Thank you to Kerri Ebert for answering so many of my miscellaneous questions and the never-ending supply of Starbursts, as they really came in handy. I have to acknowledge Tricia and Tori for coming to my rescue so many times for all things relating to stats and the lab. I am extremely grateful for Alex and Courtney and all of the camaraderie, laughter, encouragement, and assistance they have given me. I am so excited to see what they do in the future. I could not have done this project without Cliff and his dedication to many mornings of soil sampling and tomato harvesting, rain or shine (except perhaps not in the open field) and teaching me how to properly throw a football. Lastly, I would like to thank my parents and my boyfriend Braden, who have been extremely supportive these last 2.5 years.

Dedication

To this land and those who have and will continue to learn from it, eat from it, and generate new knowledge through it.

Chapter 1-Literature Review

Importance of High Tunnel Production

High tunnels are unheated structures, similar to greenhouses, where crops are grown directly in the soil. They are usually covered with greenhouse-grade polyethylene film and have adjustable sides and end walls, allowing for passive ventilation (Wells and Loy, 1993). High tunnels are often used by farmers to create a protected environment so they may extend their growing seasons both earlier and later (Carey et al., 2009). This increases the time period growers can spend at market selling high-value crops—directly supporting their livelihoods (T. Blomgren and T. Frisch, 2007; Conner et al., 2010; Everhart et al., 2009; Galinato and Miles, 2013; Sydorovych et al., 2013; Waterer, 2003; Wells and Loy, 1993). High tunnels have grown in popularity among producers for several other reasons, including: increased yields, improved produce quality, and better protection against diseases and pests (Carey et al., 2009; O’Connell et al., 2012). All these factors have made high tunnels a popular and effective tool for specialty crop growers across the United States (Carey et al., 2009).

Production benefits of high tunnels

Growers most commonly use high tunnels to plant earlier in spring and grow later into the fall (Bruce et al., 2017; Martinez et al., 2024). In some climates, they are used year-round (Wells and Loy, 1993). High tunnels achieve this by increasing air and soil temperatures, which many horticultural crops need for successful cultivation (Lamont, 2009). A spring study conducted in New Jersey highlights that this infrastructure can increase nighttime air temperature by 0.9° C and nighttime soil temperature by 6.7° C (Both et al., 2007). In tomato production, high tunnels can help growers begin harvesting fruit up to 3 weeks earlier than open-field

production (O'Connell et al., 2012). High tunnels support earlier fruit maturation due to increased early growth (Both et al., 2007; Hunter et al., 2012; O'Connell et al., 2012; Rogers and Wszelaki, 2012; Waterer, 2003). This is encouraged by higher air and soil temperatures in high tunnel environments, which also serve to protect the plants from colder nighttime conditions (Kadir et al., 2006). Lengthening the season ultimately benefits growers by allowing them to have produce outside of the natural growing season, giving them a competitive market advantage (Blomgren and Frisch, 2007; Galinato and Miles, 2013; Hunter et al., 2012; Sydorovych et al., 2013; Waterer, 2003).

While high tunnels are effective for extending the growing season, they also offer crops protection from the problematic weather events throughout the growing season. High tunnels can protect crops from several weather-related stressors, including: damaging precipitation, harmful temperatures, excessive solar radiation, and high winds (Blomgren and Frisch, 2007; Everhart et al., 2009). However, they also shelter crops from biotic stressors such as diseases and wildlife (Blomgren and Frisch, 2007; Everhart et al., 2009; Powell et al., 2014). Because high tunnels exclude precipitation, there is less foliar moisture on crops. Decreasing foliar moisture helps decrease foliar diseases, thereby increasing the yield of high-quality produce. Additionally, the careful use of drip irrigation can help growers manage soil moisture in this environment, often decreasing the incidence of blossom-end rot and cracking, blemishes which are associated with fluctuation in water (O'Connell et al., 2012; Rogers and Wszelaki, 2012). Other aesthetic characteristics, including more desirable and uniform color, have been cited as benefits of high tunnel tomato production (Talavera-Bianchi et al., 2010). High tunnels provide protection from sunlight as well. Plastic used for high tunnel covers can diffuse sunlight, encouraging more uniform light distribution on foliage, ultimately increasing photosynthesis (Kadir et al., 2006).

Light-diffusing polyethylene covers reduce infrared radiation while transmitting light in the UV spectra (Oh et al., 2011). It has also been reported to raise fall soil temperatures, increasing growing degree days (Gude et al., 2022).

The use of high tunnels in specialty crop production has been shown to increase the total and marketable yield of tomatoes when compared to open-field production (Galinato and Miles, 2013; O'Connell et al., 2012; Rogers and Wszelaki, 2012). The protection high tunnels provide not only mitigates negative quality characteristics-but also improves several growth characteristics. These have been found to include: fruit size and number, and total and marketable yields (Carey et al., 2009; Healy et al., 2017; O'Connell et al., 2012). Similarly, lettuce has also been noted as a crop that significantly benefits from high tunnel production as compared to open-field cultivation. Researchers have studied the efficacy of high tunnels for growing romaine and leaf lettuce, reporting that high tunnels improved crop quality and extended the growing season in the early spring and late fall when environmental protection was most valuable to provide a consistent growing environment (Wallace et al., 2012; Zhao and Carey, 2009).

Economic benefits and local markets

Season extension, environmental protection, and increases in high-quality yields all allow growers to spend more time at the market selling more desirable produce. It has been found that there is no shortage of demand for fresh produce year-round (Lodhi et al., 2013; Norris and Congreves, 2018), despite the fact that vegetable production is traditionally season-dependent (Lodhi et al., 2013). Because of consistent demand, prices for fresh vegetables increase significantly as supply wanes in the off-season (Lodhi et al., 2013). The production benefits that high tunnels have on the income of growers is recognized by the National Resource

Conservation Service (NRCS). The NRCS added high tunnels to their Environmental Quality Improvement Program (EQIP) to help offset the cost-share programs for high tunnel purchases in 2010. By increasing the accessibility of high tunnels, the NRCS aims to bolster local food production in environments where it is currently not feasible (Foust-Meyer and O'Rourke, 2015).

Increasing produce quality in the offseason is a challenge for many organic producers. In tomato production, growing with organic methods could decrease yields as much as 20% in (Seufert et al., 2012). The benefits associated with high tunnels make them an ideal solution for this challenge and they are quickly becoming a solution that growers worldwide use to increase year-round produce for local markets (Foust-Meyer and O'Rourke, 2015; Meyer, 2016). Tomato is the most widely grown high tunnel crop in the Midwest region (Knewtson et al., 2010), as well as the United States (Carey et al., 2009) and the world (Lamont, 2009). During the spring and fall, those who purchase produce at farmers markets are willing to pay premium prices for fresh produce, (Conner et al., 2009). High tunnels are cited by many direct-to-consumer growers as a strategy to increase farm income (Bruce et al., 2017; Martinez et al., 2010). Compared to tomatoes grown in an open-field environment, high tunnel tomatoes can generate three times the revenue (Galinato and Miles, 2013). A locally sourced tomato supply is also needed to fill market demand in farm-to-table restaurants and at high-end grocery stores (Jordan, 2007). Tomatoes are an ideal crop to source locally because they are difficult to ship over long distances while maintaining postharvest quality (Rogers and Wszelaki, 2012). Growers are capitalizing on the market need for local and organically produced tomatoes. The growth of organic tomato production has increased, while conventional tomato production has decreased (USDA, 2008; 2017).

Lettuce is another major crop for high tunnel growers in the United States. It ranks as the second most frequently cultivated high tunnel crop (Orzolek, 2012). More specifically, leaf lettuce is increasingly popular among consumers because of its high nutrient content (Kim et al., 2016). Lettuce has high concentrations of vitamins A and B6, which provide immune system support and metabolic regulation (Camejo et al., 2020). Research has also indicated that consumers care about how locally their lettuce is produced. As with tomatoes, lettuce is more marketable when it is more fresh and there are fewer stops along the supply chain (Ryder et al., 2002). Both tomato and lettuce are economically important high tunnel crops for United States growers. This calls for the sustainable cultivation of these popular and nutrient-rich fruits and greens.

Soil Health Challenges in High Tunnels

Despite the many benefits associated with high tunnels, there have been growing concerns in recent years about the long-term soil health challenges that can occur within these structures. To meet market demand, high tunnel producers use intensive growing practices, and the microclimate within a high tunnel exacerbates the associated soil degradation (Norris and Congreves, 2018). Some of these intensive practices include heavy fertilizer inputs, tillage, and shortened crop rotation intervals (Pereira et al., 2018). Tillage between crop cycles is a common practice for high tunnel growers to improve the workability of the soil and reduce weed pressure. However, it removes crop residues between cash crops (Waterer, 2003) and damages soil structure (Reddy, 2016). For many producers, tillage occurs several times per year (Lamont, 2009). This pattern results in soil degradation—a concern because soil is a relatively non-renewable resource (Pankhurst, 1998). Soil health is a key factor in not only the cultivation of

produce, but in sustaining Earth's ecosystems (Pankhurst, 1998). Soil health can be defined as "the ability of soil to perform or function according to its potential, and changes over time due to human use and management or to natural events" (Pankhurst, 1998). Norris and Congreves (2018) identified a gap in our understanding of soil health in high tunnels, stating that most studies focus on field crops instead of vegetable production.

Soil salinity challenges in high tunnels

Excessive soil salinity is a predominant issue that high tunnel producers are encountering in managing soil health (Blomgren and Frisch, 2007; Everhart et al., 2009; Knewton et al., 2010; 2012). High fertilizer and compost inputs are common in high tunnels, as is the use of drip irrigation. Drip irrigation is a popular management practice for growers to improve water use efficiency by directing irrigation water straight to plant roots. This strategy allows the plant canopy to remain dry, unlike when using overhead irrigation (Montri and Biernbaum, 2009). Fertigation, adding soluble fertilizers (in the form of salts) through irrigation water, can contribute to high soil salinity levels. With this targeted irrigation, water seldom penetrates below the top few inches of soil, as it is taken up by plants or evaporates, and the salts that are not utilized by the plants are prevented from leaching deeper into the soil profile. Since high tunnels prevent rainfall from reaching the soil beneath them, these salts cannot be leached out naturally and build up over time (Lamsal et al., 1999; Blomgren and Frisch, 2007; Knewton et al., 2010; Montri and Biernbaum, 2009). However, the severity of salinization depends on the management of inputs, irrigation, and soil type (Blomgren and Frisch, 2007; Everhart et al., 2009; Knewton et al., 2010, 2012; Montri and Biernbaum, 2009). The application of animal manure-based compost is a popular practice, especially among organic growers, that can contribute to this phenomenon. (Blomgren and Frisch, 2007; Everhart et al., 2009; Montri and

Biernbaum, 2009; Sánchez, 2015). A study conducted in Kansas over the span of eight years indicated that high tunnels managed organically had higher soil salinity compared to conventionally-managed sections of the farm (Knewton et al., 2012). It is also important for growers to monitor the quality of their irrigation water, which may have varying concentration of dissolved mineral salts. This can vary depending on if there is nearby agriculture run-off, eroding rock having high salinity levels, saline groundwater, or limited rainfall (Hanson et al., 2006). A study in Pennsylvania indicated that some growers have high tunnels with salinity levels of 9.38 dS/m (Sánchez, 2015).

Soil salinity and crop quality

Saline soils are associated with decreased crop growth (Paul, 2013). Sodium displaces crucial nutrient ions, including calcium, magnesium, and potassium, necessary for healthy plant growth and productivity. This creates nutrient deficiencies that ultimately lead to decreased crop yield (Alkharabsheh et al., 2021). When interacting with plant tissues, Na^+ can act as a toxicant, creating osmotic stress, hindering the plant's ability to take up and retain water (Kronzucker et al., 2013). When fertilizer applications exceed the amount needed by a crop, the leftover nutrients are not absorbed and accumulate in the crop root zone or soil surface (Ju et al., 2023). Areas with high evapotranspiration, where water carries salts to the soil surface, encounter this pattern more frequently (Kovda, 1949; Rengasamy, 2006). The Food and Agriculture Organization (FAO) has included soil salinization in its list of nine major issues not to be neglected as it severely harms soil ecology and harms agricultural productivity (FAO, 2015).

Soil salinity levels begin to damage tomato crops when soil EC is more than 3.5 dS/m (Blomgren and Frisch, 2007; Everhart et al., 2009). Tomato is a popular model crop for studying water relations in vegetables (Davies et al., 2000; Gillaspay et al., 1993; Johnson et al., 1992; Li et

al., 2021). In tomato, elevated salt concentrations can negatively impact fruit size, color, and flavor (Han and Li, 2024). High salinity can also reduce pollen viability, leading to flower abortion (Ghanem et al., 2009). Increased soil salinity is also associated with decreases in tomato cell turgor, shoot growth rate, photosynthetic activity, and plant ability to adapt to stress through metabolic signaling (Munns, 2002). According to Cuartero and Fernández-Muñoz (1999), decreases in yield occur at an EC of 2.5 dS m⁻¹ or higher. When EC is greater than 3.0 dS m⁻¹ an increase of 1 dS m⁻¹ results in a yield reduction of about 9–10%. At lower ECs, average fruit weight decreases, but at high ECs the number of fruit decreases. Soil salinity may increase sugar and acid content, due largely to decreased water content, but decreases firmness and shelf life (Cuartero and Fernández-Muñoz, 1998). According to a recent study, experienced high tunnel producers perceive that fertility imbalances and accumulation of salts lead to a significant decrease in tomato fruit marketability (Pierre et al., 2024).

Lettuce is more sensitive to saline conditions than tomato, having an EC threshold of 1.5 dS/m (Carpenter et al., 2021). When this threshold is exceeded, symptoms of damage can be observed throughout the life of the plant. High salinity can reduce the rate of photosynthesis, root and shoot growth, increase leaf wilting, and in severe cases, cause plant death. These conditions also decrease the nutritional content of the harvested crop (Fedeli et al., 2024). Leaf number per plant and water uptake decrease, as do concentrations of calcium (Ca) and iron (Fe) (Ünlükara et al., 2008). Consequently, tipburn is often reported as a symptom of high-saline soils (De Pascale and Barbieri, 1995). This physiological disorder is known to be evidence of calcium deficiency (Shear, 1975). Overall, properly managing for soil salinity can support higher-quality lettuce and even increase yield (Fedeli et al., 2024).

The effects of high saline conditions on crop yield and quality have significant economic

consequences for growers, while the feasibility of management practices to ameliorate these issues are less certain (Pierre et al., 2024). On a global scale, economists estimate that soil salinity costs growers \$27.3 billion (Qadir et al., 2014). Rates of soil salinization are expected to increase with climate change in the coming years (Hassani et al., 2021).

Arthropods, compaction, and nutrient management

The high tunnel production system can also be harmful to the soil ecosystem, which is comprised of a variety of organisms playing a variety of roles (Ferris and Tuomisto, 2015). These organisms are important for ensuring a healthy soil environment that supports agricultural crops (Pereira et al., 2018). By feeding on fungi and bacteria, soil macroorganisms are catalysts for the release of available soil nutrients (Lagerlöf, 1987). They can reduce weed pressure (Shearin et al., 2008) while increasing bacterial and fungal colonization to encourage crop growth and maintain soil health (Culliney, 2013; Price et al., 2011). Intensive agricultural practices negatively affect below-ground arthropod populations over time (Shearin et al., 2008); and, soil moisture content, or lack thereof, is directly correlated with arthropod declines in high tunnels (Skinner, 2020). Management practices such as tillage, frequent crop rotations, and excess fertilization have been found to damage arthropod populations and diversity (Benckiser, 1997). As explained by Erb and Lu (2013), dry soil conditions cause arthropods to dig deeper beyond the root zone. Conversely, when soil moisture levels are too high, an anoxic soil environment is created, which also negatively affects arthropod populations (Erb and Lu, 2013; Eskafi and Fernandez, 1990). Pierre et al. (2024) pointed out that future research should continue to investigate interactions between soil moisture levels with specific soil macroorganisms in the context of high tunnels.

Compaction is another primary soil health concern growers report as a challenge while

growing in high tunnels (Pierre et al., 2024). After five to ten years of high tunnel cultivation, growers struggle to manage their tunnels without tillage. While there are alternative options growers are exploring, including the integration of cover crops, there is a need for further research on how to mitigate compaction issues in high tunnels (Pierre et al., 2024). The use of more intensive practices, such as tillage, may only increase soil sustainability challenges (D. Wildung et al., 2012). Specifically, these practices can significantly increase soil compaction and bulk density (Allen and Musick, 1997; Shah et al., 2017). High levels of tillage contribute to the development of hard pans, surface crusting, and decreases in soil organic matter, ultimately reducing soil quality and plant growth (Celik et al., 2004; Shepherd et al., 2002).

The stressful environmental conditions inside high tunnels, including excessive temperatures, high soil salinity, and low moisture levels not only impact soil microorganism populations, but also have an adverse effect on the nutrient cycling processes that these populations are responsible for (Nguyen et al., 2018; Siebielec et al., 2020). Pierre et al. (2024) explain that because soil water management plays a key role in sustaining healthy high tunnel soil conditions, more research must be done to better understand how practices influence soil fertility, microbial life, nutrient cycling processes, arthropod activity, and crop productivity. They note that producers and Extension professionals have expressed the need for clear recommendations.

Current High Tunnel Soil Conservation Efforts

Despite the identified challenges of growing in a high tunnel environment, there are several management practices growers use to combat these obstacles. According to Rudolph et al. (2022), water management is a major way growers mitigate soil salinization and prevent salt buildup from occurring. There are several methods growers use to remove salts that have already

accumulated in the root zone or at the soil surface. One method, leaching, involves applying sufficient fresh water to the soil surface so that it can infiltrate through the soil profile, ideally leaching accumulated salts below the active root zone. Less effective, flushing is used to rinse away surface salts and areas that have developed salt crusts (FAO, 2017). Phytoremediation is also sometimes used but is also not as effective as leaching (Hasanuzzaman et al., 2014). A more novel approach is adding biochar (Amini et al., 2016). Other management strategies include reducing tillage and using growing crops that have lower water requirements and are more salt tolerant (Hasanuzzaman et al., 2014). Some tomato-specific strategies include grafting with salt-tolerant rootstocks and hardening seedlings with drought or NaCL (Coban et al., 2020; Cuartero et al., 2006). Vegetative intercropping can be used to improve both chemical and physical states of soil (Shi et al., 2024). There are structural modifications growers can make to allow precipitation to leach the salts from the root zone. High tunnels can be collapsed or moved, or plastic can be removed for a short time or season (Blomgren and Frisch, 2007). Some growers use flooding to leach salts. This is more appropriate if irrigation and soil permeability are not root problems (Blomgren and Frisch, 2007; Everhart et al., 2009; Sánchez, 2015). A less-common tactic is to discard the layers of soil that are compromised by high salt concentrations and replace them (Blomgren and Frisch, 2007).

These efforts reflect the conclusion that managing a high tunnel effectively and sustainably can be labor-intensive. Furthermore, the challenges associated with growing in a high tunnel may be intensified when in an urban setting due to the need to maximize production space. Generally, limitations associated with high tunnel cultivation include space, cost, labor, crop turn-around, and need for maintenance (Carpenter et al., 2021). In addition to the high capital cost of acquisition and installation labor, high tunnels increase labor costs for

maintenance and extended harvesting periods (Conner et al., 2010; Galinato and Miles, 2013; Knewton et al., 2010; Sydorovych et al., 2013). In Washington, growing tomatoes in a high tunnel is estimated to be eight times more costly for a producer when compared to open field cultivation because of labor requirements (Galinato and Miles, 2013). On average, the cost of a high tunnel will be paid off in one to five years (Blomgren and Frisch, 2007; Conner et al., 2010; Sydorovych et al., 2013; Waterer, 2003). High tunnel conservation strategies listed can be labor-intensive and vary in use (Blomgren and Frisch, 2007). Challenges related to soil health only increase labor for growers responsibly growing in high tunnels. Therefore, research is needed to identify further management practices growers can use to address these challenges that don't greatly increase labor. Historically, biodegradable and synthetic mulches have been utilized in open field vegetable crop production in order to conserve soil moisture and protect soil health.

Mulching for Horticultural Crops

Background of mulch types

Mulch can be defined as “materials that are applied to, or grow upon, the soil surface, as opposed to materials that are incorporated into the soil profile” (Chalker-Scott, 2007). Variations of mulching have existed since 500 BCE (Lightfoot, 1994). In the wake of climate change, it is particularly important for growers to use this technology in efforts to improve soil properties and maintain crop quality (Nawaz et al., 2017). Generally, mulching aids in soil moisture retention and discourages weed populations, therefore increasing crop yields and growth (Nalayini, 2007; Kader et al., 2019; Pessala and Hardh, 1997). Furthermore, mulches can decrease water runoff and evapotranspiration, while improving the infiltration capacity of soil (Rathore et al., 1998). An increase in yield is also attributed to rises in ground temperature and the facilitation of earlier planting (Abdul-Baki et al., 1992). In tomatoes, higher root zone temperatures encourage shoot

growth because of improved water and nutrient uptake (Hurewitz et al., 1984). Similarly, high tunnel lettuce yields in early spring and late fall also increase with rises in soil temperature (Bumgarner et al., 2011). Because varying radiation levels, soil moisture, and soil temperatures are associated with the use of different mulch types, it is understood that mulch color and type have significant impacts on the production environment (Filipović et al., 2016). Biodegradable or biomass-based mulches have been used for several centuries in agriculture (Mansoor et al., 2022). Materials like wheat straw, leaf matter, and/or wood chips are utilized to conserve soil moisture and contribute to overall soil health (USDA-NRCS, 2024; Zhang et al., 2021). Many vegetable growers, however, have adopted synthetic mulches that are more effective at increasing soil temperature while reducing the spread of disease (Lamont, 2009). Some synthetic mulch types used by vegetable growers include: paper mulch, polyethylene-based plastic mulch film, and woven polypropylene fabric. Silage tarps are often used to prepare beds prior to planting, but may be a mulch alternative.

Paper Mulch

Farmers have been using paper as mulch since the 1870s in an effort to protect the soil from weather conditions that limit cultivation. In the early 20th century, it was widely used to increase crop yields by way of environmental protection. It was especially popular in the 1920s among pineapple farmers in Hawaii, who used paper mulch to improve soil water retention and control weeds (Freeman, 1927; Coulter, 1934). However, these pineapple farmers began to experience higher rates of nematodes and other soil pests that diminished pineapple quality. With the only solution at the time being high-cost fumigants, paper mulch interest and research rapidly decreased in popularity (Wilson, 1948). Today, paper mulch is seen as a potential solution to issues associated with plastic mulches because they can fully decompose (Merfield, 2002;

Salokangas, 1973). Despite the fact that paper mulch degrades, some find it less labor-intensive to re-coat the degraded paper with another layer of paper, rather than remove plastic films from the field. It has also been found that paper mulch can be equally or more effective at controlling weed pressure compared to PE mulch. However, this depends on the weed pressure, environment and management practices (Anazalone et al., 2010; Cooling, 2010). Thus, there is still work to do in order to better manage the durability of paper mulch during the growing season as it is a complex issue (Haapala et al., 2014).

Research conducted in the UK reports that soil temperatures recorded under paper mulch are lower than under black PE or bare ground plots. This is generally attributed to the lighter color of the paper, which reflects light rather than absorbing it. Compared to these two treatments, the temperatures recorded under the paper were also more uniform (Runham et al., 1998). One study conducted in Kentucky also described higher soil temperatures under black plastic mulch compared to under paper mulch (Coolong, 2010). Similarly, studies in Canada (Zhang et al., 2008) and Finland (Pessala and Hardh, 1977) reported lower soil temperatures under paper mulch than bare ground. While paper mulch has been found to significantly conserve soil moisture in lettuce plots during dry spells, PE mulch was more effective (Jenni et al., 2004).

Some studies indicate no significant difference in crop yield between plots mulched with paper and plastic mulch (Harrington and Bedford, 2004; Shogren and Hochmuth, 2004). For example, one study in Massachusetts reported similar tomato yield and earliness for plots with PE and paper mulch, regardless of decreased soil temperature in the plots with paper mulch (Anderson et al., 1995).

Paper mulch may be better suited for high tunnel use than in the open field since environmental factors such as wind and rain that contribute to quicker degradation are excluded (Miles et al., 2012). A study comparing the use of WeedGuardPlus in high tunnels and open field environments revealed that it degraded approximately 20% more in an open field environment throughout the tomato production season (Miles et al., 2012). In this study, tomato yield, reported as total fruit number and weight, increased significantly in high tunnel production systems as compared to an open field environment in all three research sites (Knoxville, TN; Lubbock, TX; and Mount Vernon; WA). There was no significant difference in tomato yield between plastic mulch and paper mulch treatments at Knoxville and Lubbock and in all three locations, both treatments yield higher than bare ground (Miles et al., 2012). Another study conducted in Washington indicated that using WeedGuardPlus in high tunnel tomato cultivation increased marketable yield 14% compared to polyethylene mulch, but did not increase total yield (Cowan et al., 2014).

Polyethylene (PE) Mulch

Polyethylene-based plastic mulch (PE mulch) was first developed as a plastic film in 1938 and became increasingly utilized for agricultural purposes in the 1950s (Lamont, 2017). Since the 1960s, it has been an important tool to support commercial vegetable production (Lamont, 2005). It has helped farmers meet increasing demands for produce from a growing population (Serrano-Ruiz et al., 2021). Plastic mulch is used by growers to control weeds, regulate temperature, and reduce soil salinity by increasing water retention, thus reducing the concentration of salts that travel through the soil profile and land in the root zone, due to evaporation (Kumar et al., 2019).

There are a variety of plastic films used by growers to create different conditions depending on baseline soil conditions, the environment, and the crop being grown. Black plastic is a popular choice for growers producing many horticultural crops, including melons, eggplant, tomatoes, and peppers, as mulch absorbs the highest radiation levels (90%) compared to any other colored mulch (Teasdale and Mohler, 2000). It can be used to increase soil temperature, decrease weed pressure, and encourage earlier crop maturity and higher yields in many fruiting crops. One study revealed that the long-term application of plastic mulch improved aggregate stability, reduced bulk density, and increased aeration compared to plots without mulch (Van Der Meulen et al., 2006; Javeed et al., 2013). Additionally, the higher soil temperature and moisture levels can help support microbial life, contributing to nitrification (Lounsbury et al., 2020). Compared to clear or white mulch, darker-colored plastic mulches can modify the soil surface temperature by 5° C (Sakamoto et al., 2016; Tarara, 2000). Conversely, white plastic mulch can be used to limit warming of the soil temperature, conducting only 1% of radiation into the soil (Tarara, 2000). Tarara (2000) reports that white plastic decreases soil temperature 0.1° C at a 1-inch depth or -0.07° C at a 4-inch depth as compared to bare soil. Plastic mulch is popularly used to retain soil moisture and reduce labor spent on weeding and managing pests. Research indicates that without mulch, lettuce plots (*Lactuca sativa* L.) are faster to lose soil moisture than plots covered with PE (Matitschka, 1996). Not only does plastic mulch aid growers by raising soil temperature to increase yield, but it also saves money spent on labor (Ingman et al., 2015).

Plastic mulch is reported to help growers harvest produce earlier, with higher yield and better quality (Liu et al., 2003; Sun et al., 2019). This enhanced plant growth is attributed to increased soil temperature and microclimate humidity (Kader et al., 2019). These conditions encourage cell expansion and elongation, catalyzing plant development and growth (Franquera,

2015). In lettuce production, using black plastic mulch increases leaf area compared to bare soil. This subsequently increases photosynthetic rate, crop yield, and lettuce quality (Jenni et al., 1996; Arancibia and Motsenbocker, 2008; Rudisill et al., 2015). In a study comparing the effects of plastic mulch types on lettuce growth, it was observed that black mulch had the highest leaf number, length, and width. Second to black was white, followed by blue, silver, and olive-colored films (Shah Jahan et al., 2018). Several studies report a significant increase in tomato yield when grown with black plastic mulch (Sifola et al., 2024; Singh et al., 2020). In one study, the use of black plastic mulch corresponded with a 65% increase in marketable tomato yield compared to the bare ground treatment (Rajablariani et al., 2012). There is also research that indicates crops grown under PE rather than paper produce higher yields. One study in Spain found that tomato yields were significantly higher in plots mulched in PE rather than paper (Anzalone et al., 2010). Other research indicates that compared to bare ground, tomatoes grown with black plastic have higher levels of total soluble solids, but lower fruit firmness (Sifola et al., 2024).

The literature indicates that PE mulch is the most common mulch type used in high tunnels because it effectively warms the soil while decreasing weed and disease pressure (Lamont, 2009). Some growers apply individual rows of plastic, while others cover the entire tunnel floor (Lamont, 2009). It is used as a tool to manage key aspects of growing in high tunnels including soil, water, and fertility (Montri and Biernbaum, 2009). Research reveals that using PE mulch can increase high tunnel tomato yield by 20% (Cowan et al., 2014). One study conducted in Canada found that black PE increased soil temperatures too much for strawberry cultivation in the high tunnel environment, and white PE mulch was the most suitable for increasing yield (Medina et al., 2009). In a high tunnel experiment using a double plastic high tunnel covering,

PE reduced tomato titratable acidity (TTA) and total soluble solid (TSS) content compared to bare ground (Odediran et al., 2023).

The primary challenge that comes with the use of PE films is that they must be removed and disposed of at the end of every production season. According to Schrogen, (2004) the average removal of PE mulch costs \$600/acre. Often, growers stockpile discarded plastic, burn it, or take it to a landfill. Recycling does not commonly occur because of how dirty the films are after use and limited recycling facilities. Today, the use of plastic in agriculture is increasing worldwide (Serrano-Ruiz et al., 2021) and the lack of disposal options raises concern about water and soil pollution (Changrong et al., 2014). In 2022 alone, global plastic production totaled 370 metric tons. By 2050, this number is projected to reach 1200 metric tons (Kim et al., 2022; Dai et al., 2022; Astner et al., 2023). Increased plastic use corresponds to increases in plastic waste. By 2015, 6,300 metric tons of plastic had been discarded worldwide in total. The rate of plastic waste is expected to reach 460 metric tons per year by 2030 (Ng et al., 2018). This pollution returns to agroecosystems at a rate of 1.15-2.41 metric tons annually (Okeke et al., 2023). (Shogren and Hochmuth, 2004) estimate that PE mulch used in vegetable production contributes to 143,300 tons of plastic use in the United States annually. Moreover, removing this material from fields is challenging and often, plastic pieces are left in the soil. Over time, this can build up into significant soil pollution, harming soil sustainability and farm livelihood (Liu et al., 2014). This calls for the use of less wasteful plastic mulching alternatives.

Woven Polypropylene Fabric

Polypropylene woven fabric is similar to polyethylene-based plastic mulch used to prevent weed growth and conserve soil moisture (George et al., 2015). It is more effective than

PE against challenging weeds including nutsedge and bindweed and is commonly utilized by high tunnel growers in the Central U.S (Rivard, unpublished; Meyer, 2016). It can reduce labor because it does not need to be removed at the end of each season and may be reused for five years or more (Feldman et al., 2000; USDA-NRCS, 2024). Compared to polyethylene mulch, it can be significantly more expensive. In the case of raspberry cultivation, it has been recorded to be four times more costly than using polyethylene-based film (DeVetter et al., 2022).

Polypropylene fabric may be useful for growers wanting to retain soil moisture content. When compared to PE mulch and bare ground treatments in a study by Wang et al. (2002), it reportedly had the highest soil moisture retention effect between May and September (averaging $0.35 \text{ m}^3 \cdot \text{m}^{-3}$). In contrast, the PE and bare ground treatments had soil moisture readings in the range of $0.22\text{--}0.35 \text{ m}^3 \cdot \text{m}^{-3}$. These soil moisture levels were attributed to the semipermeable nature of the woven mulch. Because this study was not done in a high tunnel setting, rainwater was allowed to seep through the mulch and increase the moisture content (Strik et al., 2019). Regardless of the semi-permeability of the material, the density of polypropylene fabric could be a way to decrease soil-water evaporation. Furthermore, this higher soil moisture content could also lead to lower soil temperatures (Heitman et al., 2008; Zhang et al., 2021). Additionally, fabric has been found to reduce soil organic matter in some studies (Atucha et al., 2011; Choi et al., 2011; Strik et al., 2019). There is limited literature about the effects of polypropylene fabric on tomato and lettuce crop yield and quality. However, one study indicates that there were no differences in lettuce head weight, length, or diameter between fabric and plastic mulch (Wang et al., 2022). Some work has been done to reveal how it compares to organic mulches in fruit production. Strik et al. (2017) notes that it can increase irrigation needs by 50% relative to straw mulch. In the context of apple production *Malus × sylvestris* (L.) Mill. var. *domestica* (Borkh.)

Mansf., the use of fabric mulch did not have a significant effect on yield or growth (Choi et al., 2011; Nielsen et al., 2003). However, it was associated with a decrease in yield compared to organic mulches for rabbiteye blueberry (*V. virgatum* Ait.) (Strik et al., 2017), but an increase in yield for northern highbush blueberry according to a long-term organic study (Krewer et al., 2009).

Despite the fact that there has not been extensive research about the use of fabric mulch for horticultural crop production in high tunnels, it is a key tool for many growing operations in the Midwest and beyond (Gheshm and Brown, 2018; Rivard, unpublished). Unlike PE, it does not require the use of a bed shaper, which is frequently too large to use inside a high tunnel, while effectively suppressing weeds during tomato production (Gheshm and Brown, 2018; Rivard, unpublished).

Alternatives to Commercial Mulches

The utilization of silage tarps as mulch for vegetable production is a new concept that has not been tested. However, it could be a practical way to address the sustainability of PE mulches, while keeping the economic costs lower than fabric. Silage tarps are typically much thicker than PE mulch (5-10 mil) allowing for their reuse. Vegetable growers are rapidly adopting the use of tarping, also known as occultation, to prepare the soil prior to planting. Tarping is used as a mechanical way to control weeds and clear vegetation prior to planting without tillage (Chandran et al., 2018). Tarps are generally affordable, accessible, and durable for small-scale growers and have been a popular topic for producers, generating much online discussion (Kubalek et al., 2022). They are white on one side and black on the other side. The white side is used to reflect radiation, while the black side faces inward to mitigate the growth of oxygen-producing algae

with its opaque barrier (Blok et al., 2000). Growers can effectively raise soil temperature by placing the tarp black side up to absorb solar radiation. Many vegetable growers purchase tarps online or source them from local dairy or feed stores (Kubalek et al., 2022). Kublek et al. (2022) estimate that including shipping, new silage tarp costs an average of \$0.08/ft², and with a bulk discount, this could decrease to \$0.06/ft². Unlike PE film, silage tarps are reusable and are better suited to withstand windy conditions. Reports from growers on social media indicate that they can use the same tarp for up to six years (Kubalek et al., 2022). Additionally, tarp removal simply involves one to two people folding the tarp back up on a day with low wind. Tarps should be stored dry, out of the sun, and free of debris and rodents to maximize longevity (Kubalek et al., 2022).

Silage tarp may be a tool for growers to manage soil moisture by decreasing the rate of evaporation (Lounsbury et al., 2020). At the same time, it can increase soil temperatures compared to noncovered plots (Lounsbury et al., 2020). While there is not extensive literature about the effect of tarps on physical soil characteristics such as compaction, researchers predict that it would be similar to those under PE film left in place for several months. As previously described, areas with PE film have improved soil properties such as water-stable aggregate content when compared to soil with no mulch (Domagała-Świątkiewicz and Siwek, 2018; Sintim et al., 2021; Wang et al., 2017). One study found that the longer tarps cover soil, the more nitrate concentrations increase (Rylander et al., 2020), reporting that under the tarps, average nitrate concentrations of up to 42 mg·kg⁻¹ were reported, compared with bare ground concentrations of 2 mg·kg⁻¹.

Similar to PE film, silage tarp effectively increases soil temperature (Rylander et al., 2020). As mentioned, higher soil temperatures are associated with higher yields in lettuce and

greater plant growth and nutrient uptake in tomato (Bumgarner et al., 2011; Hurewitz et al., 1984). However, there have not been studies on the efficacy of using tarps in place of plastic mulch. Some growers use silage tarp in high tunnel systems during tomato cultivation for weed suppression (Gheshm and Brown, 2018). However, tarps may be able to benefit high tunnel tomato production in other ways. In high tunnel cultivation, plants receive less light than in an open field environment, as reported by Bumgarner et al. (2011), standard poly used on high tunnel decreases PAR by 23%. White silage tarp could reflect light towards the crop canopy, increasing photosynthetic rates while decreasing high temperatures that can occur in high tunnels and contribute to plant stress (Nair et al., 2013).

Grower willingness to adopt various mulch types in high tunnels

Studies indicate that growers consider soil quality and productivity in their high tunnels to be of concern (Grubinger, 2012; Rudisill et al., 2015). In one study, the majority of growers with more than five years of high tunnel experience expressed decreased yields in crops that were valuable for their livelihoods. This was mainly attributed to disease and decreases in soil fertility not experienced in their open field systems (Pierre et al., 2024). Research indicates that cost and labor savings are primary motivators for growers to try new mulching techniques (Velandia et al., 2019).

However, there are challenges associated with different kinds of mulch, and incorporating a new management practice brings further risk (Goldberger et al., 2015). For example, polypropene fabric has been associated with a high incidence of voles (Granatstein and Mullinix, 2008; Strik et al., 2017). Plastic mulch comes with several drawbacks including: environmental concerns related to plastic disposal, the cost of equipment required for installation, removal, and the process of soil tillage (Goldberger et al., 2015). Paper mulch may

be a good alternative for growers looking to be more environmentally friendly (Anzalone et al., 2010), but it can degrade too quickly (Schonbeck, 1999; Anderson et al., 1996), particularly for long-season crops and when used in the open field. If growers adopt the use of silage tarps, they should consider the weight of the material. As described by Kubalek et al. (2022), a 50 × 100-ft roll of 5-mil. silage tarp weighs approximately 120 pounds, making the tarp difficult to transport and even dangerous without adequate labor. Additionally, the novel nature of this new use for silage tarps currently lacks sufficient research.

Research Objectives

High tunnel production provides unique opportunities for urban and peri-urban growers to increase productivity and reduce the losses of specialty crops, particularly for those with limited growing spaces. However, intensive cultivation and microclimate can also reduce soil moisture and belowground arthropod populations, while increasing soil compaction and salinity. Mulching could be a mechanism to reduce damage from stressors from intensive cultivation within both field and high tunnel systems. However, there is limited research on the effects of mulches within high tunnel systems and none that utilize heavy polyethylene silage tarps as mulch. Therefore, it is clear that further information on mulch types that: conserve soil moisture, maintain soil health, and support crop productivity in high tunnel systems is greatly needed. Therefore, the research objectives for this thesis included the following:

- 1) Determine the impact of various mulches on soil moisture, soil health, and soil temperature in high tunnels during the production of cool-season and warm-season crops
- 2) Evaluate the impact of various mulches on yield and quality of lettuce and tomato grown in high tunnels and the open field

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Chapter 2-Evaluation of Mulch Types on Soil Microclimate and Health for Tomato and Lettuce Production in the Central United States

Abstract

Maintaining soil health for open field and high tunnel (HT) production of vegetables has become increasingly prioritized by growers in recent years. In particular, there have been growing concerns about the sustainability of HT systems as their hot and dry conditions, compounded by intensive practices, can lead to challenges with soil temperature and moisture management, soil compaction, soil salinity, and soil ecosystem health. This report aims to investigate how established and novel mulch types can help growers manage soil temperature, moisture, and health conditions across growing systems and climatic conditions. Tomato and lettuce trials were conducted from 2022 to 2024 in HTs and open-field plots to determine the effect of various mulch treatments (bareground, black plastic film, black woven fabric, paper mulch, white silage tarp and black silage tarp) on soil temperature, moisture, and health. Gravimetric and volumetric soil moisture content were determined weekly and bi-weekly in the lettuce and tomato trials, respectively. Soil temperatures were recorded at 10.2 cm depth throughout the growing seasons for both crops. EC, bulk density, and respiration data were collected at termination of all trials to assess soil health. In the tomato trials, the application of black plastic mulch, fabric mulch, and black silage tarp was associated with higher average soil temperatures (23.7°C-28.9°C), compared to (22.4°C-26.8°C) under white tarp and paper mulch. In the fall lettuce trials, all mulch types retained soil heat in the early season (0.7°C-2.2°C) compared to bareground. The use of silage tarp maintained up to 21% more soil moisture than

the bareground treatment for tomato. In the fall lettuce trials, all mulches were effective at managing moisture loss. Limited effects on soil health criteria were observed, though higher measurements of bulk density and EC may be associated with increases in soil moisture. This study indicates that mulch color and material affect soil temperatures and soil moisture in the summer, whereas in fall all mulches may reduce heat loss in the early period of the growing season and soil moisture (5-7%) in the late season. As growers address soil health concerns, it is likely that an integrated approach will need to be adopted that utilizes a combination of practices. This study shows that mulch color and type/material can be selected to alter the microclimate of the soil environment in HT and open field production systems. Moreover, the use of silage tarps was a highly effective tool for soil microclimate modification. More research is needed to determine how these impacts affect long-term soil health. The development of regional growing practices that ensure soil health will be instrumental to support a growing population, and our study indicates that the use of mulches for vegetable production can contribute towards this goal.

Introduction

Soil health is a key factor for sustaining agricultural and natural ecosystems worldwide (Pankurst, 1998). It can be defined as “the ability of soils to perform or function according to its potential, and changes over time due to human use and management or to natural events” (Pankhurst, 1998). Soil has multiple functions, including physically supporting plant growth, regulating water, and cycling nutrients to provide a suitable physical, biological and chemical environment for plant growth (Laishram et al., 2012). Therefore, many indicators of soil health are measures of these environmental properties (Doran and Parkin, 1994). Some of these indicators include organic matter, aggregation, texture, bulk density, electrical conductivity (E.C), and soil respiration (Laishram et al., 2012). In the past decades, the intensification of agriculture has contributed to the depletion of soil fertility and higher rates of soil degradation, harming the health and productivity of agricultural land (Rodríguez et al., 2022). High tillage and soil disturbance rates, along with a lack of crop rotation, can have significant effects on soil health over time (Wardle, 1995, Mosquera et al., 2019). The USDA-NRCS (2019) has identified four principles for protecting and improving soil health: minimizing soil disturbance, maximizing plant diversity, maintaining living roots year-round, and maximizing soil coverage.

Research indicates that high tillage rates damage soil structure and soil food webs, while no or low till agriculture has the opposite effect (Wardle, 1995; Nunes et al., 2020a). Furthermore, no-till farming results in greater organic matter levels and levels of microbial activity that contribute to more effective nutrient cycling (Nunes et al., 2018). In this practice, mechanical soil disturbance is reduced to a minimum, thus decreasing heavy field operations and erosion, while increasing the retention of nutrient-rich topsoil (Delgado et al., 2019; Hobbs et al., 2007; Mosquera et al., 2019). Additionally, the continued cultivation of the same crop has

negative effects on the diversity and function of mycorrhizal fungi, which serve to promote soil aggregation and nutrient uptake (Jansa et al., 2006; Six et al., 2004; Marschner and Dell, 1994). Hendrix et al., (1995) found that greater crop diversity is correlated with higher mycorrhizal fungal populations, as compared to non-rotated systems. Along with reducing tillage and increasing diversity in crop rotations, growers can also include cover crops into their production systems to better soil health while improving productivity (Ditmar et al., 2015). Integrating cover crops leads to a variety of positive effects on the soil ecosystem, including reducing erosion and nutrient loss while promoting nitrogen fixation and water availability (Rodríguez et al., 2022). Though the degradation of soils due to agriculture is of great concern, it can be combatted through management practices that build up soil structure and ecosystems (Rodríguez et al., 2022; Smith and Gregory, 2012). Therefore, it is important to have a thorough understanding of how different agricultural practices affect soil health across growing systems and climactic conditions.

Recently, amongst the rapid influx of vegetable growers incorporating high tunnels (HTs) into their farm operations, there have been concerns by growers over the state of soil health in these intensive systems (Knewston, 2010). HTs are unheated structures covered with greenhouse-grade polyethylene film with adjustable sides and end walls in which plants are grown directly in the soil (Wells and Loy, 1993). This technology allows growers to significantly extend the growing season (Carey et al., 2009), so that they can be at market longer with high-value crops that directly contribute to their income (Blomgren and Frish, 2007; Conner et al., 2010; Everhart et al., 2009; Galinato and Miles, 2013; Sydorovych et al., 2013; Waterer, 2003; Wells and Loy, 1993). HTs provide a variety of benefits such as protection against precipitation, wind, diseases, and pests (Blomgren et al., 2007; Ernst, 2020; Frey et al., 2020a). Growers also

adopt HTs to increase marketable crop yield (Blomgren et al., 2007; Ernst, 2020; O’Connell et al. 2012; Waterer 2003; Yao and Rosen 2011) and improve postharvest quality (Batziakas et al. 2020; Bruce et al. 2019).

In recent years, an increasing number of growers are adding HTs to their operations so they may reap the benefits of season extension, overall increased yields, produce quality, and protection against pests and diseases (Carey et al., 2009). Furthermore, between 2010 and 2010, US Department of Agriculture (USDA) Natural Resource Conservation Service cost-share programs (including the EQIP High Tunnel System Initiative) have contributed more than \$170 million to supporting HT systems (Pierre, 2024).

Despite the many benefits of HT systems, a recent review of the literature outlined many of the challenges that HT growers face in maintaining soil health (Pierre, 2024). The intensive production practices growers often use to keep up with market demand and the HT microclimate can lead to soil degradation (Norris and Cosgreves, 2018). These practices can include heavy fertilizer inputs, tillage, and shortened crop rotations (Periera et al., 2018). Because HTs do not allow precipitation to cause seasonal leaching, salts from heavy fertilization can accumulate in the rootzone (Blomgren and Frisch, 2007; Everhart et al., 2009; Knewton et al., 2010; 2012). This issue can be mitigated by better management of soil moisture (Ramos et al., 2023). Additionally, growers have also reported concerns about soil compaction and nutrient imbalances (Pierre et al., 2024). However, literature is lacking regarding the HT soil moisture levels and soil processes (Pierre et al., 2024). Norris and Congreves (2018) have identified a research gap in understanding soil health in HTs, stating that most studies focus on field crops instead of vegetable production.

The accumulation of soil salinity has been reported as a concern for many HT growers (Pierre et al., 2024). It is often represented by electrical conductivity (EC). EC can be significantly higher for organic HT soils, because of organic amendments and lack of leaching rains (Knewston et al., 2012). However, salt accumulation can be a challenge for open field growers as well, especially those using limited crop rotation (King et al., 2010). The USDA (2011) recommends a combination of irrigation and drainage to mitigate salinity buildup issues. However, EC measures also increase with soil moisture content, as this indicates a greater ability for soil to conduct electrical currents (USDA, 2011).

Compaction is another primary soil health concern growers have reported in vegetable production systems (Yang et al., 2022). Soil compaction levels are often measured through bulk density and impact available water capacity, availability of nutrients, and biological activity (USDA-NRCS, 2019). Participants in one research study indicated that compaction became a challenge after 5 to 10 years of HT cultivation, requiring tillage (Pierre et al., 2024), which can further damage soil structure long-term (USDA-NRCS, 2014). Compaction is of great concern in open field production as well, where human and mechanical traffic can greatly harm soil structure, especially if applied after a rain event (Yang et al., 2022). According to the USDA-NRCS (2019), increasing soil organic matter (OM), and thereby increasing water holding capacity, and decreasing soil disturbances can be ways to decrease compaction.

Soil organic matter helps build healthy soil structure and is related to several other soil processes, acting as a reserve for C and N, and as a pH regulator (Kotroczo et al., 2023). OM levels can be increased by keeping bare soils covered with mulch (USDA-NRCS, 2014). Similarly, soil respiration, the emission of CO₂ from the soil to the atmosphere, is one of the most important components of terrestrial metabolism. It is primarily the result of microbial

degradation processes in the soil and respiration by plant roots (Kotroczo et al., 2014; Kuzyakov, 2006). Respiration is directly related to soil organic matter, temperature, moisture, salinity, and aeration (USDA-NRCS, 2014). Decreases in soil moisture are associated with decreases in respiration (Orchard and Cook, 1983) as well as microbiome populations (Skinner et al., 2020). However, if water content is too high, (more than 80% pore space), respiration will decline (USDA-NRCS, 2014). Soil respiration levels reflect microbial activity and OM content, nutrient cycling, and can bring attention to imbalances in soil moisture, poor porosity, and available N-limiting factors to biological activity (USDA-NRCS, 2014).

Nitrogen cycling (ammonification and nitrification) generally increases as soil moisture increases (Linn and Doran, 1984). Higher soil moisture content can sometimes lead to a higher pH because more anaerobic conditions contribute to an increase in proton consumption during denitrification (Dobbie & Smith, 2001; Zárate-Valdez et al., 2006). However, pH and soil moisture generally have an inverse relationship, as dry environments are less conducive to mineral leaching (Yang et al., 2023). Soil moisture does have a significant positive relationship with available nitrogen levels because microbial life responsible for releasing nitrogen into the soil is more active (Agehara and Warncke, 2005; Cassman and Munns, 1980; Guntiñas et al., 2012; Morugán-Coronado et al., 2019; University of Minnesota Extension 2023 et al., 2023). Furthermore, available phosphorus levels plummet when soil moisture declines (Suriyagoda et al., 2014). Similarly, sufficient soil moisture is required for the availability of potassium (Kuchenbuch et al., 1986), but despite high application rates, it may quickly disappear from HT soils, resulting in a decrease in marketable tomato harvests due to yellow shoulder and uneven ripening (Sideman et al., 2020).

Mulch can be defined as “materials that are applied to, or grow upon the soil surface, as opposed to materials that are incorporated into the soil profile” (Chalker-Scott, 2007). It is an important tool for growers aiming to protect soil properties (Nawaz et al., 2017). Several mulch types used by growers include: woven polypropylene fabric, polyethylene-based plastic mulch film, and paper mulch. Silage tarps are popularly used to prepare beds prior to planting as part of a process known as occultation (Chandran et al., 2018). However, they could be utilized as an alternative to traditional mulches in HTs. Silage tarps cost less than fabric mulch (per square foot), but can still be used for multiple growing seasons. They are also much thicker (5 to 6 mil) whereas plastic mulch is typically 1 to 1.5 mil. Plastic mulch is popularly used to decrease soil moisture loss and raise soil temperature (Ingman et al., 2015). According to Loundsbury et al. (2020), silage tarp could also be used to achieve these goals. However, literature is lacking on this technology and other effects it may have on soil health qualities compared to other mulch types.

Mulch conserves soil moisture through its ability to decrease the soil surface evaporation rate, reduce soil disturbance, and absorb solar radiation to provide soil heat (Défossez et al., 2021; Liao et al., 2021; Ye et al., 2023). However, not all mulches conserve soil moisture similarly (Thakur and Kumar, 2021; Zhao et al., 2014). Factors such as mulch thickness, density, and chemical composition affect mulch permeability, as can environmental factors including temperature and humidity (Noling, 2013). However, thicker mulches are frequently less permeable, regardless of material whereas typical PE mulch is permeable (Noling, 2013). Polypropylene fabric is also permeable to water and allows air movement, while being 99.8% opaque (Martin et al., 1991; Reece et al., 1997). In contrast, silage tarps are designed to reduce aerobic spoilage of ensiled material and have a low air permeability (Borreani et al., 2014).

The difficult environmental conditions inside HTs and intensive field production practices that are common for local and/or small-scale vegetable production can have adverse impacts on several aspects of soil health (Nguyen et al., 2018; Siebielec et al., 2020; Rodríguez et al., 2022). Therefore, research is needed to better understand how crop and soil management affects soil health (Pierre et al., 2024). More specifically, conserving soil moisture could be one tool to address soil health concerns to enhance long-term sustainability of intensive systems. Research has not investigated how using silage tarp as a mulch affects soil conditions compared to growing in bare ground and existing mulch types, or if it could be effective on a commercial scale. This report is part of a larger project to identify the effect of different mulching strategies in high tunnels and the open field as they relate to soil moisture and health as well as yield and fruit quality. Observed effects on yield, marketability, and quality are provided in Barnhart et al., (Ch. 3). The specific objectives of this report are to (1) determine the impact of various mulches on soil temperature and moisture in lettuce and tomato (2) identify the effect of various mulches on soil health for HT and open field production and (3) compare the effect of mulches in warm- and cool-season crop production systems.

Materials and Methods

HT trials were conducted at the Olathe Horticulture Research and Extension Center (OHREC) from 2022 to 2024 with lettuce and tomato. The OHREC is located in Johnson County, KS (38.884347 N, 94.993426 W) and has Chase silt loam soil (pH= 6.3). Tomato trials occurred during summer 2023 and 2024 and lettuce trials occurred during fall 2022 and 2023. The tomato trials were conducted in organic HTs and open field plots and the lettuce HTs were considered transitional.

Tomato trials

HT and open field tomato trials occurred during summer 2023 and 2024 using the hybrid cultivar ‘BHN 589’ (Seedway, Hall, New York). The trials were planted in six high tunnels and six open field plots that were established more than ten years ago for production systems comparisons. The high tunnels were constructed on soil berms that were on average 67 cm above grade in order to reduce the likelihood of flooding. Otherwise, the cropping history and management of the two systems has been the same since 2011. The plots were arranged in a randomized complete block design with 3 replicates across the six identical 6.1 x 9.8 m Quonset-style HTs and the six open field plots with identical arrangements and dimensions. The individual treatment plots contained two rows each and were 2.07 m x 3.05 m. The plants were grown in six 2.7 m rows with 6 plants per row planted 45.7 cm apart. The mulching treatments included bare (control), fabric (DeWitt Sunbelt Woven Groundcover; Sikeston, Missouri, USA), plastic (Black Plastic Mulch 1 mil Embossed; Grower’s Solution, Cookeville, TN), paper (Original WeedguardPlus Standard Weight; WeedGuard Plus, Aurora, Colorado, USA), white tarp (Silage Tarp 5 mil Black/White Plastic Sheeting; Farm Plastic Supply, Addison, Illinois, USA) and black tarp (the other side of the white tarp). The six rows were planted on the north side of the tunnels and corresponding open field plots in 2023 and on the south side in 2024. Winter wheat was planted as a cover crop prior to tomato in both seasons.

Tomato seeds were planted into 50-cell propagation trays (5 cm diameter) (50 Cell Plug Flats; Johnny’s Selected Seeds Winslow, Maine, USA) with OMRI listed potting mix (Planting Pro Potting Soil; Ohio Earth Food inc., Hartville, Ohio, USA) and grown in the greenhouse. Tomatoes were transplanted into the trials on 26 Apr 2023 and 26 Apr 2024 (HT) and 18 May 2023 and 23 May 2024 (OF). At planting, an organic fertilizer blend, Re-Vita Pro (Ohio Earth

Food; Heartville, OH) (5N-4P-5K) was applied at a rate of 112 kg N per hectare. Water was applied through drip irrigation for 30 minutes three times per week using 1.9 L/hr emitters pressure regulated to 103.4 kPa. Emitters were spaced every 30.5 cm. If temperatures were greater than 35 °C, watering was increased to 45 minutes, and one hour if temperatures were greater than 37.8 °C. Tomatoes were trained using a stake and weave vertical trellis system. The main pest pressure was from tomato fruit worms and hornworms. Once worms were observed, Bt was sprayed bi-weekly until the end of the growing season. There was some aphid pressure observed. Therefore, PyGanic was also sprayed as needed. Tomato trials were terminated on 9 Oct 2023 and 9 Oct 2024 (HT) and 25 Sep 2023 and 12 Sep 2024.

Lettuce trials

In the lettuce trials, red and green loose leaf lettuce cultivars, ‘New Red Fire’ and ‘Two Star’ were grown in two of four “caterpillar” HTs (Quick Hoops Bender; Johnny’s Seed, Winslow, Maine, USA) during the fall seasons of 2022 and 2023. The HTs were 39.6 m long x 3.7 m wide x 2.1 m high. Two beds ran lengthwise within each HT (39.60 m long x 0.61 m wide). The lettuce trials were arranged in a split-plot randomized complete block design with four replicates across the two HTs. Within each replicate the four main plots (3.66 m x 4.57 m) were randomly arranged and included: bareground (control), fabric (DeWitt Sunbelt Woven Groundcover; Sikeston, Missouri, USA), white tarp, and black tarp (Silage Tarp 5 mil Black/White Plastic Sheeting; Farm Plastic Supply, Addison, Illinois, USA). Sub-plots were randomly assigned as the two different lettuce types (red and green). An additional 1.5 m “buffer” area was included on the ends of each HT to reduce any edge effects. In 2023, the lettuce was planted in the two other HTs to follow on-farm crop rotation. Buckwheat was planted

as a cover crop prior to the lettuce in 2022 and tillage radish was utilized as a cover crop prior to the lettuce in 2023.

Lettuce was seeded in the greenhouse into 72-cell propagation trays (3.8 cm diameter) (Pro-Tray 72 Cell Flats; Johnny's Selected Seeds, Winslow, Maine, USA) 26 Aug 2022 and 30 Aug 2023 with potting mix (Berger Seed Germination and Potting Mix; Hummert International, Earth City, MO, USA). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) 23 Sep 2022 and 27 Sep 2023. Water was applied twice weekly for 30 minutes using drip irrigation and 1.9 L/hr emitters pressure regulated to 103.4 kPa and spaced every 10 cm. Unfortunately, due to a breach in the outside fencing, the 2022 lettuce were destroyed by wildlife just days before the planned harvest. However, harvest data was collected in the 2023 trial on 6 Nov.

Environmental conditions

In order to provide a general description of the growing conditions, HOBOware weather data loggers (Onset Computer Corporation, Bourne, MA, USA) were installed in one HT and one open field plot during the second year of both the lettuce and tomato trials. In each trial, the loggers were placed in a bare (control) treatment plot. Data loggers tracked ground temperature (°C), canopy temperature (°C), photosynthetically active radiation (PAR) in $\mu\text{mol}/\text{m}^2/\text{s}$, which was converted to DLI for reporting, and relative humidity (%). Data was recorded in 15-minute intervals. Precipitation data was collected from the Kansas Mesonet located at the OHREC and is presented as total mm/month for the duration of the open field trials.

Soil temperature

Replicated HT and open field soil temperatures (°C) were recorded throughout all of the trials in order to understand the impact of mulch type on the soil microclimate. Within each plot,

one temperature probe (EL-USB-1; Lascar electronics, Erie, PA, USA) was located 10.2 cm below the soil surface. In the tomato trials, the probes were placed in the east row of the treatment in the center of each row. In the lettuce trials, the probes were placed in the center of the treatment plot between the two rows of lettuce on the north side. For tomato, sensors collected temperature data every 20 minutes. In 2023 and 2024, HT sensors collected data from 6 Apr to 9 Oct (166 days). In 2023, open field sensors collected data from 18 May to 25 Sep (130 days), and from 24 May to 12 Sept (111 days) in 2024. During the lettuce trials, sensors collected temperatures every 30 minutes. In 2022, data was collected from 3 Oct to 1 Nov (29 days). In 2023, soil temperature data was collected from 28 Sep to 6 Nov (39 days).

Soil moisture

Soil moisture was monitored using two methods and was observed weekly and bi-weekly in the lettuce and tomato trials, respectively. Each mulch treatment was cut in the middle of the plot and held together by rebar and sod staples so the two sides could be lifted for bi-weekly soil moisture sampling. Volumetric water content was measured using a digital TDR Freescout Moisture Meter (Turf-Tec International, Tallahassee, Florida, USA) calibrated to “standard” soil and the use of 20.3 cm probes. Volumetric data was taken at the same time as the soil samples. For tomato, the average of 5 readings taken 18-25 cm from the plants on the inside of each plot was recorded. For lettuce, this average was of 5 readings taken 10-13 cm from the plants throughout each subplot. Gravimetric soil moisture was taken through the sampling of soil cores of 0-10.2 cm depth. For both crops samples were taken at planting and at termination. In the tomato trials, the mulch was lifted for the duration of sampling. Five soil samples were collected from each plot between the two rows, 18-25 cm from the plants. In the open field trial, the second sampling date (31 May 2023) was delayed two days due to a rain event. In the lettuce

trials, the samples were collected through the mulch. Three soil samples were collected from each subplot 10-13 cm from the plants throughout the sub-plot. Samples were placed into plastic bags and stored at -14°C. Fresh and dry weights were recorded for each sample (g). Samples were dried at 70°C for 72 hours. Gravimetric water content was calculated by the equation: WC (%) = $[(FW-DW)/DW] \times 100$.

Soil health and physical properties

Soil samples were taken from each replication at planting and termination to understand if there were any effects on agronomic properties, compaction and soil health. Soil samples were tested at the Kansas State University Soil Testing Laboratory (Manhattan, KS, USA <https://www.agronomy.k-state.edu/outreach-and-services/soil-testing-lab/>) for: pH, buffer pH, phosphorus (ppm), Potassium (ppm) NH₄-N ppm, NO₃-N ppm, and organic matter (OM). Soil pH and buffer pH was measured using the 1:1 soil-water Sikora Buffer procedure. Phosphorus (ppm) was determined by Mehlich-3 extraction. Potassium (ppm) was determined by ammonium acetate extraction. NH₄-N (ppm) and NO₃-N (ppm) was measured with KCl extraction. For OM (%), the loss on ignition procedure was used.

Bulk density was measured at the termination of each of the tomato trials (9 Oct and 25 Sep 2024; 9 Oct and 12 Sep 2024) and the 2023 lettuce trial (6 Nov). Using a cylinder (2.54 cm radius x 9.09 cm length). Soil was dried similarly to the gravimetric samples. Bulk density was calculated by dividing the mass of dry soil (g) by the volume of soil collected (cm³) (USDA-NRCS, 2019). To measure soil respiration, core samples of a 10.2 cm depth were collected from each treatment at planting and termination of the 2023 and 2024 tomato trials and the 2023 lettuce trial using similar methods. Samples were air-dried for 30 days, then stored in plastic bags. Samples were transported to Kansas State University, Manhattan, KS to determine

respiration using Permanganate oxidizable C methods similar to Weil et al., 2003 as recommended by Schindelbeck et al., 2016.

Statistical analysis

All data analyses were performed with SAS (SAS version 9.4, Cary, NC, USA) using the PROC GLIMMIX model. For the temperature data, DDFM=KR was included in the MODEL statement. Fixed effects of mulch treatments, year, and a treatment x year interaction were modeled with rep in the RANDOM statement for the analysis of HT tomato and open field soil moisture, temperature, bulk density and electrical conductivity. Respiration and HT lettuce bulk density and electrical conductivity were modeled with treatment as the fixed effect and rep in the RANDOM statement. In each tomato trial, soil temperature and soil moisture data were separated into three “seasons” for analysis (early, middle, and late). Early and late seasons were utilized for the analysis of HT lettuce data. In 2023 and 2024, HT tomato early, middle, and late soil monitoring seasons were 26 May to 20 Jun, 21 Jun to 15 Aug, and 16 Aug to 9 Oct, respectively. In 2022, HT lettuce early and late soil monitoring seasons were 23 Sep to 14 Oct and 15 Oct to 4 Nov, respectively. In 2023, HT lettuce early and late soil monitoring seasons were 28 Sep to 17 Oct and 18 Oct to 6 Nov, respectively. In 2023, open field tomato early, middle, and late soil monitoring seasons were 18 May to 1 Jul, 2 Jul to 14 Aug, and 15 Aug to 25 Sep, respectively. In 2024, open field tomato early, middle, and late soil monitoring seasons were 24 May to 29 Jun, 30 Jun to 5 Aug, and 6 Aug to 12 Sep, respectively. For temperature data and HT lettuce soil moisture data, mean separation was carried out by a significant difference test (LSD) at $P < .05$. Tukey’s HSD test was used for mean separation for tomato HT and open field soil moisture, bulk density, and soil respiration.

Results

In the HT tomato trials, the range for volumetric soil moisture (25.13%-40.01%) was greater than in the open field (35.17%-46.71%). In the lettuce trials, volumetric soil moisture ranged from 45.34%-51.20%. No significant treatment effects were observed for soil moisture data in the early part of the season for any of the trials. However, significant treatment effects were found for all temperature parameters regardless of season, except for the late season of the HT tomato trial. Bulk density and electrical conductivity were each analyzed for both years of the tomato trials and the second year of the HT lettuce trial. Soil respiration is reported for both years of the HT tomato trials and one year of the open field and HT lettuce trials. Microclimate conditions throughout the 2024 tomato trials and the 2023 HT lettuce trial are reported, as are soil nutrients at the beginning and end of the HT tomato trials, 2023 open field tomato trial, and the 2023 HT lettuce trial. Microclimate data from the 2024 tomato trials and 2023 lettuce trial are presented in Tables 2.1-2.3 to provide a descriptive summary of the environmental conditions. Results of agronomic tests conducted at the beginning and end of 2023 and 2024 HT tomato trials and the 2023 HT lettuce and open field trials are presented in Table 2.4 to provide a summary of the soil conditions.

Soil temperature in the HT tomato trials

Due to the presence of a significant treatment*year interaction for maximum temperatures in the early season ($P=0.0199$), early 2023 and 2024 were analyzed separately. However, there were no significant treatment*year interactions for the other periods when the soil temperatures were analyzed. Therefore, combined annual data from 2023 and 2024 for these parameters are shown in Table 2.5. Significant year-to-year differences were observed in the early season for minimum and average temperatures ($P\leq 0.0001$; Table 2.5). In the early season, mulch treatment had a significant effect on minimum, average, and maximum temperatures

($P \leq 0.001$; Table 2.5). Treatment effects for these parameters were similar in the middle season, but there were no significant treatment effects observed in the late season.

During the early and middle seasons, soil temperatures recorded under plastic mulch were consistently higher than those under paper mulch, white tarp, and bareground treatments ($P < 0.05$; Table 2.5). During the early period of the 2024 trial, the maximum soil temperature for the plots with paper mulch was 19% lower than those with plastic mulch (Table 2.5). Compared to the paper mulch and fabric mulch treatments, the use of the black silage tarp also significantly increased soil temperature for all parameters where a treatment effect was observed, except for maximum temperature during the middle season ($P < 0.05$; Table 2.5). Generally, soil under fabric mulch had temperatures that were similar to those under black tarp, plastic mulch, and bareground than those with paper mulch or white tarp ($P < 0.05$; Table 2.5).

Soil temperature in the HT lettuce trials

There were no significant treatment*year interactions for minimum, average, and maximum temperature. Therefore, combined data are shown in Table 2.6. A significant year-to-year difference was observed for each parameter in the early season, but not the late season ($P \leq 0.0001$; Table 2.6). In the early and late seasons, mulch treatment had a significant effect on minimum ($P \leq 0.0001$; $P \leq 0.0018$; Table 2.6), average ($P \leq 0.0001$; $P \leq 0.0010$; Table 2.6), and maximum temperatures ($P \leq 0.0001$; $P \leq 0.0006$; Table 2.6).

Consistently, soil temperatures recorded under the black tarps were higher compared to the other mulch treatments ($P < 0.05$; Table 2.6). Soil temperatures under white tarp and fabric mulch were similar for all parameters observed ($P < 0.05$; Table 2.6). The lowest minimum and average temperatures in the early season were recorded in the bareground plots, but in the middle season, bareground soil temperatures were similar to those in fabric mulch and white tarp soils ($P < 0.05$; Table 2.6). In the early season, the utilization of black tarp increased the minimum,

average, and maximum soil temperatures compared to the bareground treatment 10% to 13% (Table 2.6).

Soil temperatures in the open field

Due to the presence of a significant treatment*year interaction for maximum temperatures in the late season ($P=0.0026$), late 2023 and 2024 were analyzed separately. There were no significant treatment*year interactions for the other parameters and combined annual data is shown in Table 2.7. All parameters in the early and middle seasons displayed a year-to-year variation ($P\leq 0.05$; Table 2.7). In the early season, mulch treatment had a significant effect on minimum ($P\leq 0.0005$; Table 2.7), average ($P\leq 0.0001$; Table 2.7), and maximum temperatures ($P\leq 0.0009$; Table 2.7). Treatment effects for these parameters were similar in the middle and late seasons.

Across all parameters during the early and middle seasons, the black tarp performed similarly to plastic mulch in regard to raising soil temperature ($P<0.05$; Table 2.7). Temperatures recorded in soil under fabric mulch and white tarp were similar across all analyses, as were temperatures recorded under fabric and plastic mulch ($P<0.05$; Table 2.7). Soils under white tarp and paper mulch were significantly cooler than those under fabric mulch, plastic mulch, and silage tarp for all parameters except maximum temperature during the late season ($P<0.05$; Table 2.7). Compared to fabric mulch, the utilization of black tarp increased average soil temperature 6% and 4% in the early and middle seasons, respectively. Meanwhile, the soil in the paper mulch plots had 4% to 8% lower average soil temperature in the early, middle and late seasons (Table 2.7).

Soil moisture in the HT tomato trials

There were no significant treatment*year interactions for gravimetric or volumetric soil moisture. Therefore, the combined annual data is shown in Table 2.8. Year-to-year variation was

observed for all analyses ($P \leq 0.05$; Table 2.8), except for gravimetric soil moisture in the middle season. Significant treatment effects were found for gravimetric soil moisture in the late season ($P \leq 0.0003$; Table 2.8) and volumetric soil moisture in the middle ($P \leq 0.0001$; Table 2.8), and late seasons ($P \leq 0.0001$; Table 2.8). No significant treatment effects were observed in the early season. In the late season, the plots with plastic mulch had 18% and 20% higher gravimetric soil moisture compared to bareground and plastic mulch treatments, respectively (Table 2.8). However, volumetric measurements of soil moisture were 19% higher on average when white and black tarps were used compared those with fabric mulch, paper mulch, and bareground treatments in the middle season. Similarly, they were an average of 16% higher in the late season (Table 2.8).

Soil moisture in the HT lettuce trials

There were no significant treatment*year interactions for gravimetric or volumetric soil moisture. Therefore, the combined annual data are shown in Table 2.9. Significant year-to-year differences were observed for all parameters ($P \leq 0.0001$; Table 2.9) except volumetric soil moisture in the early season. Mulch treatment effects were only significant for the late-season gravimetric ($P \leq 0.0171$; Table 2.9) and volumetric ($P \leq 0.0001$; Table 2.9) soil moisture measurements. During the late season, gravimetric soil moisture was an average of 6% higher for soil under black tarp and with no tarp, than those under fabric mulch and white mulch (Table 2.9). However, volumetric measurements indicate that the soil had 5-7% higher soil moisture when fabric mulch or black and white tarps were applied than in the bareground treatment (Table 2.9).

Soil moisture in the open field

Due to the presence of a significant treatment*year interaction for volumetric soil moisture in the late season ($P = 0.0092$), late 2023 and 2024 were analyzed separately. However,

there were no other significant treatment*year interactions for gravimetric or volumetric soil moisture. Therefore, combined annual data for these parameters are shown in Table 2.10. Mulch treatment only had a significant effect on volumetric soil moisture during the late 2024 season ($P \leq 0.0001$; Table 2.10). Volumetric soil moisture readings during the late 2024 season displayed a higher moisture content for soils mulched with black tarp compared to all other treatments except plastic mulch, which performed similarly ($P < 0.05$; Table 2.10). Overall, the application of the black silage tarp increased the volumetric soil moisture in this season 13% to 23% compared to paper mulch, fabric mulch, white tarp, and bareground treatments (Table 2.10).

Bulk density

There were no significant treatment*year interactions for bulk density. Therefore, the combined annual data for both tomato trials is shown in Table 2.11. There was only one year of data collected for the HT lettuce trials. A year-to-year variation was observed for HT and open field bulk density ($P \leq 0.0001$; Table 2.11), though no significant treatment effects were observed. However, in the HT lettuce trials, the utilization of the black silage tarp increased the bulk density 12% compared to the bareground treatment ($P \leq 0.0376$; Table 2.11).

Soil respiration

Due to the presence of a significant treatment*year interaction for HT tomato soil baseline respiration ($P = 0.0231$), data was analyzed by year and reported in Table 2.12. Only one year of data from the open field tomato trials and HT lettuce trials was collected. Out of eight soil respiration analyses, there were no treatment effects observed (Table 2.12). However, for most treatments across trials, means for termination soil respiration decreased or were similar to means of measurements recorded from baseline samples. Generally, means for the HT tomato trials were lower in 2024 compared to those reported for 2023. Overall, the highest means values reported were in the HT lettuce trial.

Discussion

The overall goals of this report were to determine the impacts of various mulches on soil temperature, soil moisture, bulk density, EC, and respiration during tomato and lettuce production in the Central United States. As is common in the region, summer tomato trials were conducted in HTs and the open field and lettuce trials were conducted in the fall in HTs. The soil temperatures that we observed in these trials with plastic mulch in high tunnels were similar to those reported in previous studies from the same site (Gude, 2022). In addition, bareground soil temperatures in our trials were similar to those reported by a study in Illinois (Wortman et al., 2016). In the HT tomato trial, mulch type affected temperature in the early and middle seasons and soil moisture in the middle and late seasons. In the lettuce trials and open field tomato trials, significant effects on temperature were observed throughout all seasons, though treatment effects for soil moisture were only observed in the late part of the season. In our study, there were significant discrepancies between soil moisture as measured by % gravimetric and % volumetric methods. For the purpose of discussion, % volumetric data is utilized, as this method is more common in the literature (Wu et al., 2022; Kim and Park, 2024; Vennem et al., 2023).

Soil temperature and moisture: tomato

Plastic Film Mulch

Polyethylene-based plastic film mulch has been an important tool in supporting commercial vegetable production since the 1960s (Lamont, 2005). In our tomato trials, the application of plastic mulch in the HT increased temperature means higher than any other treatment. It also significantly increased minimum, average, and maximum temperatures in the early season compared to paper mulch, white tarp and bareground treatments. In the open field tomato trials, the application of plastic mulch affected soil temperatures similarly to fabric mulch

and black tarp, except for late in the 2024 season. One of the reasons that plastic films are utilized as mulches by growers is that it has shown to increase early season soil temperatures (Lamont, 2009). Black mulch absorbs the highest radiation levels (90%) compared to other colored mulches (Teasdale and Mohler, 2000). Compared to white mulch, darker-colored plastic mulches have been reported to modify the soil surface temperature by 5°C (Sakamoto et al., 2016; Tarara, 2000). Temperature increases observed in this study were not as extreme, though they were similar to reports by Liu et al. (2014) that soil temperatures were increased 1-3°C compared to the bareground treatment. In all seasons of the HT tomato trials, soil moisture levels under plastic mulch were similar to the other mulch types. However, in the open field trials in late 2024, soil moisture with plastic mulch was 12% to 20% higher than the bareground, white tarp, and paper mulches. Snyder et al. (2015) also noted soil moisture increases up to 20% with the application of black plastic mulch compared to bareground in the open field. Plastic mulch is suggested to aid farmers with soil moisture management (Emmert, 1957), though our results indicate this treatment was inconsistent in achieving this effect. Plastic mulch films are air and water-permeable (Noling, 2013), and it is possible that in the late season of the 2024 open field trials, that this material allowed precipitation to reach the soil, while decreasing evaporation afterward.

Woven Fabric Mulch

Although plastic film is cited as being a popular mulch for growers to maximize productivity in the open field, fabric mulch is the predominant material utilized by high tunnel growers in the Central US, particularly for long-season crops like tomato (Lamont, 2009; Meyer, 2016). Like plastic film, polypropylene woven fabric is a semi-permeable synthetic material, but is significantly thicker and more durable. This allows it to be re-used for 5+ years and has been

recommended to prevent weed growth (George et al. 2015). Overall, soil temperatures in the open field fabric plots were similar to those reported by Monks et al. (1997), with the majority ranging from 21-26°C. Because it is a dark-colored mulch, it seems likely that fabric mulch would increase soil temperature, as reported in other studies (Sakamoto et al., 2016; Tarara, 2000; Monks et al., 1997; Schonbeck and Evanylo, 1998). Soil temperatures recorded under fabric mulch in the HT and open field tomato trials were similar to those in the bareround treatment throughout all seasons, likely because it is made of woven polypropylene material, which is water and air-permeable (Martin et al., 1991; Reece, et al., 1997). Interestingly, in the early season of the HT tomato trials, minimum and average soil temperatures of the fabric mulch plots were slightly lower than plots with plastic mulch. The difference between these two dark mulches could be attributed to higher thermal conductivity values associated with polyethylene film compared to woven polypropylene fabric (Choy, 1977). Moreover, a study in West Virginia, though conducted in the open field, reported a similar pattern (Monks et al., 1997). Although the fabric mulch did not warm the soil as dramatically as plastic film mulch, the temperatures were frequently higher than those recorded under paper mulch and white tarp in the HT and open field trials.

Similarly to soil temperature, this study indicates that the application of fabric mulch had no large effect on soil moisture conservation in HT or open field cultivation for tomato. This is contrary to reports by Wang et al. (2002) that the utilization of fabric mulch increased soil moisture compared to bareground and plastic mulch treatments. The study by Wang et al. (2002) was conducted in an open field where it is difficult to control the potential effects of precipitation. There is limited literature on woven polypropylene fabric, but one explanation for the results in this study is that because fabric mulch has higher air and water permeability, it can

behave similarly to the bareground treatment in regards to soil moisture and temperature, when exposed to warm summer conditions (Martin et al., 1991; Reece et al., 1997). Although this material may not conduct thermal energy similar to plastic film mulch, fabric mulch is dramatically thicker and can be re-used by growers for weed management and as an alternative to plastic mulches, which contribute significantly to landfills worldwide (Changrong et al., 2014).

Paper Mulch

Paper mulch has been proposed for several decades as a potential solution to address environmental sustainability issues related to plastic mulches (Merfield, 2002; Salokangas, 1973). However, their durability in the field is limited and they may be more useful in HTs, where rain and strong winds are excluded (Miles et al., 2012). In the HT trials, early and middle season temperatures in the paper mulch plots were significantly lower than the soil temperatures in the plastic mulch, fabric mulch, and black tarp plots for most parameters, and were similar to white tarp mulch. Temperatures recorded under paper mulch in the open field trials were consistently lower than those under the black tarp and the plastic mulch. In fact, soil temperatures under the paper mulch were frequently similar to the bareground treatment, especially in the middle and late seasons. This is consistent with reports that applying paper mulch limits soil warming compared to dark mulch and a bareground treatment (Runham et al., 1998; Zhang et al., 2008; Pessala and Hardh, 1977). Because on the lighter color of the paper, light is reflected instead of absorbed, affecting soil temperature (Nair, 2013).

Soil moisture levels under paper mulch in the middle and late seasons of the HT tomato trials were similar to all treatments except the white tarp and black tarp. In the late season of the

2024 open field trial, the moisture levels for soils with paper mulch were similar to all treatments except plastic mulch and black tarp. Our results were contrary to previous research reporting that paper mulch has been found to conserve soil moisture compared to bareground lettuce cultivation (Jenni et al., 2004). This could also be explained by the paper mulch breaking down throughout the season, as significant differences in soil moisture between treatments were not observed until the middle and late seasons, when it was functionally similar to the bareground treatment. Because lettuce has a shorter season, treatment effects may have been more easily observed by Jenni et al. (2004). There was not ample space to include paper mulch in our lettuce trials, but it would be useful for future investigations due to the shorter season, which reduces concerns of durability and may impact soil moisture conservation efforts.

Black Silage Tarp Mulch

Silage tarps are much thicker (5-10 mil) than plastic film mulches, allowing for their reuse, while having low water and air permeability. In the HT tomato trials, average temperatures for soils under black tarp were similar to those observed for soils under fabric mulch during the middle season, though they were higher in the early season. The soil temperatures we observed under the black tarp were similar to those recorded under plastic mulch throughout all of the seasons in the HT trials. However, in the open field trials, the utilization of black tarp increased average soil temperatures up to 1.6°C compared to the fabric mulch. This could be a result of the thermal conduction effect being exaggerated by increased DLI in the open field as polypropylene less effectively conducts thermal energy than polyethylene material (Choy, 1977). Our results are in agreement with reports from Rylander et al. (2020) that similar to plastic mulch, silage tarp effectively increases soil temperature. Black silage tarps are primarily used by growers to warm the soil in an effort to reduce weed pressure

as part of a process known as occultation (Kubelek et al., 2022; Chandran et al., 2018). However, one study describes that when black tarp is applied to cover crops, decreased soil temperatures were seen compared to no tarp (Lounsbury et al., 2018). This result could be due to evidence that contact between the mulch material and soil is important for maximal heat transfer (Ham et al., 1993; Ham and Kluitenberg, 1994; Liakatas et al., 1986).

In the middle and late seasons, the utilization of black silage tarp significantly increased soil moisture compared to all treatments except for the plastic mulch and white tarp, which were similar. During these seasons, the utilization of black silage tarp significantly increased soil moisture by 16% to 21% compared to fabric mulch. In the late period of the 2024 trial, soil under the black tarp had higher soil moisture levels than all treatments, except for the plastic mulch. Similarly, in the 2024 open field trial, soil under the black tarp had 13% higher soil moisture levels than the fabric treatment during the late period. This indicates that the utilization of black silage tarps as mulch can be used to conserve soil moisture, but may do so comparably to other mulch types, and only during the middle to late parts of the growing season. To our knowledge, similar studies have not yet been conducted in high tunnels. Rylander et al. (2020) conducted a field experiment in which soil moisture was measured in untarped soil and soil with black tarp. However, that study was researching the effects of occultation, not mulching. In 5 of 10 trials, black tarp increased the soil moisture, and in only 2 out of 10 trials was the soil moisture similar to that of the untarped soil. Conversely, an open field occultation study in Maine indicated that soil moisture under black tarps was similar to untarped soil (Birthisel and Gallandt, 2019). Another report in a cover cropping study claims that the utilization of black tarp can increase the stability of soil moisture levels after rain events (Lounsbury et al., 2018).

White Silage Tarp Mulch

Unlike the black silage tarp, the application of white silage tarp decreased soil temperature compared to fabric and plastic mulch in the early and middle seasons of the HT tomato trials, and soil temperatures were generally lower than those observed with the black tarp. The application of white silage tarp had a similar effect on soil temperatures in the middle season to bareground and paper mulch treatments. Similar to the HT trials, soil temperatures under the white tarp in the open field trials were lower than those observed under the fabric mulch and similar to those observed with paper mulch and in the bareground plots. Interestingly, minimum and maximum temperatures in the late season were similar to those reported in the plastic mulch treatment. Though there has not been extensive research on the utilization of white tarp as a mulch, white plastic film mulch is used by growers for crops susceptible to heat stress, such as lettuce (Snyder et al., 2015; Vargas et al., 2018). Light-colored plastic film mulches can reduce soil warming and reflect solar radiation back into the plant canopy (Nair, 2013). Tarara (2000) reports that white plastic decreases soil temperature 0.1°C at a 1-inch depth or $-.07^{\circ}\text{C}$ at a 4-inch depth as compared to bare soil, as it only conducts 1% of solar radiation into the soil. These findings are similar to the results presented in this study, although most statistical differences between soil temperatures in the white tarp and bareground treatments were observed during the fall trials.

In the middle and late periods of the growing season, the application of white tarp increased soil moisture significantly compared to all of the mulch treatments except black tarp and plastic film. In these seasons, the application of white tarp increased soil moisture 22% to 24%, compared to fabric mulch, which is primarily used in HT production. In contrast to the HT tomato trials, soils in the open field that were mulched with white tarp had similar soil moisture levels as the fabric mulch during the late period of the 2024 trial. Additionally, soils that were

covered with white silage tarp in the open field had similar soil moisture levels as most treatments in the late period of the 2024 trial, which were significantly lower than those observed in black tarp and plastic mulch treatments. The increase of soil moisture in the HT trials could be attributed to the low air permeability of silage tarp material, as this decreases moisture escaping the soil surface through evaporation (Borreani et al., 2014) However, when significant soil moisture differences were observed in the open field trial, the white tarp did not conserve soil moisture as effectively as the black tarp. This is similar to results by Zhang et al., 2020 who suggested that in the open field, the presence of the mulch prevented rainfall from reaching the soil.

Soil temperature and moisture: lettuce

Woven Fabric Mulch

As established in the discussion of the tomato trials, woven polypropylene fabric is a semipermeable material and these patterns suggest that in the fall, fabric mulch primarily serves to insulate the soil against solar radiation (Martin et al., 1991; Reece et al., 1997). Average soil temperatures under the fabric mulch ranged from 14.1°C to 21.4°C throughout the growing season. However, in the early period, average temperatures were 1.0°C greater than in the bareground treatment. In both the early and late seasons, temperatures were 1.2°C less than under the black silage tarp. Soil temperatures observed under the fabric mulch were similar to those under the white silage tarp throughout this study.

The fabric mulch treatment increased soil moisture levels compared to the bareground treatment during the late season by 7%, though moisture levels were similar between the fabric and silage tarp treatments. There are reports of this kind of material reducing drought effects in China (Wu et al., 2022). Furthermore, a study in Washington also indicated that soil moisture in

double-cropped strawberry system was retained by the application of fabric mulch compared to bareground (Wang, 2022). Though this material is semipermeable, it appears to be effective at decreasing soil evaporation rates when air temperatures are cooler, although we did not see similar results in the summer HT trials.

Black Silage Tarp Mulch

The utilization of black tarp increased soil temperature parameters more than any other treatment in the HT lettuce trials throughout the growing season, increasing the average soil temperature 2.2°C compared to the bareground treatment in the early season. Though similar studies have not been conducted with silage tarps, Wang (2022) reported increased soil temperatures under black plastic film mulch compared to the bareground during the fall months of their strawberry/lettuce study. Additionally, a fall HT study in Tennessee reported that the application of black plastic mulch increased soil temperature between 0.8 and 1.3 °C (Zheng et al., 2019). Temperature differences in prior experiments were not as extreme as those observed in this study. This could be because polyethylene mulch is semi-permeable and much thinner than black silage tarp.

The utilization of black silage tarp increased soil moisture levels 5% compared to the bareground treatment in the late season, though soil moisture levels were also similar to those observed under the fabric mulch and with white silage tarp. Prior research indicates that without mulch, lettuce plots are faster to lose soil moisture than those covered with black plastic mulch (Matitschka, 1996). A heavier, less permeable silage tarp could allow for even less moisture loss (Borreani et al., 2014).

White Silage Tarp Mulch

Soil temperatures observed under the white silage tarp mulch were similar to those under the fabric mulch during both early and late seasons. However, the average temperature was increased 0.7°C compared to the bareground treatment early in the season, though maximum average temperatures between these two treatments were similar. Compared to the black silage tarp, average temperatures were 1.5°C and 1.4°C lower in the early and late seasons, respectively. An open field study in New England also reported that average daily soil temperatures under white plastic film were mulch greater than those observed in plots with no mulch, but lower than under black mulch (Gheshm and Brown, 2020). While the study in New England did not include silage tarps, it reinforced our observed effects of insulation and thermal radiation, respectively. Despite white and black silage tarp being the same material, the white silage tarp performed more similarly to the fabric mulch. While it does not conduct thermal radiation as effectively as black plastic mulch is known to, it did insulate the soil and retain some heat in the early part of the season, before temperatures declined in winter (Tarara, 2000; Borreani et al., 2014).

Similar to the fabric and black silage tarp, the application of white silage tarp increased soil moisture 7% compared to the bareground treatment. While there is limited literature on the effects of white mulches on soil moisture during cool seasons, this result is consistent with observations made for this treatment during the tomato trials and with other studies that highlight its ability to decrease moisture loss, due to the thick polyethylene material (Borreani et al., 2014).

Effects of various mulches on soil health for tomato and lettuce

Maintaining soil health is critical for sustaining crop productivity and ensuring farm profitability (Nielsen, 2023). In particular, there have been increasing concerns about the long-

term soil health challenges that can occur within HT production systems (Pierre et al., 2024). High tunnel producers frequently use intensive growing practices to keep up with market demands, and the microclimate created in a high tunnel exacerbates the associated soil degradation (Norris and Congreves, 2018). Some rising concerns include soil compaction, and the health of the soil ecosystem (Pierre et al., 2024; Blomgren and Frisch, 2007; Everhart et al., 2009; Knewton et al., 2010, 2012). To ensure the sustainability of HT systems, it is crucial to understand the dynamics between the HT microclimate, growing practices, and soil properties (T. Blomgren and T. Frisch, 2007; Conner et al., 2010; Everhart et al., 2009; Galinato and Miles, 2013; Sydorovych et al., 2013; Waterer, 2003; Wells and Loy, 1993). In this study, bulk density, and soil microbial respiration were the criteria utilized to measure soil health.

Bulk density is an important factor for soil health as it corresponds directly to infiltration rates, available water capacity, soil porosity, soil microorganism activity, root proliferation, and nutrient availability. (Indoria and Reddy, 2020). Reichert et al. (2009) explains that factors such as particle size, soil texture, organic matter content, and management practices affect the optimal and critical limits of soil bulk density. Good, fair, and bad ranges for bulk density (g/cm) are less than or equal to 1.3, 1.3 to 1.55, and greater than 1.8 g, respectively (Mukhopadhyay and Srivastava, 2019). In this study, bulk density ranged from .97 (g/cm) as observed in the bareground treatment of the HT lettuce trials to 1.84 (g/cm) under the black tarp in the open field experiment. Though there were no treatment effects observed in the tomato trials for bulk density, bulk density was 12% higher for soils under the black tarp than those with no tarp in the HT lettuce trials. This could be attributed to the higher soil moisture levels observed under the black tarp. All treatments were walked upon during management and data collection and the foot traffic on moist soil likely contributed to increased compaction (Farrior, 2005).

Respiration as measured by POX-C describes the carbon pool that serves as a food source for soil microbes and is a useful indicator of soil health (USDA-NRCS, 2019). Higher levels indicate more effective soil organic matter accumulation and long-term carbon sequestration (Hurisso et al., 2016). Various mulch types in this study showed no effect on soil respiration measured by the POX-C procedure likely because treatments were only applied to the soil for six months. Kubalek et al. (2022), suggests that higher soil temperatures, such as those observed under tarps could reduce labile carbon in the soil and other reports have indicated that these conditions expedite labile carbon decomposition Qi et al. (2016). More long-term research is needed to better understand if mulch type has a significant effect on soil respiration.

In the literature, there are varying reports on how mulching with polyethylene film affects long-term soil health. Some indicate that this material improves reduces bulk density and increases aeration compared to plots without mulch (Van Der Meulen et al., 2006; Javeed et al., 2013). Wang et al. (2022) also suggest that the utilization of plastic film mulch can promote soil microaggregate formation, thereby improving soil structure. On the contrary, other authors relay that this plastic film mulch decreases infiltration, porosity, and discourages the development of crop roots (Souza et al., 2018; Wan et al., 2019; Qi et al., 2018).

Interestingly, Kubalek et al. (2022) predict that the application of black tarp on soil would have a similar effect on soil properties as the long-term utilization of plastic mulch. In our study, this translated to increased soil moisture levels in the HT trials, which have been shown to correlate with increased arthropod abundance in HTs (Skinner, 2020). However, research by Kinnebrew et al. (2023), implies that the application of silage tarps may have negative, long-lasting effects on soil-dwelling arthropods. In contrast, paper mulch is made to completely

degrade. Though this process may produce some carbon dioxide, there are no significant negative impacts on soil (Merfield, 2002).

Although in this study there were few significant treatment effects observed on soil health parameters, there are several other criteria that future studies should investigate to better understand how various mulch types can improve soil health in HTs. Including infiltration would give further insight into how the application affects soil structure, a key component of soil health, and an effective indicator of compaction issues (Bassat et al., 2023). Furthermore, replicated soil organic measurements (SOM) and measurements over time would be helpful in understanding the extent to which covering HT soils could affect the soil environment. Some studies indicate that applying mulch can help conserve the amount of plant residue that is able to remain in the soil (Liu et al., 2023b; Zhang et al., 2017). Autoclaved citrate-extractable protein (ACE) as a soil health indicator could also be productive, as it measures a soil nitrogen fraction highly sensitive to management practices while being related to soil properties and long-term yields (Sainju et al., 2022). Furthermore, repeating the study in the same arrangement and on the same space may have been helpful to determine long-term effects. In the case of our study, crops were rotated over time and space in order to coincide long-term cropping strategies and is required for organic certification.

Effects of mulches in warm- and cool-season crop production systems

In Kansas, cool-season crops are grown during spring and fall, and warm-season crops are planted in spring and grown through the summer. Therefore, air and soil temperatures vary dramatically between the cultivation of these crop types, as displayed by our microclimate data and soil temperature data. Monthly air temperature averages during the tomato trials ranged from

17.5°C to 26.6°C, though in the lettuce trials ranged from 10.2°C to 26.7°C. Meanwhile, soil temperatures recorded in bareground plots during summer and fall ranged from 21.7°C to 29.3°C and 13.6°C to 20.6°C, respectively. In spring and summer, mulch appeared to conduct or inhibit thermal radiation in the soil, depending on mulch type. However, during the cooler fall months, mulch likely retains soil heat, keeping it from escaping and resulting in seasonal cooling. Furthermore, semi-permeable mulch was more effective at retaining soil heat and moisture in the fall, though not in the summer, when air temperatures were more extreme. It is important to understand differences in thermal and soil moisture dynamics as affected by mulch types during the cultivation of cool- and warm-season crops, as the same mulching techniques may not be optimal for both. Expanding knowledge about these relationships will lead to better recommendations for growers aiming to select the most appropriate mulch to improve farm management in differing climates, seasons and crops.

In both the summer and fall studies, the utilization of black plastic mulch and black silage tarps were generally associated with warmer soil temperatures compared to other mulch types. In comparison, the application of white tarp often led to lower soil temperatures during the summer. Although, during the fall trials, the application of white tarp affected soil temperature similar to fabric mulch. Additionally, the fabric mulch was more effective at retaining soil heat during the first part of the fall season than it was during the summer trials. For spring production, black plastic mulch or black silage tarp could be useful in increasing root zone temperatures for lettuce cultivation. However, Gheshm and Brown (2020) suggest that increased lettuce yield is more directly associated with nutrient uptake than root zone temperature. Furthermore, growers should be aware that soil temperatures may increase too much for cool-season crops as summer approaches. For this reason, white plastic film is often the recommended mulch type. (Snyder et

al., 2015; Vargas et al., 2018). Therefore, black plastic film or silage tarp mulches may be better suited for warm-season crops with early planting dates. It should also be noted that paper mulch could be more appropriate for lettuce production because it has a shorter growing season and less time to degrade. Based on trends observed in our summer trials, both the paper mulch and white silage tarp were effective at moderating warm soil temperatures, which would better suit cool-season crops.

Overall, differences in soil moisture levels were more drastic in the middle and late seasons of the summer trials than in the late fall, likely due to seasonal climatic conditions that lead to increased soil evaporation. In the late seasons of the summer HT trials, soil moisture differences up to 18% were observed between the silage tarp and bareground treatments, in comparison to 7% in the fall trials. This indicates that applying mulch to retain soil moisture may be more effective during summer HT production, as the growing season is longer and warmer, and fluctuations in soil moisture levels can be more extreme. Interestingly, the utilization of fabric mulch effectively conserved soil moisture levels in the fall trials but was not effective at conserving soil moisture in the summer. This finding suggests that the semi-permeable material was more effective at retaining moisture when temperatures were cooler. This may be of note for HT growers producing cool-season crops that are seeking to conserve soil moisture with a reusable tool they likely already utilize in their production systems (Meyer, 2016).

Conclusion

Vegetable growers throughout the US are looking to implement practices that: maintain soil health, extend the growing season, provide environmental protection, and increase crop quality and yield. Among these practices, the utilization of plasticulture technologies like

mulches and high tunnels have are common. However, production in HTs and the utilization of certain mulches can have dramatic effects on the soil environment, which may have impacts on soil health. The results presented in this study highlight the effect of mulch color on soil temperature, whereas the mulch material largely drives soil moisture retention properties. In these trials, we were able to identify mulches that effectively increase soil moisture conservation while maintaining high soil temperatures that drive crop productivity. However, it is unclear to what extent mulch types will affect soil health long-term. This was a two-year study and the plots were re-located and re-randomized each year. Future research should focus on how the application of various mulch types across seasons and systems affects soil health indicators and environmental factors long-term. Furthermore, the use of larger plots could also help identify further treatment effects that may not arise in small-plot research with limited space. Ultimately, the decision to implement different mulching practices will be reliant not only on the soil health ramifications, but also any potential benefits to vegetable yield. Similarly, our anecdotal evidence indicated that the cost to install and maintain the different mulch types varied widely and a thorough economic analysis is warranted. As vegetable growers in the Central US continue to rely on HT production systems, it will be important to ensure their long-term sustainability. Soil health is paramount to ensuring production system durability and management of soil moisture may play a pivotal role in an integrated approach to managing and promoting healthy soils.

Tables

Table 2.1 Soil temperature, air temperature and relative humidity in a HT tomato trial during summer 2024 in Olathe, KS.

Month ^z		Soil Temp °C ^y	Air Temp °C	RH%	DLI
Apr	Min	18.7	12.5	39.4	12.2
	Max	29.9	36.2	93.8	
	Avg	23.2	21.3	73.3	
May	Min	19.3	12.6	44.3	21.8
	Max	29.4	31.2	93.4	
	Avg	23.6	21.2	73.0	
Jun	Min	23.5	19.2	49.2	34.8
	Max	32.9	34.2	92.2	
	Avg	27.4	26.3	71.6	
Jul	Min	24.1	19.6	51.2	28.6
	Max	31.6	35.0	93.4	
	Avg	27.5	26.6	75.0	
Aug	Min	23.4	18.6	49.9	33.8
	Max	28.8	34.2	94.1	
	Avg	25.8	25.3	75.9	
Sep	Min	19.6	13.1	44.7	19.2
	Max	25.1	31.4	94.6	
	Avg	22.2	21.2	74.2	
Oct	Min	16.5	8.3	32.6	15.9
	Max	22.3	29.2	93.0	
	Avg	18.9	17.5	66.0	

^zExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18" apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^yHOBOWare weather data loggers were installed in a bare (control) treatment plot. Data was recorded in 15-minute intervals.

Table 2.2 Soil temperature, air temperature and relative humidity in a HT lettuce trial during fall 2023 in Olathe, KS.

Month ^z		Soil Temp °C ^y	Air Temp °C	RH%	DLI
Sep	Min	22.9	17.9	33.6	20
	Max	29.3	37.9	92.8	
	Avg	25.7	26.7	65.5	
Oct	Min	15.4	7.2	42.4	13.3
	Max	20.2	24.6	94.2	
	Avg	17.5	14.2	74.3	
Nov	Min	9.8	1.9	42.4	15.1
	Max	13.6	17.9	86.1	
	Avg	11.9	10.2	72.6	

^zExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 27 Sep 2023.

^yHOBOWare weather data loggers were installed in a bare (control) treatment plot. Data was recorded in 15-minute intervals.

Table 2.3 Soil temperature, air temperature and relative humidity in an open field tomato trial during summer 2024 in Olathe, KS.

Month ^z		Soil Temp °C ^y	Air Temp °C	RH%	DLI	Precip. ^x (mm)
May	Min	19.1	13.2	50.5	45.2	23.11
	Max	28.7	29.2	94.1		
	Avg	23.8	21.0	73.9		
Jun	Min	22.6	18.4	52.2	47.7	99.31
	Max	31.1	32.3	91.4		
	Avg	26.6	25.4	73.6		
Jul	Min	22.3	18.8	55.9	41.7	117.28
	Max	32.7	32.7	94.6		
	Avg	26.9	25.5	77.5		
Aug	Min	21.2	17.9	53.4	33.8	77.46
	Max	31.8	32.1	94.7		
	Avg	25.7	24.4	77.8		
Sep	Min	11.9	9.7	41.0	35.7	0
	Max	28.5	29.8	94.6		
	Avg	19.9	19.2	72.2		

^zExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^yHOBOWare weather data loggers were installed in a bare (control) treatment plot corresponding to the HT trial. Data was recorded in 15-minute intervals.

^xIn 2023, total monthly precip. (mm) was: May, 88.39; June, 27.43; July, 173.23; August, 58.68; September, 51.3). Precipitation data was recorded by the Kansas Mesonet at the Olathe Horticulture Research and Extension Center.

Table 2.4 Agronomic conditions in HT tomato trials during 2023 and 2024 and in HT lettuce and open field tomato trials during 2023 in Olathe, KS.

2023 HT tomato ^z							
Baseline ^w	4.2 ^v	87.7	7.2	7.2	0.3	16.7	177.0
Termination	4.3	83.0	6.7	7.0	21.4	16.2	193.7
2024 HT tomato							
Baseline	3.4	55.2	7.7	7.4	39.3	6.2	138.7
Termination	3.6	132.3	7.9	7.5	60.7	9.2	228.1
2023 HT lettuce ^y							
Baseline	3.8	49.0	7.0	7.2	1.0	7.2	122.8
Termination	4.3	94.5	7.2	7.2	0.2	18.3	178.8
2023 open field ^x							
Baseline	3.6	48.0	6.6	7.0	10.5	2.3	193.7
Termination	4.1	69.3	6.5	7.0	42.2	13.7	191.3

^zExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^yExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 27 Sep 2023.

^xExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^wSoil samples were tested at the Kansas State University Soil Testing Laboratory for: pH, buffer pH, phosphorus (ppm), Potassium (ppm) NH₄-N ppm, NO₃-N ppm, and organic matter (OM). Soil pH and buffer pH was measured using the 1:1 soil-water Sikora Buffer procedure. Phosphorus (ppm) was determined by Mehlich-3 extraction. Potassium (ppm) was determined by ammonium acetate extraction. NH₄-N (ppm) and NO₃-N (ppm) was measured with KCl extraction. For OM (%), the loss on ignition procedure was used.

^vData presented is the average of results from each rep.

Table 2.5 Average minimum, average, and average maximum soil temperatures (°C) under different mulch types in HT tomato trials during 2023 and 2024 in Olathe, KS.

Treatment ^y	Avg min temps ^x			Avg temps			Avg max temps			
	Early ^w	Middle	Late	Early	Middle	Late	Early 23 ^u	Early 24	Middle	Late
Bare ^z	21.69 bc	26.03 bc	22.93	23.46 b	27.38 bc	24.17	24.46 bc	26.63 bc	29.08 ab	25.62
Black	22.96 a	26.91 ab	23.92	24.71 a	28.25 ab	25.13	26.14 a	27.67 ab	29.97 ab	26.60
White	21.32 cd	25.59 c	22.24	22.66 c	26.77 c	23.43	22.13 d	24.72 d	28.47 b	25.28
Fabric	21.85 b	26.73 ab	24.31	23.69 b	28.33 ab	26.04	25.74 ab	26.32 c	30.98 a	27.00
Paper	20.92 d	25.31c	22.63	22.37 c	26.42 c	23.66	24.21 c	24.04 d	27.82 b	26.09
Plastic	22.76 a	27.01 a	23.89	24.89 a	28.75 a	25.66	26.43 a	28.71 a	31.13 a	28.51
Year ^v	<.0001	ns	ns	<.0001	ns	ns			ns	ns
Treatment	<.0001	0.0038	ns	<.0001	0.0026	ns	0.0008	<.0001	0.0309	ns
Treatment x Year	ns	ns	ns	ns	ns	ns			ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^xWithin the east row of each treatment, one temperature probe was located 10.2 cm below the soil surface. Sensors recorded temperature data every 20 minutes.

^wSeasonal soil moisture was analyzed by early (26 May - 20 Jun), middle (21 Jun - 15 Aug), and late (16 Aug - 9 Oct) seasons in 2023 and 2024.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the soil temperature parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to LSD paired comparisons where $\alpha = 0.05$.

^uEarly avg max temps were analyzed separately for each year due to the presence of a significant treatment*year interaction $P = 0.0199$

Table 2.6 Average minimum, average, and average maximum soil temperatures (°C) under different mulch types in HT lettuce trials during 2022 and 2023 in Olathe, KS.

Treatment ^y	Avg min temps ^x		Avg temps		Avg max temps	
	Early ^w	Late	Early	Late	Early	Late
Bare ^z	17.55 c	13.58 b	19.00 c	14.72 b	20.63 c	16.31 b
Black	19.87 a	15.30 a	21.19 a	16.36 a	22.73 a	17.73 a
White	18.52 b	14.26 b	19.68 b	15.22 b	20.91 bc	16.51 b
Fabric	18.76 b	14.09 b	20.01 b	15.16 b	21.44 b	16.49 b
Year ^v	<.0001	ns	<.0001	ns	<.0001	ns
Treatment	<.0001	0.0018	<.0001	0.0010	<.0001	0.0006
Treatment x Year	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, and fabric mulch. Each treatment was 3.66 m x 4.57 m.

^yExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 23 Sep 2022 and 27 Sep 2023.

^xBetween the two rows of lettuce within each north subplot, one temperature probe was located 10.2 cm below the soil surface. Sensors recorded temperature data every 30 minutes.

^wEach year was analyzed by early (23 Sep-14 Oct; 28 Sep-17 Oct) and late (15 Oct-4 Nov; 18 Oct-6 Nov) seasons in 2022 and 2023, respectively.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the soil temperature parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to LSD paired comparisons where $\alpha = 0.05$.

Table 2.7 Average minimum, average, and average maximum soil temperatures (°C) under different mulch types in open field tomato trials during 2023 and 2024 in Olathe, KS.

Trt ^y .	Avg min temps ^x			Avg temps			Avg max temps			
	Early ^w	Middle	Late	Early	Middle	Late	Early	Middle	Late ^u 2023	Late 2024
Bare ^z	23.62 bc	25.42 bc	23.18 bcd	25.78 bc	27.14 bc	24.87 bc	28.28 bc	29.34 ab	32.82 a	28.29 ab
Black	26.04 a	27.22 a	24.82 a	28.09 a	28.89 a	26.43 a	30.58 a	31.08 a	26.97 b	30.28 a
White	22.72 c	24.66 c	22.63 cd	24.56 cd	26.07 cd	24.02 c	26.65 c	27.88 b	25.74 bc	26.03 c
Fabric	24.52 ab	26.09 b	23.92 ab	26.50 b	27.77 b	25.44 ab	28.79 ab	29.93 a	26.56 b	27.98 bc
Paper	22.58 c	24.32 c	22.93 d	24.46 d	25.85 d	24.00 c	26.61 c	27.89 b	25.06 c	27.29 bc
Plastic	25.92 a	26.66 ab	23.49 bc	27.04 ab	28.41 ab	25.92 ab	30.38 ab	30.60 a	26.66 b	27.19 bc
Year ^v	0.0007	0.0153	ns	<.0001	<.0001	0.0004	0.0017	<.0001		
Trt.	0.0005	<.0001	0.0036	<.0001	<.0001	0.0005	0.0009	0.0022	0.0015	0.0492
Trt. x Year	ns	ns	ns	ns	ns	ns	ns	ns		

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^xWithin the east row of each treatment, one temperature probe was located 10.2 cm below the soil surface. Sensors recorded temperature data every 20 minutes.

^wEach year was analyzed by early (18 May -1 Jul; 24 May- 29 Jun), middle (2 Jul - 14 Aug; 30 Jun - 5 Aug), and late (15 Aug - 25 Sep; 6 Aug - 12 Sep) seasons in 2023 and 2024, respectively.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the soil temperature parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to LSD paired comparisons where $\alpha = 0.05$.

^uLate avg max temps were analyzed separately for each year due to the presence of a significant treatment*year interaction $P = 0.0026$

Table 2.8 Gravimetric and volumetric soil moisture (%) under different mulch types in HT tomato trials during 2023 and 2024 in Olathe, KS.

Treatment ^y	% Gravimetric ^x			% Volumetric		
	Early ^w	Middle	Late	Early	Middle	Late
Bare ^z	13.94	9.60	11.93 b	37.08	28.47 b	25.54 b
Black	15.40	11.98	13.13 ab	39.86	35.70 a	29.80 a
White	14.75	11.09	13.48 ab	40.01	34.57 a	31.28 a
Fabric	14.28	10.13	11.53 b	37.56	28.39 b	25.13 b
Paper	13.96	9.97	13.05 ab	37.14	28.33 b	26.14 b
Plastic	14.35	11.22	14.48 a	37.71	31.57 ab	28.74 ab
Year ^v	0.0359	ns	<.0001	<.0001	<.0001	<.0001
Treatment	ns	ns	0.0003	ns	<.0001	<.0001
Treatment x Year	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^xSoil moisture measurements were taken biweekly. Gravimetric soil moisture was measured by sampling five soil cores of 0-10.2 cm depth from each plot between the two rows, 17.8-25.4 cm from the plants. Samples were dried at 70°C for 72 hours and the gravimetric water content was calculated by the equation: WC (%) = [(FW-DW)/FW]x100. Volumetric water content was measured using a digital TDR Freescout Moisture Meter with 20.3 cm. probes. The average of 5 readings taken 17.8-25.4 cm from the plants on the inside of each plot was recorded.

^wSeasonal soil moisture was analyzed by early (26 May - 20 Jun), middle (21 Jun - 15 Aug), and late (16 Aug - 9 Oct) seasons in 2023 and 2024.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the soil

temperature parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey's HSD.

Table 2.9 Gravimetric and volumetric soil moisture (%) under different mulch types in HT lettuce trials during 2022 and 2023 in Olathe, KS.

Treatment ^y	% Gravimetric ^x		% Volumetric	
	Early ^w	Late	Early	Late
Bare ^z	19.29	22.55 b	45.56	47.63 b
Black	20.36	22.65 b	45.34	49.98 a
White	20.10	23.91 a	46.77	51.14 a
Fabric	19.79	23.80 a	45.89	51.20 a
Year ^v	<.0001	<.0001	ns	<.0001
Treatment	ns	0.0171	ns	<.0001
Treatment x Year	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, and fabric mulch. Each treatment was 3.66 m x 4.57 m.

^yExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 23 Sep 2022 and 27 Sep 2023.

^xSoil moisture measurements were taken weekly. Gravimetric soil moisture was measured by sampling three soil cores of 0-10.2 cm depth throughout each subplot, 10.2-12.7 cm from the plants. Samples were dried at 70°C for 72 hours and the gravimetric water content was calculated by the equation: $WC (\%) = [(FW - DW)/FW] \times 100$. Volumetric water content was measured using a digital TDR Freescout Moisture Meter with 20.3 cm. probes. The average of 5 readings taken 10.2-12.7 cm from the plants throughout each subplot was recorded.

^wEach year was analyzed by early (23 Sep-14 Oct; 28 Sep-17 Oct) and late (15 Oct-4 Nov; 18 Oct-6 Nov) seasons in 2022 and 2023, respectively.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the soil moisture parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to LSD paired comparisons where $\alpha = 0.05$.

Table 2.10 Gravimetric and volumetric soil moisture (%) under different mulch types in open field tomato trials during 2023 and 2024 in Olathe, KS.

Treatment ^y	% Gravimetric ^x			% Volumetric			
	Early ^w	Middle	Late	Early	Middle	Late 2023 ^u	Late 2024
Bare ^z	15.05	21.70	17.84	45.05	42.79	43.47	38.57 c
Black	16.45	18.98	17.43	46.32	45.81	44.07	45.87 a
White	16.36	16.93	17.05	46.71	43.98	44.10	36.74 c
Fabric	16.05	18.39	17.88	45.64	43.74	45.85	39.70 bc
Paper	16.12	17.81	17.44	45.10	41.94	43.47	35.17 c
Plastic	16.37	19.09	19.35	46.34	44.79	44.60	44.00 ab
Year ^v	<.0001	ns	<.0001	<.0001	ns		
Treatment	ns	ns	ns	ns	ns	ns	<.0001
Treatment x Year	ns	ns	ns	ns	ns		

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^xSoil moisture measurements were taken biweekly. Gravimetric soil moisture was measured by sampling five soil cores of 0-10.2 cm depth from each plot between the two rows, 17.8-25.4 cm from the plants. Samples were dried at 70°C for 72 hours and the gravimetric water content was calculated by the equation: WC (%) = [(FW-DW)/FW]x100. Volumetric water content was measured using a digital TDR Freescout Moisture Meter with 20.3 cm. probes. The average of 5 readings taken 17.8-25.4 cm from the plants on the inside of each plot was recorded.

^wEach year was analyzed by early (18 May -1 Jul; 24 May- 29 Jun), middle (2 Jul - 14 Aug; 30 Jun - 5 Aug), and late (15 Aug - 25 Sep; 6 Aug - 12 Sep) seasons in 2023 and 2024, respectively.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the soil moisture parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey’s HSD.

^uLate volumetric data were analyzed separately for each year due to the presence of a significant treatment*year interaction $P=0.0092$

Table 2.11 Bulk density (g/cm) at termination in HT and open field tomato trials during summer 2023 and 2024, and a high tunnel lettuce trial in 2023 in Olathe, KS.

	HT ^x	Open field ^w	Lettuce ^v
Treatment	Bulk density ^u (g/cm)	Bulk density (g/cm)	Bulk density (g/cm)
Bare ^{zy}	1.41	1.75	0.97 b
Black	1.36	1.84	1.09 a
White	1.40	1.77	1.07 ab
Fabric	1.41	1.83	1.05 ab
Paper	1.35	1.78	
Plastic	1.32	1.78	
Year ^t	<.0001	<.0001	
Treatment	ns	ns	0.0376
Treatment x Year	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yTreatments included bare ground, black tarp, white tarp, and fabric mulch. Each treatment was 3.66 m x 4.57 m.

^xExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^wExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^vExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 27 Sep 2023.

^uBulk density was measured by collecting a soil sample from each treatment plot using a cylinder (2.54 cm radius x 9.09 cm length). Soil was dried similarly to the gravimetric samples. Bulk density was calculated by dividing the mass of dry soil (g) by the volume of soil collected (cm³).

^tThe generalized linear mixed model was used to test which coverings had a significant effect on the bulk density and electrical conductivity parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey’s HSD.

Table 2.12 Soil respiration (mg/CO₂/g soil) at termination in HT and open field tomato trials during summer 2023 and 2024, and a high tunnel lettuce trial in 2023 in Olathe, KS.

	2023 ^s		2024		2023		2024 open field	
	HT tomato ^x		HT tomato		HT lettuce ^w		tomato ^v	
Treatment	Baseline ^u	Term.	Baseline	Term.	Baseline	Term.	Baseline	Term.
Bare ^{zy}	49.37	25.430	20.05	20.64	30.78	26.78	24.55	26.99
Black	28.14	22.50	19.26	19.85	29.73	25.80	21.36	20.61
White	28.66	23.23	21.12	21.42	32.26	25.34	20.79	26.25
Fabric	28.87	22.67	20.02	21.79	30.87	26.30	23.33	23.21
Paper	31.75	24.34	20.48	19.64			24.98	24.53
Plastic	29.47	24.74	22.87	21.21			24.08	21.93
<i>P</i> -value ^t	ns	ns	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yTreatments included bare ground, black tarp, white tarp, and fabric mulch. Each treatment was 3.66 m x 4.57 m.

^xExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^wExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 27 Sep 2023.

^vExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^uSoil core samples of a 0-10.2 cm depth were collected from each treatment at planting and termination and were transported to Kansas State University, Manhattan, KS to determine respiration (Permanganate oxidizable C).

^tThe generalized linear mixed model was used to test which coverings had a significant effect on the soil respiration parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey’s HSD.

^sHT years were analyzed separately due to the presence of a significant year*treatment interaction $P=0.0231$ for the baseline parameter

Table 2.13 Effects of year and mulch type for high tunnel tomato, high tunnel lettuce, and open field tomato trials in Olathe, KS.

Trial	Parameter	<i>P</i> values		
		Year	Treatment	Year*treatment
HT tomato	Early avg min temps	<.0001	<.0001	0.4120
	Middle avg min temps	0.7479	0.0038	0.1639
	Late avg min temps	0.3442	0.1401	0.2768
	Early avg temps	<.0001	<.0001	0.0614
	Middle avg temps	0.2869	0.0026	0.1896
	Late avg temps	0.7192	0.1014	0.3620
	Early 2023 avg max temps		0.0008	
	Early 2024 max temps		<.0001	
	Middle avg max temps	0.4920	0.0309	0.2624
	Late avg max temps	0.8692	0.2386	0.6263
	Early gravimetric soil moisture	0.0359	0.8666	0.9987
	Middle gravimetric soil moisture	0.0701	0.5988	0.9982
	Late gravimetric soil moisture	<.0001	0.0003	0.2570
	Early volumetric soil moisture	<.0001	0.3294	0.9935
	Middle volumetric soil moisture	<.0001	<.0001	0.9709
	Late volumetric soil moisture	<.0001	<.0001	0.4210
	Bulk density	<.0001	0.1239	0.9385
	2024 baseline respiration		0.2407	
	2024 termination respiration		0.8782	
HT lettuce	Early avg min temps	<.0001	<.0001	0.9517
	Late avg min temps	0.1818	0.0018	0.9548
	Early avg temps	<.0001	<.0001	0.7543
	Late avg temps	0.9072	0.0010	0.8198
	Early avg max temps	<.0001	<.0001	0.5526
	Late avg max temps	0.4965	0.0006	0.3628
	Early gravimetric soil moisture	<.0001	0.9293	0.5765
	Late gravimetric soil moisture	<.0001	0.0171	0.4886
	Early volumetric soil moisture	0.6395	0.9401	0.9915
	Late volumetric soil moisture	<.0001	<.0001	0.5392
	Bulk density		0.0376	
	2023 baseline respiration		0.1051	
	2023 termination respiration		0.3788	
Open field tomato	Early avg min temps	0.0007	0.0005	0.6902
	Middle avg min temps	0.0153	<.0001	0.8721
	Late avg min temps	0.1732	0.0036	0.5960
	Early avg temps	<.0001	<.0001	0.6418
	Middle avg temps	<.0001	<.0001	0.4963
	Late avg temps	0.0004	0.0005	0.6572
	Early avg max temps	0.0017	0.0009	0.4274

Middle avg max temps	<.0001	0.0022	0.2583
Late 2023 avg max temps		0.0015	
Late 2024 avg max temps		0.0492	
Early gravimetric soil moisture	<.0001	0.9106	0.9723
Middle gravimetric soil moisture	0.4245	0.6575	0.5749
Late gravimetric soil moisture	<.0001	0.4843	0.3237
Early volumetric soil moisture	<.0001	0.4672	0.8446
Middle volumetric soil moisture	0.9605	0.3525	0.5477
Late 2023 volumetric soil moisture		0.8266	
Late 2024 volumetric soil moisture		<.0001	
Bulk density	<.0001	0.7346	0.8245
2023 baseline respiration		0.0570	
2023 termination respiration		0.1889	

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Chapter 3-Evaluation of Mulch Types on Yield and Quality of

Tomato and Lettuce

Abstract

High tunnels (HT) are utilized by vegetable growers to extend the growing season and improve the yield and quality of crops. However, concerns about the sustainability of HT soil health can have direct effects on yield and profitability. Recently, growers and researchers have expressed concerns related to soil moisture in high tunnels and potential negative consequences

to soil health. The use of non-permeable polyethylene tarps has become popular for urban and small-scale vegetable farmers to manage weeds through occultation. Similar tarps could also be used as mulch, but little is known about how this will affect crop productivity compared to other mulch types. The goal of this study was to examine silage tarps and other mulch types in HTs and the open field to determine how this practice may affect yield and quality of tomato and lettuce. Tomato and lettuce trials were conducted from 2022 to 2024 in HTs and open-field plots to determine the effect of various mulch treatments (bareground, black plastic film, black woven fabric, paper mulch, white silage tarp and black silage tarp) on tomato and lettuce yield and quality. For tomato, harvesting occurred weekly to monitor total, marketable, and non-marketable yield. Texture and organoleptic quality were assessed from 3 harvests across the two years. In 2023, lettuce were harvested and yield data were collected. Leaf color and water content were also assessed. In the HT tomato trials, mulch had the greatest effects on yield during the early season and the application of white silage tarp and plastic film mulch increased early marketable fruit yield by 58% compared to the bareground treatment. Mulch type had no significant effect on tomato or lettuce on the postharvest qualities that were assessed. Our data indicate that silage tarps may be an effective mulch, particularly for HT growers that are looking to conserve soil moisture and ultimately improve soil health. Yield and quality of tomato and lettuce were not penalized when tarps were utilized, and in some cases, yield was improved. As growers continue to adopt practices that help sustain or improve soil health, it is likely that silage tarps and other mulch types can be effective at maintaining crop productivity.

Introduction

The United States is the second largest tomato producer in the world (Reimers and Keast, 2016). Producers in the United States are able to meet about 40% of domestic fresh-market tomato demands, as tomato is the second most produced vegetable, second to potato (Guan et al., 2018). Tomato can significantly contribute to a healthy diet and maintain much of their nutritional value when cooked or processed (Bhowmik et al., 2012). Another crop, leaf lettuce, is becoming increasingly popular among health-conscience consumers because of its high nutrient content (Kim et al., 2016). According to the USDA, lettuce is the third most consumed vegetable in the United States (2015). Additionally, 22% of the world's lettuce is produced in the United States (Mou, 2008). Both tomato and lettuce are widely grown and consumed in the United States. Furthermore, they are both important crops for local and fresh markets (Galinato and Miles, 2013). Locally produced tomato is in high demand by farm-to-table restaurants and high-end grocery stores (Jordan, 2007). Local production also increases the marketability of lettuce, as its quality is affected by freshness and consumers express preference for locally produced food (Ryder et al., 2002). Localizing the food system allows producers and consumers to recycle resources more effectively (Eigenbrod and Gruda, 2015; Smit et al., 2001). Furthermore, it can reduce food waste by making distribution more efficient, thus increasing food access for community members in need (Smit et al., 2001).

Tomato and lettuce can be produced in high tunnel (HT) and open field systems (Singh et al., 2021; Zhao and Carey, 2009). Though open field production is simpler and less expensive, growers face more abiotic and biotic stressors (Nordey et al., 2017). Therefore, tomato and lettuce are two crops frequently cultivated in HT production systems. HTs are unheated greenhouse-like structures used by growers to extend the season and protect crops from the open

field environment. They utilize passive ventilation and are not typically heated (Janke et al., 2017). HTs are reported to help warm the soil earlier in the season and reduce disease by keeping excess moisture out of the growing environment. The protected environment typically allows for earlier and greater tomato production (Carey et al., 2009; O’Connell et al., 2012). Tomato is the most frequently grown HT crop in the world (Lamont, 2009), the United States (Carey et al., 2009), and the Midwest region (Knewston et al., 2010). Because HTs significantly extend the growing season (Lamont, 2009; Reeve and Drost, 2012), increase yield (Waterer, 2003), and improve fruit quality (O’Connell et al., 2012), they are extremely useful for growers producing solanaceous crops in the Midwest (Carey et al., 2009; Lamont, 2009). Compared to tomatoes grown in an open-field environment, high tunnel tomatoes can generate three times the revenue compared to crops in the open field (Galinato and Miles, 2013). Lettuce is the second most frequently cultivated HT crop (Orzolek, 2012) because cultivation can be significantly extended during the spring and fall seasons for leafy green crops (Carey et al., 2009). A recent study in Kansas indicated that consumers prefer spinach grown in local high tunnels compared to the field and those purchased from local retail suppliers (Batiakas et al., 2019).

The protected environment in HTs are also useful for meeting the demand for high quality tomato and other vegetables (Carey et al., 2009), where standards can be challenging for producers to meet (Huang and Snapp, 2009). In urban areas, HTs can help fill local markets with the high-quality, local produce farm-to-table restaurants and high-end grocery stores demand, while allowing growers to increase production capacity on less land (Jordan 2007; Ernst 2020). However, one study reports that the shelf life of open field tomato is shorter than HT tomato because fruits require greater washing to remove field particles such as dirt or pesticides from greater pest pressure (Figàs et al., 2018; Cook and Calvin, 2005). Furthermore, open field tomato

may have greater levels of some antioxidants such as lycopene, because of greater environmental stress (Sahlin et al., 2003; Jagadeesh et al., 2011). Commercial produce quality is judged by consumers and depends on external attributes such as size, color, and firmness as well as taste, including, acidity and sugar content (Bertin and Génard, 2018). Lettuce is also an economically important crop worldwide and demand for quality lettuce has increased in recent years (Fallovo et al., 2009; Díaz-Pérez et al., 2024). In lettuce, texture, and perception of freshness are important quality attributes for consumers (Esturk et al., 2014). Color is also important to consumers. Red leaf lettuce not only adds visual appeal to mixed salads, but some consumers identify color as a way to add antioxidants to their diet (Liu et al., 2024; Esturk et al., 2014). Similarly, green lettuce is associated with high chlorophyll content and is a visual indicator of freshness (Llorach et al., 2008).

Even though HTs and intensive production significantly contribute to the cultivation of horticultural crops and the local food system, many growers have expressed concern over the long-term sustainability of these systems because of challenges related to maintaining soil health (Knewston, 2010). HT management practices are often intensive and are compounded by the stressful hot and dry microclimate, accelerating soil degradation (Norris and Cosgreves, 2018). This can lead to challenges with increased soil salinity (Blomgren and Frisch, 2007; Everhart et al., 2009; Knewton et al., 2010, 2012), which can contribute to decreased crop growth (Paul, 2013) and nutritional quality (Fedeli et al., 2024). Ultimately, these factors can have economic consequences for growers (Pierre et al., 2024). Intensive practices such as frequent tillage and the heavy application of inputs are also common in open field vegetable production and have led to rising concerns about soil health and long-term fertility (Rodríguez et al., 2022). One strategy that growers utilize to mitigate soil health challenges in HTs and the open field is mulch.

Mulching increases soil moisture retention and suppresses weeds, ultimately supporting crop productivity (Nalayini, 2007; Kader et al., 2019; Pessala and Hardh, 1997).

Using mulch as a production management practice generally has a positive effect on vegetable yield and crop growth (Pessala and Hardh, 1997). Increases in yield are often attributed to higher soil temperatures and season extension (Abdul-Baki et al., 1992). In tomato, a higher root zone temperature is associated with increased growth due to higher rates of water and nutrient uptake (Hurewitz et al., 1984). When plastic mulch is used for tomato production, there is consistently an increase in yield (Sifola et al., 2024; Singh et al., 2020). In one study, researchers found that using plastic mulch increased tomato yield by 65% compared to the bareground treatment (Rajablariani et al., 2012). Similar to tomato, lettuce yield in HT can increase with rises in soil temperature in early spring and late fall (Bumgarner et al., 2011). Leaf area increases when lettuce is grown with plastic mulch compared to bare soil (Jenni et al., 1996; Arancibia and Motsenbocker, 2008; Rudisill et al., 2015). In a study comparing the effects of plastic mulch types on lettuce growth, the lettuce grown with black plastic had the highest leaf number, length, and width. The study revealed that lettuce grown with white plastic mulch was also larger than plants grown with blue, silver, and olive film (Shah Jahan et al., 2018).

There have been varying reports on the effect of mulch type on tomato quality, and most are from studies conducted in the open field. According to one study comparing the effects of different mulch types on tomato production, there was no difference in tomato quality, although yield increased with the use of plastic mulch (Mendonça et al., 2021). Another study indicated that compared to fruit grown on bareground, tomatoes grown with black plastic have higher levels of total soluble solids, but lower fruit firmness (Sifola et al., 2024). Other research indicates that the use of paper mulch increased total soluble solids of tomatoes compared to those

grown without mulch (Islam et al., 2021). For lettuce, black plastic mulch is associated with greater leaf area, and therefore photosynthetic rates, contributing to higher lettuce quality (Jenni et al., 1996; Arancibia and Motsenbocker, 2008; Rudisill et al., 2015). Research has also shown that the color of mulch influences phytochemical concentrations and the nutritive value of lettuce. Black plastic in particular increases chlorophyll, anthocyanin, phenols, and carotenoids (Jahan et al., 2018). While it is unknown how silage tarp may affect tomato and lettuce yields, it has been known to increase soil temperature similar to plastic mulch (Rylander et al., 2020). However, silage tarps are much thicker than plastic mulch (5-10 mil), allowing for their reuse, while their design intentionally allows for low air permeability to reduce aerobic spoilage of ensiled material (Borreani et al., 2014). Black silage tarp is currently primarily used by growers for its soil heating properties to mitigate weed pressure prior to crop planting as part of a process known as occultation (Kubelek et al., 2022; Chandran et al., 2018). It is possible that tarps could be utilized as a reusable alternative to plastic mulch that effectively conserves soil moisture and controls soil temperature.

HTs are growing in popularity and help growers meet the yield and quality demands of tomato and lettuce in urban and local food systems (Janke et al., 2017). However, the sustainability of the HT system and viability of intensive production is threatened by soil health challenges (Pierre et al., 2024; Knewston, 2010). Different mulch types may mitigate these issues while potentially affecting the yield and quality of lettuce and tomato. This report is part of a larger project to identify the effect of different mulching strategies in high tunnels and open field as it relates to water conservation, soil health, as well as yield and fruit quality. Observed effects on soil moisture, microclimate, and soil health properties are provided in Barnhart et al., (Ch. 2). The specific objectives of this study are to (1) evaluate the impact of various mulches on

yield and marketability of tomato and lettuce grown in HTs and the open field (2) determine the effect of specific mulches on the color, texture and organoleptic quality of tomato, color and water content of lettuce when grown in HTs, and (3) determine the viability of silage tarp as a mulch for HT and open field vegetable production.

Materials and Methods

HT trials were conducted at the Olathe Horticulture Research and Extension Center (OHREC) from 2022 to 2024 with lettuce and tomato. The OHREC is located in Johnson County, KS (38.884347 N, 94.993426 W) and has Chase silt loam soil (pH= 6.3). Tomato trials occurred during summer 2023 and 2024 and lettuce trials occurred during fall 2022 and 2023. The tomato trials were conducted in organic HTs and open field plots and the lettuce HTs were considered transitional.

Tomato trials

HT and open field tomato trials occurred during summer 2023 and 2024 using the hybrid cultivar ‘BHN 589’ (Seedway, Hall, New York). The trials were planted in six high tunnels and six open field plots that were established more than ten years ago for production systems comparisons. The high tunnels were constructed on soil berms that were on average 67 cm above grade in order to reduce the likelihood of flooding. Otherwise, the cropping history and management of the two systems has been the same since 2011. The plots were arranged in a randomized complete block design with 3 replicates across the six identical 6.1 x 9.8 m Quonset-style HTs and the six open field plots with identical arrangements and dimensions. The individual treatment plots contained two rows each and were 2.07 m x 3.05 m. The plants were grown in six 2.7 m rows with 6 plants per row planted 45.7 cm apart. The mulching treatments included bare (control), fabric (DeWitt Sunbelt Woven Groundcover; Sikeston, Missouri, USA),

plastic (Black Plastic Mulch 1 mil Embossed; Grower's Solution, Cookeville, TN), paper (Original WeedguardPlus Standard Weight; WeedGuard Plus, Aurora, Colorado, USA), white tarp (Silage Tarp 5 mil Black/White Plastic Sheeting; Farm Plastic Supply, Addison, Illinois, USA) and black tarp (the other side of the white tarp). The six rows were planted on the north side of the tunnels and corresponding open field plots in 2023 and on the south side in 2024. Winter wheat was planted as a cover crop prior to tomato in both seasons.

Tomato seeds were planted into 50-cell propagation trays (5 cm diameter) (50 Cell Plug Flats; Johnny's Selected Seeds Winslow, Maine, USA) with OMRI listed potting mix (Planting Pro Potting Soil; Ohio Earth Food inc., Hartville, Ohio, USA) and grown in the greenhouse. Tomatoes were transplanted into the plots on 26 Apr 2023 and 26 Apr 2024 (HT) and 18 May 2023 and 23 May 2024 (OF). At planting, an organic fertilizer blend, Re-Vita Pro (Ohio Earth Food; Hartville, OH) (5N-4P-5K) was applied at a rate of 112 kg N per hectare. Water was applied through drip irrigation for 30 minutes three times per week using 1.9 L/hr emitters (model, mfr?) pressure regulated to 103.4 kPa. Emitters were spaced every 30.5 cm. If temperatures were greater than 35 °C, watering was increased to 45 minutes, and one hour if temperatures were greater than 37.8 °C. Tomatoes were trained using a stake and weave vertical trellis system. The main pest pressure was from tomato fruit worms and hornworms. Once worms were observed, Bt was sprayed bi-weekly until the end of the growing season. There was some aphid pressure observed. Therefore, PyGanic was also sprayed as needed. Tomato trials were terminated on 9 Oct 2023 and 9 Oct 2024 (HT) and 25 Sep 2023 and 12 Sep 2024.

Lettuce trials

In the lettuce trials, red and green loose leaf lettuce cultivars, 'New Red Fire' and 'Two Star' were grown in two of four "caterpillar" HTs (Quick Hoops Bender; Johnny's Seed,

Winslow, Maine, USA) during the fall seasons of 2022 and 2023. The HTs were 39.6 m long x 3.7 m wide x 2.1 m high. Two beds ran lengthwise within each HT (39.60 m long x 0.61 m wide). The lettuce trials were arranged in a split-plot randomized complete block design with four replicates across the two HTs. Within each replicate the four main plots (3.66 m x 4.57 m) were randomly arranged and included: bareground (control), fabric (DeWitt Sunbelt Woven Groundcover; Sikeston, Missouri, USA), white tarp, and black tarp (Silage Tarp 5 mil Black/White Plastic Sheeting; Farm Plastic Supply, Addison, Illinois, USA). Sub-plots were randomly assigned as the two different lettuce types (red and green). An additional 1.5 m “buffer” area was included on the ends of each HT to reduce any edge effects. In 2023, the lettuce was planted in the two other HTs to follow on-farm crop rotation. Buckwheat was planted as a cover crop prior to the lettuce in 2022 and tillage radish was utilized as a cover crop prior to the lettuce in 2023.

Lettuce was seeded in the greenhouse into 72-cell propagation trays (3.8 cm diameter) (Pro-Tray 72 Cell Flats; Johnny’s Selected Seeds, Winslow, Maine, USA) 26 Aug 2022 and 30 Aug 2023 with potting mix (Berger Seed Germination and Potting Mix; Hummert International, Earth City, MO, USA). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) 23 Sep 2022 and 27 Sep 2023. Water was applied twice weekly for 30 minutes using drip irrigation and 1.9 L/hr emitters pressure regulated to 103.4 kPa and spaced every 10 cm. Unfortunately, due to a breach in the outside fencing, the 2022 lettuce were destroyed by wildlife just days before the planned harvest. However, harvest data was collected in the 2023 trial on 6 Nov.

Tomato harvest

Fruit with any visible red/orange color was harvested weekly from each plot. Fruit were graded as marketable or nonmarketable and marketable fruit were sized based on USDA size classes: small medium, large, and extra-large (U.S. Standards for Grades of Fresh Tomatoes, 1991). Nonmarketable fruit was determined based on the presence of decay, mold, cracking that extended beyond the shoulder, small size (smaller than 4 cm diameter), pest damage, and other defects. The fruit number and weight were recorded for each grade. At the end of each growing season, all fruit larger than 4 cm were harvested and weighed. HT tomatoes were harvested from 20 Jun to 9 Oct in 2023 and 25 Jun to 9 Oct in 2024. Open field tomatoes were harvested from 21 Jul to 25 Sep in 2023 and 23 Jul to 12 Sep 2024, respectively.

Postharvest analysis of high tunnel tomato fruit

The trial was sampled three times in order to determine the quality of tomato fruit at harvest. Fruit samples were taken twice during 2023 and once during 2024 and analyzed at the K-State Postharvest Physiology Lab. At each sampling, six fruit at the red maturity stage were utilized from each plot. The harvest dates for quality observations were 27 Jul and 22 Sep in 2023 and 13 Aug in 2024. On the day of harvest, the fruit was transported in an air-conditioned vehicle to the postharvest lab (approximately a 20-minute drive). All chemicals and reagents were purchased from Thermo Fisher Scientific (Waltham, MA, USA).

Tomato color, texture, and organoleptic quality

Color data were collected from each fruit by taking two measurements at opposite 45-degree angles on the blossom end with an A5 Chroma-Meter (Minolta CR-400; Minolta Co. Ltd., Osaka, Japan). The instrument was calibrated with the Minolta calibration standard white reflector plate before sampling fruit. L^* , a^* , and b^* readings, which were transformed to those of the L, a, b color space for the reporting of chroma, hue, and lightness.

Firmness was measured for each fruit using a TA-58, TA.XT plus texture analyzer (Texture Technologies Corp., Scarsdale, NY, USA). The peak force (g) needed for 2 mm compression deformation when using a TA-30 75 mm diameter flat plate was measured. Firmness (N) values were calculated as the average slope in the deformation curve divided by the peak force (g) (Jenkins et al., 2022; Jackman et al., 1990). After firmness was measured, the fruit was cut into thirds from the stem end to the blossom end. One third from each of the six fruits were weighed (g) and oven dried (Precision™, Thermo Fisher Scientific, Waltham, MA, USA) at 60 °C until weights were constant to determine water content $WC (\%) = [(FW - DW) / FW] \times 100$ (Batziakas et al., 2020; Agüero et al., 2008)

Another third from each of the six fruit per replication was blended, and 20 g of the puree was centrifuged. The hydrophilic supernatant was used for the determination of titratable acidity (TA) and SSC. To measure TA, 5 mL of the tomato supernatant was mixed with 45mL of deionized water and measured with an automated titrator (862 Food/Beverage Compact titrosampler, Metrohm, Herisau, Switzerland) (Jenkins et al., 2022). The results are reported as % citric acid. SSC was measured with a hand-held digital refractometer (AR200, Reichert, Depew, NY, USA). A drop of the hydrophilic tomato fraction was placed onto the refractometer lens. The results are reported as °Brix.

Lettuce harvest

Lettuce was harvested once it reached marketable/commercial size. Harvesting was performed in the morning by cutting the above ground part of the plant at the soil level using a harvesting knife (Harris Seeds, Rochester, NY, USA). There is only one year of lettuce data presented due to pest interference. In 2023, the harvest took place 6 Nov, which was six weeks after transplanting. Eight plants were randomly selected from each plot within the central 2.7 m

and weighed (g). On the day of harvest, the lettuce was transported in an air-conditioned vehicle to the Postharvest Physiology Lab.

Lettuce color and water content

Color of red and green lettuce were measured on the day of harvest and was determined based on four randomly selected plants per plot. The undamaged outermost leaf was chosen from each plant. Two measurements were taken on the left and right side of the midrib, 1 to 3 cm from the tip (Ilić et al., 2017). Color was measured using an A5 Chroma-Meter (Minolta CR-400; Minolta Co. Ltd., Osaka, Japan), calibrated with the Minolta calibration standard white reflector plate. L*, a*, and b* readings were recorded. Measurements were transformed to those of the L, a, b color space as described by Gude (2022) and reported as chroma, hue, and lightness. Water content (WC) of the lettuce leaves was determined by measuring the cumulative fresh leaf tissue (FW) and dry weight (DW) of four randomly selected plants per replication. Tissue was dried using an oven (Precision™, Thermo Fisher Scientific, Waltham, MA, USA) set at 60 °C. After 48 hours, the dry weight (DW) was measured (g). The water content was calculated by the equation $WC (\%) = [(FW - DW) / FW] \times 100$ (Batziakas et al., 2020; Agüero et al., 2008).

Statistical analysis

All data analyses were performed with SAS (SAS version 9.4, Cary, NC, USA). The PROC GLIMMIX model was used for all analyses. Yield parameters were determined on a per-plant basis for analysis and presentation of the data. Weekly yield data from the tomato trials were combined into early, middle, and late-season time periods in order to better understand the impact of mulch treatment on fruit yield. In 2023, HT early, middle, and late harvest seasons were 20 Jun - 18 Jul, 27 Jul - 29 Aug, and 5 Sep - 9 Oct, respectively. In 2024, HT early, middle, and late seasons were 25 Jun - 30 Jul, 6 Aug - 3 Sep, and 10 Sep - 9 Oct, respectively. In 2023, open field early, middle, and late seasons were 21 July – 10 Aug, 17 Aug – 31 Aug, and 7 Sep –

25 Sep, respectively. In 2024, open field early, middle, and late seasons were 23 July – 6 Aug, 14 Aug – 27 Aug, and 3 Sep – 12 Sep, respectively. For tomato yield, size distribution, and quality, the fixed effects included treatment, year, and a treatment x year interaction modeled with rep in the RANDOM statement. Fixed effects for tomato quality analysis included harvest, treatment, and treatment x harvest and were modeled with rep as the random effect. Open field size data were natural log-transformed to improve data normality. All data were back-transformed for presentation in the tables. For lettuce yield and quality, the fixed effect treatment was modeled with rep in the RANDOM statement. Tukey's HSD test was used for means separation for yield and quality data. For size data, mean separation was carried out by a significant difference test (LSD) at $P < .05$.

Results

In the HT tomato trials, the cumulative marketable and total fruit weight (kg/plant) for all of the treatments ranged from 5.8 to 7.7 and 7.6 to 9.9 kg/plant in 2023 and 2024, respectively. Out of 48 analyses of HT and open field tomato yield and size distribution, there were 38 occurrences where year had a significant effect and two significant year*treatment interactions ($P \leq 0.05$). There were no significant treatment effects observed for any of the parameters tested during the late season, except for the size distribution of the open field tomatoes in 2024.

Yield in the HT tomato trials

There were no significant treatment*year interactions for marketable and total fruit yield. Therefore, combined data from 2023 and 2024 are shown in Table 3.1. Out of twelve parameters measured, ten resulted in significant effects for year ($P \leq 0.0001$; Table 3.1). In the early season, mulch treatment had a significant effect on tomato marketable weight ($P \leq 0.01$; Table 3.1), marketable number ($P \leq 0.005$; Table 3.1), total weight ($P \leq 0.0001$; Table 3.1) and total number

($P \leq 0.0001$; Table 3.1). Significant effects were observed in the middle season for the total fruit weight ($P \leq 0.05$; Table 3.1) and number ($P \leq 0.05$; Table 3.1).

In the early season, the utilization of black tarp, white tarp, and plastic mulch increased marketable fruit weight and number compared to the bareground treatment up to 37% and 31%, respectively ($P < 0.05$; Table 3.1). Additionally, a higher total fruit weight and number were observed for plants mulched with black tarp, white tarp, and plastic mulch compared to those mulched with paper mulch and in the bareground plots ($P < 0.05$; Table 3.1). Compared to using no mulch, the white tarp increased total weight 49% and the plastic mulch increased total fruit number 44% (Table 3.1). However, during the middle season, the utilization of only the white tarp and black tarp increased crop productivity, and total fruit weight ranged from 3.1 to 3.5 kg/plant, compared to the paper mulch and bareground treatments, which ranged from 2.7 to 2.8 kg/plant. ($P < 0.05$; Table 3.1) Furthermore, a 25% increase in total fruit number was observed for plants grown with white tarp, compared to those grown with paper mulch or no mulch (23%) ($P < 0.05$; Table 3.1).

There were no treatment*year interactions observed for tomato size distribution of marketable fruit as indicated in Table 3.2. Yearly data were combined and there were no significant effects for mulch treatment (Table 3.2). However, the data is presented here to provide a descriptive summary of the abundance of different sized fruit that resulted from the trials.

Fruit quality in the HT tomato trials

Fruit were sampled during three harvests across the two years of the study. The probability values of the main effects of mulch type and harvest can be found in Table 3.3. There were no harvest*treatment interactions for any parameters and therefore the three harvests were combined to provide the main effects. With the exception of TA, there were highly significant

effects of harvest date for all quality criteria assessed ($P \leq 0.0001$; Table 3.3). However, there were no significant effects of mulch treatment.

Water content ranged from 90.1% for fruit grown with paper mulch to 91.4% for the black tarp and bareground treatments. Plants grown with no mulch had the lowest TA means, 0.36 % citric acid, while plastic had the highest, 0.41 % citric acid. SSC ranged from 5.30 °Brix to 5.62 °Brix for fruit grown in bare and white, respectively.

Yield in the HT lettuce trial

Red and green leaf lettuce marketable and total fresh weights (g) were analyzed independently, but similarly. There were no significant effects of mulch type on marketable or total yield of red or green lettuce (Table 3.4). However, both types of lettuce grown with black tarp and bareground treatments had the highest and lowest means, respectively, for marketable and total weight.

Crop quality in the HT lettuce trial

Table 3.5 presents the effects of mulch treatments on water content and color metrics for red and green loose-leaf lettuce harvested during the 2023 trial. There were no significant effects of mulch treatment in any of the criteria assessed. The water content was statistically similar between treatments. However, the means both for red and green lettuce grown with black tarp were 10% higher compared to lettuce grown in the bareground plots (Table 3.5). Mulch treatment had no effect on fruit color reported as chroma, hue, and lightness.

Yield in the open field tomato trials

The treatment*year interaction for total fruit weight in the late season was ($P=0.0315$) and data were therefore analyzed separately for 2023 and 2024. However, there were no significant treatment*year interactions for the other periods when the yield was analyzed. Therefore, the data from 2023 and 2024 were combined and presented in Table 3.6. Treatment

effects were observed for marketable number ($P \leq 0.01$; Table 3.6) and marketable weight ($P \leq 0.01$; Table 3.6) in the early and middle seasons, respectively. Significant treatment effects occurred for total weight during the early and middle seasons as well ($P \leq 0.001$; Table 3.6). However, treatments only had a significant effect on total fruit number in the early season ($P \leq 0.001$; Table 3.6).

In the early season, the white tarp treatment increased marketable fruit number compared to paper mulch and bareground treatments 26% and 28%, respectively ($P < 0.05$; Table 3.6). A significant increase for total fruit weight and total fruit number were observed for plants grown in plots with white tarp, compared to those grown with plastic mulch and bareground ($P < 0.05$; Table 3.6). Furthermore, plants grown in the bareground plots produced fruit with less total weight compared to those mulched with black tarp (36%), white tarp (47%), and fabric mulch (36%). ($P < 0.05$; Table 3.6). During the middle season, plants mulched with white tarp produced a higher marketable and total fruit weight, compared to plants grown with black tarp (31% and 28%) and fabric mulch (24% and 25%) ($P < 0.05$; Table 3.6).

Table 3.7 presents the effects of mulch treatments on tomato size distribution throughout 2023 and 2024. Large tomato in the late season was analyzed separately for 2023 and 2024 due to the presence of a significant treatment*year interaction, ($P = 0.0426$; Table 3.7). There were no treatment effects observed for the small and medium fruit sizes. In the early season, the utilization of white tarp produced up to 40% more extra-large fruits than plastic mulch, paper mulch, or the bareground treatments ($P < 0.05$; Table 3.7). During the middle season, the white tarp significantly increased the number of extra-large tomatoes, compared to plants grown with no mulch, black tarp, and fabric mulch treatments ($P < 0.05$; Table 3.7). However, in the late

season of 2024, plants grown with fabric mulch had significantly more large fruit, compared to the plants grown with bareground, black tarp, and plastic mulch treatments ($P < 0.05$; Table 3.7).

Discussion

The overarching objective of this report was to better understand the effects of various mulches on tomato and lettuce yield and quality. Tomato trials were conducted in the summer in the open field and HT, and lettuce trials during the fall in HT. By including multiple crops and production systems, this report also aimed to develop insight into the viability of utilizing silage tarps as mulch across cultivation systems and seasons. Previous studies have not investigated the use of silage tarp as mulch, though it has been well documented as a tool that small-scale growers can use to prepare soil prior to planting (Birthisel and Gallandt, 2019; Caldwell and Mohler, 2001; Lounsbury et al., 2020; Rylander et al., 2020). Unfortunately, we were only able to collect one year of yield data for lettuce, which makes it difficult to draw direct conclusions. Lettuce yield was not affected by the mulch treatments, and no significant differences were observed in quality for HT tomato or lettuce. For tomato, the large variation in yield across years was significant, but the lack of year*treatment interactions indicated that this variation had little effect on the impact of mulch type on yield. Within the growing season, the time period (early vs. middle vs. late) highly influenced the effect of various mulch types. Most of the significant treatment effects on yield were observed in the early period of the harvest season and out of 48 analyses, only (name the analysis here) was observed in the late season that had a significant effect. Mulches have been reported to increase root zone temperatures early in the growing season, leading to more plant growth and higher yield (Díaz-Pérez and Batal, 2002; Lamont, 1993). Early yields are important for growers who want to maximize season extension. Lengthening the season ultimately benefits the growers by allowing them to have produce at

market earlier, giving them a competitive market advantage (Blomgren and Frisch, 2007; Galinato and Miles, 2013; Hunter et al., 2012; Sydorovych et al., 2013; Waterer, 2003). This report coincides with Barnhart et al. (Ch. 2), which provides soil temperature, soil moisture, and soil health parameters. It should be noted that date ranges used for the analysis of middle and late seasons of soil temperature and moisture align closely with the early and middle harvest periods utilized for analysis of tomato yield.

Tomato Fruit Yield and Quality

Plastic Film Mulch

Polyethylene-based plastic mulch (PE mulch) is often used by growers to increase early yields as it has shown to warm soil temperature (Lamont, 2005). Annual marketable and total weights collected for tomato harvested from plants with plastic mulch in the HTs had greater overall yields than those reported in a previous study conducted at the same site with ‘BHN 589’ tomatoes and plastic mulch (Gude, 2022). Differences in yield could be attributed to the use of a different HT structure, longer growing season, and year to year variations in climate. In the early season of the HT trials, the application of plastic mulch increased total fruit number 21% compared to fabric mulch, likely due to increased soil temperatures (Seyfi and Rashidi, 2007; Ch. 2). In the open field trials, marketable and total yield for the plots with plastic mulch were statistically similar to bareground cultivation. However, other open field research with ‘San Marzano’ tomato in Italy reported that applying black plastic mulch resulted in a 25% increase in marketable weight compared to bareground (Di Mola et al., 2023). In late 2024, plants with plastic mulch produced 26% less large fruits than those with fabric mulch in the HT. However, the plants in open field plots with plastic mulch produced similar-sized fruit compared to those planted without mulch. This is contrary to other open field study findings, which reveal that fruit

diameter was increased by the use of plastic mulch compared to bareground (Tesfaye et al., 2016). However, Di Mola et al. (2023) reported there was no difference in average fruit weight produced by plants across the two treatments.

Woven Fabric Mulch

Polypropylene woven fabric is frequently used to prevent weed growth (George et al., 2015) and results in less waste than plastic film-based mulches as it can be re-used. Polypropylene fabric is also permeable to water and allows air movement, while being 99.8% opaque (Martin et al., 1991; Reece et al., 1997). In this study, tomato yield in the HT trials were very similar to results reported by a study conducted on the same site using ‘BHN 589’ tomatoes and fabric mulch (Meyer, 2016). Because fabric is the predominant mulch utilized by HT growers (Meyer, 2016), it can be referred to as a positive control in that system (Meyer, 2016). In the HT trials, plants mulched with fabric performed comparably to all other treatments for all parameters, except for one. There was a decrease in total fruit number during the early season compared to those grown with black tarp and plastic mulch. In the early season of the open field trials, the use of fabric mulch appeared to increase total weight compared to the bareground treatments. However, in the middle season, the fabric-mulched plants produced similar yields to all other treatments, except white tarp. In the open field, tomato plants mulched with fabric produced similar amounts of extra-large large tomatoes in the middle season compared to those with black tarp, plastic mulch, and no mulch, but produced less than plots with white tarp and paper mulch. In the late period of the 2024 harvest season, the utilization of fabric mulch increased the amount of large tomatoes compared to the plastic, black, and bare tarps, and it performed similar to white, and paper treatments.

Paper Mulch

Paper mulch is often promoted as an alternative to plastic mulches due to the environmental impact of the latter (Merfield, 2002; Salokangas, 1973). Paper mulch may be particularly useful in HT conditions, where rain is excluded (Miles et al., 2012). The plants mulched with paper had similar total and marketable yield compared to the fabric mulch, and they had 26% more extra-large tomatoes in the middle period of the open field trials compared to those with fabric mulch. This could be attributed to the lighter color of mulch and/or moderation of high soil temperature during peak summer heat (Nair, 2013), which were observed in the present study (Ch. 2). There are varying reports on the effects of paper mulch on yield. One HT study indicates that the use of paper mulch decreased tomato yields compared to the use of black plastic film mulch and no mulch (Martin, 2013). The yields for plants grown with paper mulch were generally lower than those reported in this study. However, a study conducted in Washington indicated that using WeedGuardPlus for HT tomato cultivation increased marketable yield 14% compared to polyethylene mulch, but did not increase total yield (Cowan et al., 2013). In the open field trials, the paper mulch performed poorly and was subject to severe degradation and wind damage. In fact, the results of our study for this treatment in the open field were similar to the bareground across all parameters.

Black Silage Tarp Mulch

Silage tarps are much thicker than plastic mulch (5-10 mil), allowing for their reuse, while having low water and air permeability. While it is unknown how silage tarp may affect tomato and lettuce yields, it has been shown to increase soil temperatures similar to plastic film mulch (Rylander et al., 2020). In our trials, we found that the use of black silage tarp as a mulch affected soil temperature comparably to plastic film mulch (Barnhart et al., Ch 2). Similar to the

plastic film mulch, the black tarp had differing effects on HT and open field tomato yield parameters when compared to fabric mulch. Yields for this treatment were similar to those observed in the black plastic mulch treatment plots and those reported by Rogers and Wszelaski (2012), who conducted an organic experiment with ‘BHN 589’ tomatoes in Tennessee using black plastic mulch. In the Tennessee study, there were no observed differences between the HT and open field. However, in this study, HT yield for plants mulched with black silage tarp increased total fruit number by 20% in the early season compared to those with fabric mulch. In the open field, marketable and total yield were similar for plants grown in plots with black tarp fabric mulch, and plastic mulch. Interestingly, average soil temperatures observed in all three of these treatments in the open field were similar (Ch. 2).

White Silage Tarp Mulch

In the HT trials, plants mulched with white tarp and fabric mulch had comparable results for all yield parameters. There are no reports on the effects of using white silage tarp as mulch that we are aware of. However, white plastic film mulch can be used to limit soil warming, as it conducts only 1% of radiation into the soil (Tarara, 2000). Differences in root zone temperature or light reflectivity could be explanations for the difference in yield between the white silage tarp and fabric mulch in the middle season (Barnhart et al., Ch. 2; Nair et al., 2013). The average temperature in soil under fabric mulch was 2.6°C warmer than under the white tarp. Yields of the tomatoes planted with white tarp were greater in this study than those previously reported from a HT trial in Georgia using ‘Red Snapper’ tomato and white polyethylene film mulch, (Diaz-Perez et al., 2024).

In the middle season of the open field trials, marketable and total weights were 32% to 33% greater and there were 29% more extra-large tomatoes compared to the fabric mulch. In the

HT trials, no significant differences were observed for tomato size distribution across treatments. This result was similar to the findings of Martin (2013), where the average marketable weight per fruit (kg) was similar for paper mulch, black mulch, and bareground treatment for HT tomatoes grown in Tennessee. It is not clear why there were significant effects found in the open field trials, whereas no differences were seen in the HTs. One possible explanation could be that higher levels of solar radiation expected in the open field, where the average DLI was 40 between May and September, in comparison with 27 in the HTs. This may have led to a greater physiological impact from light or dark-colored mulch (Ch. 2).

Effects on Tomato Quality

Tomatoes from the HT trials were sampled three times across the two growing seasons and analyzed for quality. Mulch type did not appear to have a significant effect on the texture or organoleptic qualities of HT tomato. In fact, in our study the specific harvest date had a significant effect indicating that the environment and/or crop stage was more important for driving effects on fruit quality. It is important to note that this was not the primary focus of this study and further investigations would benefit from increased sampling. In this study, the water content of ‘BHN 589’ tomato ranged from 90.0% to 91.9%, and firmness ranged from 11.8 N to 12.7 N. This is significantly lower than previously reported by Lang et al. (2020), who reported a range of 26.5 N to 29.4 N (2.3 to 3 kgf) for non-grafted ‘BHN 589.’ Titratable acidity ranged from 0.36 to 0.41 (% citric acid) and soluble sugar content ranged from 5.30-5.62, similar to Lang et al. (2020). Tomato fruit texture is the second most important fruit trait for affecting consumer acceptance and sensory perception, second to organoleptic quality, and varies depending on postharvest handling, growing environment and plant genotype (Causse et al., 2003; Cause et al., 2010; Aurnd et al., 2012). Water content determines fruit firmness and taste

by increasing cell turgor and increasing solute dispersal, as sugars comprise most soluble solids in tomatoes (Hou et al., 2019; Guichard et al., 2001; Bertin and Génard, 2018). Organoleptic qualities are greatly influenced by the growing environment (Panthee et al., 2012). Overall, this study indicates that tomato texture and taste were not significantly impacted by the utilization of different mulch types. However, this study would likely benefit from more sampling points to determine the relationship between increases in yield and fruit quality, as it may correlate with differences in texture and organoleptic quality (Bertin et al., 2000; Fanasca et al., 2007).

Lettuce Yield and Quality

Lettuce crop productivity was statistically similar across all of the mulch types that we tested (bareground, fabric, white tarp, black tarp). Total weight per plant (g) ranged from 31.4 to 47.9 for red and 28.5 to 45.5 for green, comparable to results from Gude (2022), who previously utilized plastic mulch in the same HTs. Both types of lettuce grown with black tarp had the highest mean marketable and total weight and the bareground treatments had the lowest means. An open field study conducted in New England found that the use of black and white polyethylene film mulch increased the yield of crisphead lettuce compared to bareground (Gheshm and Brown, 2020). White plastic mulch is often recommended for growing heat-sensitive crops (Snyder et al., 2015; Vargas et al., 2018). Because only one year of yield data was collected, more information is needed before drawing direct conclusions. However, in both years of this study, soil temperatures observed were the greatest under the black tarp, similar beneath the fabric mulch, white tarp, and bareground treatments in the late season, and the lowest in the bareground treatment during the early season (Ch.2). Previous HT research has indicated that romaine lettuce yield can be significantly increased in spring and fall with higher soil temperatures (Bumgarner et al., 2011). Further studies that investigate the dynamics of mulch

effects in spring vs fall-planted lettuce as their impact could have variable effects on productivity. Previous work indicates that some environmental factors have a greater effect on lettuce yield in spring than fall and that solar radiation is highly variable across the growing seasons (Gude, 2022). Furthermore, average DLI during the lettuce trial was 16.1 in 2023, which was lower than previously described in the summer trials (Ch. 2).

Lettuce Quality

Quality is an important aspect for growers, particularly those catering to local markets and/or utilizing HT systems. In this study, there were no effects of mulch type on any of the quality parameters that were tested. Lettuce has high water content, approximately 95% (Kim et al., 2016). The results of this study were significantly lower, ranging from 69.9%-70.9%. However, water content was similar across all treatments after drying for 48 hours. The color of loose-leaf lettuce is an important factor that determines consumer acceptability (Gazula et al., 2007). Light intensity and temperature can influence the accumulation of secondary metabolites, which contribute to more vibrant colors (Landi et al., 2020). Our data indicate that in fall, mulch type does not significantly affect lettuce color reported as lightness, hue angle, and chroma. For both lettuce types, chroma was similar to values previously reported by Gude (2022) although hue angle for red lettuce was higher (less red) in this study.

Viability of Silage Tarps as Mulch

Growers have ready access to silage tarps and may be interested in their use as mulch in high tunnel and open field production systems. Silage tarps are impermeable to water and air (Borreani et al., 2014), which could be beneficial for conserving soil moisture, but detrimental to crop growth. In our trials, both tarp treatments affected soil moisture (% volumetric) during the middle and late periods during the HT tomato experiment, although they had differing effects on

soil temperature early in the season (Ch. 2). With regards to yield, the results from this report also indicate that silage tarp is a viable mulch material for the cultivation of tomato and lettuce in the Central US. None of our results indicated that crop productivity was negatively affected with the use of silage tarps as mulch. However, tomato was observed to benefit more significantly from the silage tarp treatments than lettuce. It is not clear why the differences were more pronounced with tomato since lettuce productivity can be affected by mulch type (Gheshm and Brown, 2020; Snyder et al., 2015; Vargas et al., 2018). In our trials, the average growing season duration for tomato was 158 days, compared to 42 days for lettuce, and involved much warmer temperatures (Ch. 2). Monthly temperature averages during the tomato trials ranged from 17.5°C to 26.6°C, and ranged from 10.2°C to 26.7°C in the lettuce trials (Barnhart et al., Ch. 2). It is important to note that there was only one year of yield data for lettuce.

In the HT tomato trials, silage tarp proved to be a viable mulch type as it did not negatively affect fruit yield compared to common mulching practices (Lamont, 2009; Meyer, 2016). In fact, this material affected yield similar to, and in one instance, more positively than the fabric mulch and plastic film mulch, which are frequently utilized in tomato cultivation (Lamont, 2009; Meyer, 2016). Furthermore, this study indicated that the use of silage tarps as mulch had no negative effects on fruit quality. In general, early and middle season fruit yield increased with the utilization of silage tarp compared to bareground. The black silage tarp had similar effects on all yield parameters as the plastic film mulch and increased early season total fruit number per plant 20% compared to the fabric mulch. Overall, the white tarp also had similar effects on yield as the black tarp, fabric mulch, and plastic film mulch treatments. The black tarp warmed the soil similar to plastic film mulch, whereas significantly cooler temperatures were observed under the white tarp (Ch. 2). Additionally, both tarp treatments increased soil moisture

(% volumetric) compared to the fabric mulch, paper mulch, and bareground treatments during the middle and late seasons, similar to the plastic mulch film.

Polyethylene film is the most prevalent mulch type for open field tomato production in the US. Large scale application of silage tarps would likely be difficult but may be practical for small-scale and/or urban farming production systems. Overall, yield data from the open field suggests that silage tarp can also be used in this production system, as neither tarp color had negative effects on yield compared to plastic film mulch. This study shows that the utilization of black tarp affected all parameters of yield similar to fabric mulch and plastic film mulch. Interestingly, in the open field tomato trials, plants mulched with white tarp appeared to perform similar to, or better than those with black tarp, fabric mulch, and plastic film. It should be reiterated that plants mulched with white tarp yielded 45% and 40% greater marketable and total weight, respectively, compared to the black tarp during the middle period of the harvest season. Similarly, the black tarp mulch increased yields 24% to 25% compared to the fabric mulch. Furthermore, early season total weight and fruit number per plant observed for plants in these treatment plots was 22% and 23% greater than plastic film mulch. These observations coincide with average soil temperatures under the black tarp being similar to those observed under the plastic film mulch throughout the season. In contrast, soil temperatures under the white tarp were significantly lower, and similar to the bareground treatment. Soil moisture was less affected by mulch type in the open field, but in the late 2024 season soil moisture was more effectively retained by the application of black tarp than all other treatments except for plastic film mulch (Ch. 2). These findings suggest that the application of silage tarps may provide different yield effects depending on color (white vs black) and production system.

In the case of lettuce, our results did not provide clear guidance on a mulching strategy for growers in regards to using silage tarp. Neither black nor white silage tarp appeared to harm lettuce yield, as it was comparable to yields observed with fabric mulch and bareground. This suggests that silage tarps may be a viable mulching strategy for cool-season crops. Furthermore, mulching with silage tarps did not diminish the quality of the lettuce. As described, the lettuce trials occurred during a shorter, cooler season, where effects on soil moisture and temperature were not as extreme as those observed during the summer production. However, silage tarps did affect soil temperature and moisture in the fall trials (Ch 2). The use of black tarp significantly increased overall soil temperature compared to the other treatments, though not detrimentally, as is a concern with cool-season crops (Levine et al., 2023). In contrast, white tarp performed similar to the fabric mulch in retaining soil heat during the early part of the fall season (Barnhart ch. 2). Both tarps conserved soil moisture similarly to the fabric mulch, and more so than the bareground treatment, suggesting that this material can promote soil moisture retention, without oversaturating the soil (Ch. 2). Although it is outside the scope of this report, we observed issues in the field with rodents causing crop damage in the silage tarp plots. This issue was not a problem for tomato, but was particularly severe for lettuce. Lettuce transplants were regularly eaten by voles (*Microtus* spp.) in these plots in 2022, requiring regular replacement. In 2023, we found that eliminating large, contiguous spans of tarp prevented damage and a bareground “break” between the plots was useful. Growers that are raising crops that are particularly subject to rodent damage should be cautious when implementing silage tarps as mulch.

Conclusion

Maintaining soil health is a critical component to effectively manage any crop production system. Mulches can be a valuable strategy for maintaining soil health. In this report,

we investigated the impact of various mulches on the yield and quality of tomato and lettuce in high tunnels and the open field. Furthermore, we investigated the utilization of silage tarps as a potential method to conserve soil moisture while promoting high productivity. In specialty crop production, silage tarps had primarily been studied in their capacity to prepare soil prior to cultivation. To our knowledge, this is the first report that addresses yield when tarps are used as mulch and our data indicate that silage tarps can also be used as mulch in vegetable production. However, their benefit is most pronounced for summer crops like tomato. Furthermore, tarp color may affect yield differently in HTs versus the open field. Frequently, silage tarps performed similarly to plastic mulch film and may serve as a reusable alternative to this material. It is not clear what the lifespan of silage tarps would be when utilized in this way and there is a critical need for more economic data surrounding this topic. Plastic films are very inexpensive, but hold significant machinery and disposal costs (and access), whereas tarps are more expensive, can be installed by hand, but may be reusable for multiple seasons. In contrast, fabric mulch also requires no machinery and is reusable, but is more expensive than tarps. Although we saw significant differences in this study, the plastic film, fabric, and silage tarps all provided fairly similar results when it came to yield and/or crop productivity. As growers continue to adapt to a changing climate and consumer needs, steps to ensure long-term sustainability will be critical to their success. Ultimately, better understanding how specific mulches effect crop yields and quality, and how that translates to a grower's bottom line will likely determine their adoption.

Tables

Table 3.1 Marketable and total yield of ‘BHN 589’ tomato grown HTs in Olathe, KS in 2023 and 2024

Treatment ^y	Marketable Yield ^w						Total Yield					
	Weight (kg/plant)			No./plant			Weight (kg/plant)			No./plant		
	Early ^x	Middle	Late	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late
Bare ^z	1.18 b	2.25	2.86	6.0 b	13.6	18.1	1.74 b	2.76 b	3.66	10.3 c	17.5 b	25.3
Black	1.80 a	2.41	2.70	8.6 a	14.4	17.6	2.57 a	3.06 a	3.48	14.7 a	19.7 ab	24.9
White	1.87 a	2.86	2.93	8.3 a	16.3	19.2	2.60 a	3.54 a	3.76	13.5 ab	21.5 a	26.7
Fabric	1.67 ab	2.38	2.43	7.8 ab	14.0	16.2	2.21 ab	2.93 ab	3.23	11.7 bc	18.4 ab	23.3
Paper	1.48 ab	2.11	2.17	7.0 ab	12.8	13.7	2.00 b	2.71 b	2.90	11.0 c	17.2 b	20.0
Plastic	1.86 a	2.24	2.60	8.7 a	12.9	16.5	2.57 a	4.0 ab	3.29	14.8 a	10.1 ab	23.3
Year ^v	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0001	ns	<.0001	ns

Treatment	0.0086	ns	ns	0.0017	ns	ns	<.0001	0.0175	ns	<.0001	0.0206	ns
Treatment x Year	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^xEach year was analyzed by early (20 Jun - 18 Jul; 25 Jun - 30 Jul), middle (27 Jul - 29 Aug; 6 Aug - 3 Sep), and late (5 Sep - 9 Oct; 10 Sep - 9 Oct) seasons in 2023 and 2024, respectively.

^wFruit with any visible color were harvested weekly in 2023 and 2024 and graded as marketable based on the absence of large cracks, pest damage, rot, and blossom end rot. Values are presented on a per plant basis.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the yield parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey’s HSD.

Table 3.2 Tomato size distribution of marketable fruit harvest from 'BHN 589' tomato grown in HTs in Olathe, KS in 2023 and 2024.

Treatment ^y	Small (No./plant) ^w			Med. (No./plant)			Large (No./plant)			Extra-Large (No./plant)		
	Early ^x	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Bare ^z	0.14	0.76	1.50	0.83	3.33	5.40	1.99	5.99	6.36	3.00	3.54	4.85
Black	0.25	0.83	1.71	0.82	3.68	5.32	3.35	6.25	6.64	4.17	3.62	3.96
White	0.15	0.57	2.07	0.58	3.67	5.74	2.75	6.82	6.61	4.81	5.29	4.76
Fabric	0.17	0.74	1.64	0.54	3.12	5.00	2.72	5.94	5.39	4.35	4.20	4.15
Paper	0.33	1.08	0.85	0.71	3.18	4.15	2.51	5.17	5.06	3.49	3.36	3.60
Plastic	0.19	0.78	1.33	0.74	3.06	5.00	2.82	5.57	5.47	4.97	3.54	4.67
Year ^v	ns	0.0006	<.0001	ns	<.0001	ns	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Treatment	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatment x Year	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^x Each year was analyzed by early (20 Jun - 18 Jul; 25 Jun - 30 Jul), middle (27 Jul - 29 Aug; 6 Aug - 3 Sep), and late (5 Sep - 9 Oct; 10 Sep - 9 Oct) seasons in 2023 and 2024, respectively.

^wFruit size class harvested weekly during 2023 and 2024 seasons presented as number per plant.

^vThe generalized linear mixed model was used to test which coverings had a significant effect on the yield parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to LSD paired comparisons where $\alpha = 0.05$.

Table 3.3 Fruit quality of ‘BHN 589’ tomato fruit grown in HTs in 2023 and 2024.

Treatment ^y	Water (%)	Chroma	Hue	Lightness	TA	SSC	Firmness (N)
Bare ^z	91.4 ^x	40.1	49.5	44.6	0.36	5.30	11.8

Black	91.4	39.6	49.2	44.2	0.40	5.44	12.5
White	90.9	39.7	49.2	44.5	0.39	5.62	12.7
Fabric	91.2	39.2	49.4	44.3	0.37	5.41	12.2
Paper	90.9	39.9	49.4	44.6	0.38	5.54	11.8
Plastic	91.3	39.7	50.0	44.8	0.41	5.33	12.4
Harvest ^w	<.0001	<.0001	<.0001	<.0001	0.0883	<.0001	<.0001
Treatment	ns	ns	ns	ns	ns	ns	ns
Harvest x treatment	ns	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical HTs (1/2 rep per tunnel). In each treatment plot, 12 plants were planted (6 per row) 18" apart in 2023 and 2024. Planting dates were 26 Apr 2023 and 26 Apr 2024. The six rows were planted on the north side of each HT in 2023 and on the south side in 2024.

^xValues represent the LSMEANS of six fruit per replication harvested at the red ripeness stage from two harvests in 2023 and one harvest in 2024.

^wThe generalized linear mixed model was used to test which coverings had a significant effect on the yield parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey's HSD.

Table 3.4 Yield of green and red loose leaf lettuce grown in HTs in Olathe, KS in 2023.

Treatment ^y	Marketable Yield (g/plant)		Total Yield (g/plant)	
	Red	Green	Red	Green
Bare ^z	29.06 ^x	22.82	31.04	28.49
Black	46.64	40.68	47.91	45.50
White	31.04	26.22	33.17	33.03
Fabric	32.46	30.05	36.15	40.26
<i>P</i> -value ^w	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, and fabric mulch. Each treatment was 3.66 m x 4.57 m.

^yExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 27 Sep 2023.

^xValues represent the LSMEANS of fruit harvested at the termination of the 2023 season. Eight lettuce heads per replication were harvested from the base of the plant and weighed. Values are presented on a per plant basis.

^wThe generalized linear mixed model was used to test which coverings had a significant effect on the yield parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey's HSD.

Table 3.5 Quality of red and green loose leaf lettuce grown in HTs in 2023.

Treatment ^y	Red				Green			
	Water (%)	Chroma	Hue	Lightness	Water (%)	Chroma	Hue	Lightness
Bare ^z	69.9 ^x	13.5	49.4	32.7	66.7	37.2	118.9	51.9
Black	79.9	14.4	54.4	29.7	77.0	34.7	120.8	50.1
White	73.9	14.5	54.5	30.9	69.7	30.9	103.4	45.8
Fabric	70.9	14.7	55.6	29.6	72.8	35.6	119.6	49.6
<i>P</i> -value ^w	ns	ns	ns	ns	ns	ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, and fabric mulch. Each treatment was 3.66 m x 4.57 m.

^yExperiment was arranged in a split-plot RCBD with four blocks across two identical HTs (2 reps per tunnel). Sixteen lettuce plants were transplanted in a staggered double row within each subplot bed (26.7 cm between plant, 26.7 cm between rows) on 27 Sep 2023.

^xValues represent the LSMEANS of green and red loose leaf lettuce harvested at the end of the 2023 fall season. Color was measured on the day of harvest and was determined based on four randomly selected plants per replication. An undamaged outermost leaf was chosen from each plant and two measurements were taken on the left and right side of the midrib, 1 to 3 cm from the tip.

^wProbability value for the overall ANOVA F-test using Type III hypothesis test where $\alpha = 0.05$.

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey's HSD.

Table 3.6 Marketable and total yield of 'BHN 589' tomato grown in an open field in Olathe, KS in 2023 and 2024.

Treatment ^y	Marketable Yield ^w						Total Yield						
	Weight (kg/plant)			No./plant			Weight (kg/plant)				No./plant		
	Early ^x	Middle	Late	Early	Middle	Late	Early	Middle	Late ^y 2023	Late 2024	Early	Middle	Late
Bare ^z	1.73 ^y	2.23 ab	0.83	6.8 b	12.4	6.1	2.08 c	2.53 ab	1.39	0.91	8.3 c	14.1	9.0
Black	2.32	1.93 b	1.18	8.4 ab	10.4	7.6	2.82 ab	2.25 b	2.34	0.74	10.8 ab	12.4	11.2
White	2.35	2.79 a	1.08	8.7 a	13.0	7.7	3.05 a	3.14 a	1.77	0.99	12.0 a	14.9	10.7
Fabric	2.29	2.12 b	1.36	8.1 ab	10.6	9.2	2.83 ab	2.36 b	2.07	1.41	10.3 abc	12.0	13.0

Paper	1.89	2.47 ab	1.07	6.9 b	12.7	7.3	2.57 abc	2.80 ab	1.77	0.97	9.9 abc	14.7	10.6
Plastic	1.89	2.23 ab	1.17	7.0 ab	11.1	7.7	2.39 bc	2.48 ab	2.20	0.70	9.3 bc	12.8	10.6
Year ^u	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001			<.0001	<.0001	<.0001
Treatment	ns	0.0059	ns	0.0064	ns	ns	0.0015	0.0086	ns	ns	0.0005	ns	ns
Treatment x Year	ns	ns	ns	ns	ns	ns	ns	ns			ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. Planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^xEach year was split into early (21 July – 10 Aug; 23 July – 6 Aug), middle (17 Aug – 31 Aug; 14 Aug – 27 Aug), and late (7 Sep – 25 Sep; 3 Sep – 12 Sep) seasons in 2023 and 2024, respectively.

^wFruit with any visible color were harvested weekly in 2023 and 2024 and graded as marketable based on the absence of large cracks, pest damage, rot, and blossom end rot. Values are presented on a per plant basis.

^vTotal weight (kg/plant) is presented separately for Late 2023 and Late 2024 due to the presence of a significant treatment*year interaction.

^uThe generalized linear mixed model was used to test which coverings had a significant effect on the yield parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to Tukey’s HSD.

Table 3.7 Tomato size distribution of marketable fruit harvest of 'BHN 589' tomato grown in an open field in Olathe, KS in 2023 and 2024.

Treatment ^y	Small (No./plant) ^w			Med. (No./plant)			Large (No./plant)			Extra-Large (No./plant)			
	Early ^x	Middle	Late	Early	Middle	Late	Early	Middle	Late ^v 2023	Late 2024	Early	Middle	Late
Bare ^z	0.03	0.24	0.28	0.17	2.15	1.66	3.28	4.57	2.47	0.91 bcd	3.28 b	4.54 bc	0.95
Black	0.02	0.27	0.38	0.37	2.08	2.15	4.39	4.00	3.12	0.79 dc	4.39 ab	4.00 c	1.12
White	0.05	0.36	0.26	0.53	2.33	2.08	5.44	4.76	3.26	1.34 abc	5.44 a	6.10 a	1.58
Fabric	0.02	0.22	0.38	0.16	1.83	2.47	4.21	3.85	3.58	1.68 a	4.21 ab	4.34 c	1.99
Paper	0.03	0.37	0.13	0.30	2.32	1.95	3.48	4.49	2.78	1.38 ab	3.48 b	5.87 ab	1.25
Plastic	0.07	0.15	0.27	0.21	2.06	2.00	3.30	4.13	3.96	0.76 d	3.30 b	4.71 abc	1.00

Year ^u	ns	ns	<.0001	0.0053	ns	<.0001	<.0001	<.0001			<.0001	<.0001	<.0001
Treatment	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.0325	0.0182	0.0290	ns
Treatment x Year	ns	ns	ns	ns	ns	ns	ns	ns			ns	ns	ns

^zTreatments included bare ground, black tarp, white tarp, fabric mulch, paper mulch, and plastic mulch. Each treatment was 1.22 m x 3.05 m.

^yExperiment was arranged in a RCBD with each of the three blocks across two of six identical open field plots (1/2 rep per plot). In each treatment plot, 12 plants were planted (6 per row) 18” apart in 2023 and 2024. The planting dates were 18 May 2023 and 23 May 2024. The six rows were planted on the north side of each open field plot in 2023 and on the south side in 2024.

^x Each year was split into early (21 July – 10 Aug; 23 July – 6 Aug), middle (17 Aug – 31 Aug; 14 Aug – 27 Aug), and late (7 Sep – 25 Sep; 3 Sep – 12 Sep) seasons in 2023 and 2024, respectively.

^wFruit size class harvested weekly during 2023 and 2024 seasons presented as number per plant.

^vTotal weight (kg/plant) is presented separately for Late 2023 and Late 2024 due to the presence of a significant treatment*year interaction.

^uThe generalized linear mixed model was used to test which coverings had a significant effect on the yield parameters ($P \leq 0.05$).

Means differentiated by letter are significantly different ($P < 0.05$) according to LSD paired comparisons where $\alpha = 0.05$.

Table 3.8 Effects of year and mulch type for high tunnel tomato, high tunnel lettuce, and open field tomato trials in Olathe, KS.

Trial	Parameter	<i>P</i> values		
		Year	Treatment	Year*treatment
HT tomato	Early marketable yield (weight)	<.0001	0.0086	0.3581
	Middle marketable yield (weight)	<.0001	0.0763	0.5381
	Late marketable yield (weight)	<.0001	0.1620	0.3164
	Early marketable yield (no./plant)	<.0001	0.0017	0.0890
	Middle marketable yield (no./plant)	<.0001	0.1743	0.3978
	Late marketable yield (no./plant)	<.0001	0.2112	0.6041
	Early total yield (weight)	<.0001	<.0001	0.3003
	Middle total yield (weight)	<.0001	0.0175	0.5390
	Late total yield (weight)	0.0001	0.1387	0.4226
	Early total yield (no./plant)	0.6075	<.0001	0.6403
	Middle total yield no./plant)	<.0001	0.0206	0.2785
	Late total yield (no./plant)	0.1209	0.1523	0.8222
	Early small (no./plant)	0.8475	0.6609	0.3007
	Middle small (no./plant)	0.0006	0.6887	0.4361
	Late small (no./plant)	<.0001	0.6032	0.6202
	Early medium (no./plant)	0.456	0.5651	0.7633
	Middle medium (no./plant)	<.0001	0.8106	0.4621
	Late medium (no./plant)	0.0513	0.5233	0.8523
	Early large (no./plant)	<.0001	0.0911	0.1787
	Middle large (no./plant)	<.0001	0.2318	0.3923

HT lettuce	Late large (no./plant)	<.0001	0.3345	0.6119
	Early extra-large (no./plant)	<.0001	0.0908	0.7782
	Middle extra-large (no./plant)	<.0001	0.0617	0.8290
	Late extra-large (no./plant)	<.0001	0.3847	0.2276
	*Water content	<.0001	0.7430	0.8078
	*Chroma	<.0001	0.6432	0.7781
	*Hue	<.0001	0.7865	0.3143
	*Lightness	<.0001	0.6132	0.5490
	*TA	0.0883	0.9582	0.8137
	*SSC	<.0001	0.1963	0.4013
	*Firmness	<.0001	0.4384	0.3265
	Red marketable yield (g/plant)		0.1061	
	Green marketable yield (g/plant)		0.0569	
	Red total yield (g/plant)		0.1336	
	Green total yield (g/plant)		0.0706	
	Red water content		0.0996	
	Red chroma		0.3008	
	Red hue		0.8277	
	Red lightness		0.4473	
	Green water content		0.3603	
Open field tomato	Green chroma		0.4891	
	Green hue		0.4092	
	Green lightness		0.4045	
	Early marketable yield (weight)	<.0001	0.0134	0.1046
	Middle marketable yield (weight)	<.0001	0.0059	0.6091
	Late marketable yield (weight)	<.0001	0.1174	0.0750
	Early marketable yield (no./plant)	<.0001	0.0064	0.0525
	Middle marketable yield (no./plant)	<.0001	0.0526	0.4226
	Late marketable yield (no./plant)	<.0001	0.0826	0.1028
	Early total yield (weight)	<.0001	0.0015	0.2659
	Middle total yield (weight)	<.0001	0.0086	0.6239
	Late 2023 total yield (weight)		0.1036	
	Late 2024 total yield (weight)		0.0647	
	Early total yield (no./plant)	<.0001	0.0005	0.4400
	Middle total yield no./plant)	<.0001	0.0456	0.3022
	Late total yield (no./plant)	<.0001	0.0639	0.0752
	Early small (no./plant)			
	Middle small (no./plant)			
	Late small (no./plant)	<.0001	0.6245	0.5182
	Early medium (no./plant)	0.0053		
	Middle medium (no./plant)			

Late medium (no./plant)	<.0001	0.3566	0.4490
Early large (no./plant)	<.0001		
Middle large (no./plant)	<.0001		
Late 2023 large (no./plant)		0.6750	
Late 2024 large (no./plant)		0.0325	
Early extra-large (no./plant)	<.0001	0.0182	
Middle extra-large (no./plant)	<.0001	0.0290	
Late extra-large (no./plant)	<.0001		

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