UTILIZING LOW-TECH PORTABLE CATERPILLAR TUNNELS TO INCREASE PRODUCTIVITY OF WARM-SEASON VEGETABLES AND SMALL FRUITS

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

High tunnels and greenhouses effectively extend the growing season and protect crops from adverse environmental conditions. However, production in the less expensive and portable caterpillar tunnel has not been reported. The research aimed to evaluate the phenology, yield and quality of eight paste tomato, eight bell pepper, and two cold-hardy wine grapes grown in the caterpillar tunnel compared to the open field. In 2022, tomato and bell pepper cultivars were severely affected by tomato spotted wilt virus. Caterpillar tunnels extended the growing season and accelerated the key phenological stages of all three species. The tunnel increased the yield and quality of tomato and bell pepper. Impacts on wine grape yield across production systems were inconsistent, however the caterpillar tunnel showed potential for improving grape quality. ‘Marquette’ showed greater winter hardiness in the tunnel, while ‘Petite Pearl’ showed reduced winter hardiness in the caterpillar tunnel compared to open field production system.

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DEDICATION

To my parents Tika Datta Ghimire and Saradha Ghimire, brother Bipin Ghimire, sisters Sangita Ghimire and Suchita Ghimire for all the support, love, and faith.

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LIST OF ABBREVIATIONS

BER .... Blossom End Rot

CSA .... Community Sustainable Agriculture

CT .... Caterpillar Tunnel

GDD .... Growing Degree Days

HT .... High Tunnel

IPM .... Integrated Pest Management

Kmph .... Kilometer Per Hour

Mg .... Megagram

mm .... Millimeter

NDAES .... North Dakota Agricultural Experiment Station

NDAWN .... North Dakota Agricultural Weather Network

NDSU .... North Dakota State University

NOAA .... National Oceanic and Atmospheric Administration

ppm .... Parts Per Million

RH .... Relative Humidity

TA .... Titratable Acidity

TSS .... Total Soluble Solid

TSWV .... Tomato Spotted Wilt Virus

USDA .... United States Department of Agriculture

VWC .... Volumetric Water Content

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CHAPTER 1

Introduction

Since 2000, global fruit and vegetable production has been increasing rapidly with a total production volume of approximately 910 million Mg and 1.2 billion Mg, respectively, in 2021 (FAO, 2022). This accounts for 63% and 71% of the growth of fruit and vegetable production from 2000 to 2021. Globally, the Midwestern US is recognized for its field crop production; this region also holds potential for high-value specialty crop production (Kistner et al., 2018). However, high-value crops' production and quality are limited by natural stressors such as sudden fluctuations in temperature and precipitation, heavy winds, frosts and extreme cold. In addition to these constraints, a short growing season is another concern for growers (Aipperspach et al., 2020; Rana, 2021; Splichal, 2020).

Historically, commercial fruit and vegetable growers in the northern region have used environmental modification techniques to extend the growing seasons and improve plant growth and performance (Aipperspach et al., 2020; Rowley et al., 2011; Waterer, 2003; Wien, 2009). Additionally, high-value crops are more sensitive to unfavorable conditions and require more precise management. Therefore, implementation of various scientific practices plays a vital role in successful production of specialty crops in the Upper Midwest regions.

Among the various strategies, protected agriculture is one of the most important management strategies to modify the growing environment (Lang et al., 2020). Different forms of protected agriculture strategies encompass greenhouses, high tunnels (HTs), caterpillar tunnels (CTs), low tunnels, row covers, frost blankets, mulches, and soil heating cables.

Caterpillar tunnels and HTs are both used primarily to minimize environmental impacts on crop production by improving the microclimate throughout the growing season; protecting the crops from natural events such as heavy wind, hail, and sudden rainfall; improving disease and pest management and thus improving the quantity and quality of the final produce (Borrelli et al., 2013). On average, North Dakota has a frost-free period of approximately 130 days (Aipperspach et al., 2020; Borrelli et al., 2013; Rana, 2021). The short growing season and climatic constraints pose a threat to field production of high-value crops in North Dakota; specifically, much of the potential fall harvest of fruits and vegetable remains unharvested or harvested with poor quality, and some perennial crops fail to survive the winter, due to early first fall frost/freezing temperatures.

Caterpillar tunnels modify the microclimate by passively trapping solar energy, thus increasing the air and soil temperatures and relative humidity (RH) (Nian et al., 2023). In comparison to HTs, CTs are simpler, smaller, and more portable structures. With the cost approximately one-fourth that of HT, CT is considered a more basic and cost-effective form of HT (Grubinger, 2016). The benefit of using the CTs lies in their portability, allowing easy removal when not in use. Furthermore, removing the polyethylene covering during the winter protects the structure from wear and tear and helps to leach the soluble salts that may have accumulated throughout the growing season.

While some articles and few advertisements show that CTs extend the growing season, enhance crop quality, increase production, and positively influence local markets in many states, there is no reported research on CT production system to substantiate these claims.

Importance of the research

The demand for locally grown produce has been increasing recently with even greater growth at the local farmers’ markets. The US Department of Agriculture National Farmers Market Directory reported over 8,771 registered farmers markets with 150,000 farmers and ranchers selling their produce directly to the consumers across the nation with an average growth of 7% a year (USDA, 2022a). Further, it was also reported that the sales of local foods have increased at intermediary markets such as grocery stores, restaurants, and distributors. There are over 54 farmers markets and several on-farm sales, roadside stands, community sustainable agriculture (CSA) shares, U-pick, and other purchase systems across the state, involving over 125 growers in the local markets in North Dakota (Goehring, 2023). The introduction of controlled environment agriculture has significantly contributed to the growth and development of both local and commercial markets in North Dakota. However, the studies on season extension structures and their impact on production and marketability of fruits and vegetables are limited. Therefore, further study on low-cost season extension structures can play a vital role in enhancing reliability and predictability as well as improving the economic production value.

CHAPTER 2

Literature Review

Protected agriculture

Protected agriculture is the modification of growing environment to improve microenvironment for plant growth (Lamont, 2009; McCartney and Lefsrud, 2018). Modifications are made to extend the growing season, pest control, and increase productivity and quality (Blanco et al., 2019; Borrelli et al., 2013; Carey et al., 2009; Sideman, 2020). Modifications can be imposed to air and root temperature, light intensity, water, and nutrition, growing media, air quality by adjusting humidity and carbon dioxide levels, and protection from biotic and abiotic factors. The discovery of polyethylene polymer in 1930s and its introduction in 1950s revolutionized the commercial production of vegetable crops and increased the popularity of plasticulture (Lamont, 2005). The first plastic-covered greenhouse was built at the Kentucky Agricultural Experiment Station in 1953 by Dr. Emmert. Since then, different forms of plastic-covered greenhouses have increased in popularity to increase yield and improve crop quality.

High tunnel versus caterpillar tunnel

The use of season extension structures in high-value crop production has gained popularity in the US in recent years with high tunnels (HTs) as a viable option (Carey et al., 2009; Kaiser and Ernst, 2021). Caterpillar tunnels (CTs) are plastic covered, passive solar-heated structures used to alter growing environments. They are smaller and shorter than HT. They are three-season structures and are 1.6 m (6ft) to 2.4 m (8ft) high and 3 m (10ft) to 6 m (20ft) wide but can be customized according to the specific requirements. Unlike HTs, they do not have built-in end walls or side walls and are less stable, therefore they are considered a more temporary/movable option. Further, they are easy to dismantle and can be removed when not in use. In colder regions such as North Dakota, uncovering the soil during winter proves advantageous as it enables snowfall to facilitate the leaching of soluble salts that tend to accumulate over a time due to fertigation and irrigation. A study on “Effects of plastic mulches and HT raspberry production systems on soil physicochemical quality indicators” reported that the limited exposure of HT soils to routine leaching from rainfall leads to the gradual accumulation of soluble salts resulting due to the regular application of hard water and fertilizers (Domagała-Świątkiewicz and Siwek, 2018). However, the easily removable CT covering provides the resolution to soil issues related to salt buildup. Additionally, the removal of polyethylene covering during the late fall and winter months safeguards the covering from wear and tear, especially in the upper Midwest climatic regions.

The use of HTs in high-value crop production has gained popularity in the US (Carey et al., 2009; Lamont, 2005). The primary purpose of a HT is to minimize the environmental impacts on crop production by increasing the temperature and facilitating early spring planting, accelerating the ripening and extending harvest later into the fall, as well as providing the protection from adverse weather conditions (Borrelli et al., 2013; Carey et al., 2009; Kadir et al., 2006; Kaiser and Ernst, 2021; Knewtson et al., 2010). The microclimate within HT can result in temperature differentials of 17-21 °C warmer than the surrounding air temperature on sunny days (Kaiser and Ernst, 2021). This microclimate manipulation benefits small market gardens, and large-scale farms by extending the growing seasons, enhancing crop yields, and improving quality (Blanco et al., 2019; Sideman, 2020). Retamal-Salgado et al. (2015) reported that a HT built with a single layer of polyethylene film raised night-time minimum temperatures by 2 °C at 1.2 m above the ground, advancing blueberries harvest by 14 days and resulting in a 44% increase in yield. Similarly, primocane-bearing raspberry cultivars yielded two to three times more marketable fruit in HT compared to field conditions (Demchak, 2009). According to Rho et al. (2020) tomatoes and jalapeno peppers were transplanted 25 and 41 days earlier in HT in 2018 and 2019 respectively compared to the open field (OF) in Texas. Research on strawberries in northern Utah reported four weeks earlier planting in HT compared to OF production (Rowley et al., 2011). Similarly, the HT accumulated higher growing degree days (GDD) due to a higher average maximum temperature, leading to earlier maturity compared to OF environment (Both et al., 2007; Rho et al., 2020). The GDD is the amount of heat required by plants to develop from one point in their lifecycle to another (Miller et al., 2001). Furthermore, a blueberry production study in Georgia reported advancement in flower initiation by more than four weeks in HT compared to OF controls (Ogden and Van Iersel, 2009).

Many HTs use a single layer of plastic, which provides poor insulation when drastic temperature changes occur and are prone to tearing under windy conditions when compared to double-poly HTs (Cemek et al., 2006; Zhao and Carey, 2009). The CT provides similar season extension as single poly-HTs but at a lower cost, thus increasing the return on investment. Therefore, CTs are excellent alternatives to consider for producers seeking the advantage of protected agriculture with minimal investment.

North Dakota climate

The 30-year average number of days between the last and first frost measured in North Dakota is approximately 138 days (NOAA, 2021). Also, on average, the maximum wind speed over the past five years during the growing season (2015-2022) was 38.3 Kmph and the average 13.10 Kmph (NDAWN, 2024). Given the short and challenging growing season and harsh weather circumstances in North Dakota, extending the growing season becomes crucial for enhancing fruit and vegetable productivity both early and late in the season (Rader and Karlsson, 2006).

Vegetable crops

Tomato

Tomato (*Solanum lycopersicum*) comprise a substantial sector within the agricultural industry and have emerged as a fundamental dietary staple for human consumption in various regions across the globe (Beecher, 1998). Tomatoes have an Andean origin and belong to the Solanaceae family (Saavedra et al., 2017). Approximately 189 million Mg of tomato was produced on about 5.2 million ha in 2021 worldwide, of which 39 million Mg was used for processing purposes (FAO, 2022). The cultivation of tomatoes was first mentioned in the US by Thomas Jefferson in 1781 (Sims, 1980). Since then, the tomato industry has experienced rapid growth with tomatoes now being grown across almost all states. California followed by Florida are the biggest producers of tomatoes in the US (USDA, 2023).

Tomatoes are highly nutritious and low-calorie fruits. One medium sized tomato (123 g) provides 22 kcal, 1 g protein, and 5 g of carbohydrates (USDA, 2016b). Additionally, tomatoes are rich in calcium, sodium, iron, vitamin C, fiber, and vitamin K. They are free from cholesterol and saturated fat; therefore, they are an excellent dietary option for heart and diabetes patients. Similarly, studies reported that tomatoes and tomato-based products play an important role in preventing different forms of cancers as well as reducing the risk of atherosclerosis, carcinogenesis, and cardiovascular diseases (Brandt et al., 2006; La Placa et al., 2000; Levy et al., 1995). This protective effect has been attributed to beneficial phytochemicals including β-carotene, lutein, zeaxanthin, and lycopene. The inclusion of tomatoes in dietary practices is therefore understood not only for their nutritional richness but also for their health-promoting attributes.

Bell pepper

Peppers (*Capsicum annum*) are warm season vegetable crop and belong to the Solanaceae or Nightshade family (Anaya-Esparza et al., 2021). They are native to Southern Mexico and Central and South America and have been spreading throughout the world since late 1400s (Bosland, 1992; Carrizo García et al., 2016; Clement et al., 2010). Capsicum comprises about 30 species, of which *C. annuum* L., *C. frutescens* L., *C. chinense* Jacq., *C. baccatum* L., and *C. pubescens* are the major cultivated species (Bosland, 1992; Wang and Bosland, 2006). The plants are perennial, but in colder regions, they are best grown as an annual crop (Votava et al., 2005). The fruits are classified as berries. They are green when immature and change the color from green to red, yellow, orange, purple, black and white depending on cultivars (Sun T. et al., 2007). Bell peppers are the only species from the genus Capsicum that do not contain capsaicin, therefore they are also known as sweet peppers (Uarrota et al., 2021).

The production and consumption of bell peppers increased rapidly during the 20th century due to their role as both vegetable and a spice (Pathirana, 2013). The global bell pepper industry was valued at $4,812.4 million in 2021 and is estimated to reach $7,683.2 million by 2031 (BRI, 2024). The growing demand for bell pepper has been attributed to its anti-inflammatory and nutritional composition. A decent sized green bell pepper (100 g) provides 94.1 g water, 23 Kcal energy, 0.72 g protein, 4.78 g carbohydrate, and 0.9 g dietary fiber. Similarly, it is rich in minerals like calcium, potassium, magnesium, phosphorus and vitamin C (USDA, 2022b). The consumption of one decent-size pepper meets double the daily recommended intake of vitamin C (Hallmann and Rembiałkowska, 2012).

The different color of ripened bell peppers is associated with the presence of different carotenoids, phenolics and flavonoids including carotene, zeaxanthin, lutein, capsorubin, β-cryptoxanthin, capsanthin, and capsanthin 5,6-epoxide (Crosby, 2008; Hallmann and Rembiałkowska, 2012; Sun T. et al., 2007). The composition and concentration of these antioxidant compounds vary among different colored peppers, resulting in varying levels of antioxidant activities. These antioxidant compounds have abilities to prevent the oxidation of cholesterol and docosahexaenoic acid, playing an important role in preventing major oxidation-linked diseases such as diabetes and cardiovascular, carcinogenic, and neurological disorders (Shetty, 2004).

Fruit

Grape

Grape (*Vitis* spp.) is one of the earliest domesticated (Myles et al., 2011) and the most commonly cultivated fruit crops (Karataş et al., 2014; Unusan, 2020). It belongs to the Vitaceae family and is a highly prestigious crop because of its ancient connections with human civilization. Several hypotheses exist regarding the origin and distribution of grapes.

According to the study by Aradhya et al. (2003) using microsatellite markers to the deoxyribonucleic acid (DNA) of 222 cultivated and 22 wild grapes from various regions, French cultivars were found to have close geographical origins to the wild grapes from Southwestern France and Tunisia. Similarly, the study of chloroplast DNA polymorphisms of 1,201 grapes found that *V. vinifera* subsp. *vinifera* and *V. vinifera* subsp. *sylvestris* share close affinity with regions including Near East, Middle East, Eastern Europe, Balkan Peninsula, Italian Peninsula, Northern Africa, Central Europe, and the Iberian Peninsula (Arroyo-GarcÍA et al., 2006). Furthermore, a study by Myles et al. (2011) suggested that the origin of *V. vinifera* subsp.

vinifera can be traced to the Near East. Additionally, genomic and archeological data further indicates that grapevine domestication dates back to approximately 6,000-8,000 years ago from the population of *V. vinifera* subsp. *sylvestris* in the Transcaucasian region (Zhou et al., 2017).

In the US, grapes were introduced and first cultivated in 1629 (Krochmal and Grierson, 1961). The US produced 21% of approximately 75 million Mg of grapes produced in the world in 2014 (Unusan, 2020). In 2022, nearly six million Mg of grapes were commercially produced in the US, with California accounting for 5.5 million Mg. Other prominent grape-growing states include Washington and New York (USDA, 2023). Approximately, 60% of grapes produced in the US are used for winemaking, and the rest are used as fresh fruit or processed into various products such as jam, juice, grape seed extract, jelly, grape seed oil, raisins, and vinegar.

Cold-hardy wine grapes

The cultivation of table and wine grape cultivars was confined to the areas with milder climates until the introduction of cold-hardy interspecific hybrids (Pedneault et al., 2013). While European grape (*Vitis vinifera)* produces high-quality grapes with desirable characteristics for wine production, it lacks cold hardiness (Ferguson et al., 2013; Mills et al., 2006). The development of cold-hardy interspecific hybrids has provided opportunities for northern winemaking. River grape (*Vitis riparia)* and Concord grape (*Vitis labrusca)* can tolerate temperatures as low as -35 °C to -40 °C (Andrews et al., 1984; Patrick and Stushnoff, 1980) and -26 °C to -29 °C respectively (Zabadal et al., 2007). The development of cold hardy interspecific hybrids has enabled the commercialization of cold-climate wines in the regions like the upper Midwest in the US (Pedneault et al., 2013). However, the natural climate remains the constraint factor on wine grape production in cold regions, limiting the production of high-quality wines.

Cultivar trial

Cultivar trials for vegetables hold significant value for the producers because they offer comparative analysis of crucial performance and quality traits (Warren et al., 2015). Traits like marketable yield, number and size of fruits, fruit composition are significant for growers. Particularly in the upper Midwest region, earliness in ripening is an important trait that producers consider when selecting cultivars. Catalogue descriptions can give valuable information such as disease resistance, estimated yield and days to maturity. However, the descriptions may not reflect the condition of the particular area (Loria, 2019). Therefore, varietal trials minimize the expense, time and effort farmers must put into identifying the most suitable cultivars for commercial production (USDA, 2023).

Temperature and summer vegetables

High and low temperature stress is detrimental to the morphology, yield and productivity of warm-season vegetable crops (Haghighi et al., 2014). Both low temperature stress (<10 ºC) and high temperature stress (>35 ºC) disrupt physiological processes by increasing the level of reactive oxygen species (Kang and Saltveit, 2002; Rajametov et al., 2021). These reactive oxygen species cause damage to membrane lipids, proteins and nucleic acids delaying germination, inhibiting the growth and development, reducing flower and fruit set, and ultimately compromising yield and quality. At sub-optimal temperatures, the period between the onset of anthesis and fruit ripening increases due to slow growth and development. A study by Haghighi et al. (2014) reported a significant reduction in shoot and root dry weight of tomatoes at 10 ºC and 40 ºC compared to 25 ºC. Similarly, a study by Sato et al. (2000) reported reduction in the number of pollen grains and percentage of fruit set in tomato cultivars grown at 32/26 ºC day/night temperature compared to plants grown at 28/22 ºC.

Spring and fall temperature extremes and the chilling temperatures in North Dakota have always been a concern for summer-vegetable growers (Rana, 2021; Splichal, 2020). Late spring cool soil and air temperatures became the main limiting factor for establishing seedlings, affecting the growth and development if transplanted earlier in the field condition. Similarly, early fall chilling temperatures increase the incidence of physiological disorders including catface and scars as well as end the harvesting season early (Kang and Saltveit, 2002).

Tomato and bell pepper pests and diseases

Tomato spotted wilt virus

Tomato spotted wilt virus (TSWV) is one of the most devastating viruses, with a host range of more than 1000 plant species across more than 85 plant families (Gupta et al., 2018; Nachappa et al., 2020; Parrella et al., 2003). Some commercial fields in the US have reported nearly 100% losses due to TSWV. Western flower thrips (*Frankliniella occidentalis)* is the major vector of TSWV (Gupta et al., 2018).

Plants infected with TSWV show several symptoms, including dieback of the growing tips, stunted growth, mottling, and dark streaks on the terminal stems. Additionally, young leaves turn bronze and develop numerous small, dark spots. Similarly, the infected plants may develop one-sided growth habits. Infected plants may fail to produce fruits, and if they do, the fruit may show symptoms such as concentric ring spots, raised bumps, deformation, and uneven ripening.

Host resistance and vector control or avoidance are the major approaches to manage the disease. Once plants are infected, they cannot recover, therefore removal of all infected plants is important to prevent disease transmission. The complete elimination of thrips in the field is impractical due to the host range and the number of thrips species transmitting the virus, coupled with insecticide resistance. Therefore, preferred management practices include reducing thrips populations by eliminating alternate host plants, using reflective mulches, field sanitation, crop rotation and use of TSWV-tolerant cultivars (Goldberg and French, 2016; Sherwood et al., 2003).

Aphid

Aphids (family *Aphididae*) are economically important pests of tomatoes and bell peppers, are tiny sap sucking insects that inhabit the undersides of the leaves (Ali, 2023; Singh R. and Singh, 2021). They are known for their prolific reproduction rate with a host range of 400 plant species, and vectoring about 100 plant viruses (das Graças do Carmo et al., 2021; Splichal, 2020). Aphids can reproduce rapidly by asexual reproduction with an individual aphid capable of producing over hundreds of female offspring weekly under warm conditions.

Aphids disrupt the normal functioning of plants by sucking sap (a fluid transported in xylem cells or phloem) from plant cells and transmitting viruses in the process or disrupting the normal function. Further, the disruption of normal functioning is exacerbated by the release of honeydew, a sweet excretion that attracts opportunistic fungi, leading to the formation of dark layer (black sooty mold) covering leaves and fruits, thus obstructing the photosynthetic activities, and reducing the fruit quality (Riddick, 2017; Valenzuela and Hoffmann, 2015).

Insecticide application has been a primary method for aphid control (Anstead et al., 2005). However, chemical control has led to the evolution of insecticide resistance in aphid populations due to mutations. Therefore, integrated pest management (IPM) practices emerge as a crucial strategy for effective aphid population management (Riddick, 2017). These practices involve a comprehensive approach integrating cultural, mechanical, and biological methods before deciding into chemical approach. Removal of plant debris from the field, destruction of alternative hosts and their proper disposal, and use of reflective mulches early in the season are the most important cultural practices (UCANR, 2012). Similarly, biocontrol methods, such as releasing natural predators like lady bird beetles (family *Coccinellidae*), lacewings (family *Chrysopidae*) and syrphid flies (family *Syrphidae*), play a significant role in managing aphid populations (Riddick, 2017). Application of insecticidal soap is organically acceptable method. Further, to monitor the aphid populations, yellow sticky traps can be set in the field before planting and the decision for insecticide application should be based on the threshold population (UCANR, 2012).

Blossom end rot

Blossom end-rot (BER) is one of the most important physiological disorders in tomato and other solanaceous crops (Taylor et al., 2004). It is a common challenge in all the tomato producing regions of the world and can cause losses of up to 50%. It is characterized by increased permeability and deterioration of the cell membrane resulting in the loss of turgor and leakage of cell liquids at the blossom end of the fruit (Hagassou et al., 2019).

The development of BER is linked to a localized calcium (Ca^{2+}) deficit at the blossom end of the fruit (Adams and Ho, 1993). The deficiency is attributed to different stress factors. Different salt stresses like Potassium (K^{+}), Magnesium (Mg^{2+}) and Ammonium (NH_4^{+}) are found to have antagonistic effect on calcium, leading to reduction in Ca^{2+} uptake and distribution from soils with high concentration of these cations (Bar-Tal and Pressman, 1996; Nukaya et al., 1997). Furthermore, increased BER may be associated with reduction on plant and fruit growth due to different stress factors such as water stress, relative humidity stress, heat stress, and root restriction (Balate et al., 2018; Indeche et al., 2020; Sun Y. et al., 2013; Syengo et al., 2019; Taylor et al., 2004).

North Dakota soil contains plenty of calcium (Kalb, 2024). Therefore, soil and water should be checked for salinity before planting to avoid overapplication of antagonistic ions (Taylor et al., 2004). Focus should be given to regular watering, avoiding overfertilization, temperature regulation and using less susceptible cultivars. Application of nitrate fertilizer instead of ammonium fertilizer is another recommended strategy to avoid BER (Heeb et al., 2005). Another viable option involves foliar spraying of calcium chloride or calcium nitrate at 0.5% (Hagassou et al., 2019).

Research Objectives

Objective 1: Evaluate the physiological, morphological, and productive differences among three species (grape, pepper, and tomato) and two to eight cultivars of each species with regard to caterpillar tunnel and open field production systems.

Objective 2: Determine air and soil temperature differences as well as relative humidity differences between caterpillar tunnel and field and what influence these differences have on plant physiology, morphology, and productivity.

Objective 3: Determine caterpillar tunnel influence on fruit ripening and overwintering of grape cultivars.

CHAPTER 3

Tomato

Introduction

Tomato is one of the most profitable crops grown in high tunnel (HT) (Carey et al., 2009; Knewtson et al., 2010). Based on the production statistics of vegetables in the US, tomato is one of the most cultivated vegetable crops (USDA, 2023). Approximately 668 thousand Mg of fresh market tomatoes and 10.4 million Mg of processed tomatoes were harvested on approximately 106.8 thousand ha in 2022, for a total value of nearly $1.8 billion in the US. Commercially, they are grown in both fields and HTs for fresh market consumption and for use in processed products such as juice, purees, and whole packs (Decoteau, 2000).

Growing tomatoes in a HT makes it possible to transplant cultivars about a month earlier and extend harvesting six weeks later than field-grown tomatoes (Hunter et al., 2012). Similarly, HTs advanced the ripening of tomatoes by more than four weeks compared to field-grown tomatoes (O'Connell et al., 2012). Improved environmental conditions in HTs facilitated the accumulation of growing degree days (GDDs), influencing earlier maturity, and significantly impacting overall plant growth dynamics (Reeve and Drost, 2012). A study by Splichal (2020) on season extension of warm season vegetables using HTs reported the increase in tomato yield by 1.4 times than the open field (OF) production system. Similarly, O'Connell et al. (2012) reported that although the HT and OF production systems had comparable total yield (100 $t \cdot ha^{-1}$) in the first season of organic heirloom tomato production, the HT outperformed the field production system by 33% in the second season (90.7 $Mg \cdot ha^{-1}$ and 60.8 $Mg \cdot ha^{-1}$, respectively).

High tunnels are less permanent than greenhouses but are also not easily taken down during the winter or moved to another location to mitigate the issues such as soil-borne pathogens and salinity buildup when tomatoes are grown consecutively in the same location (Warren et al., 2015). In contrast, the use of caterpillar tunnel (CT) offers a solution by enabling more convenient relocation when crops are grown consecutively (Grubinger, 2016; Nian et al., 2023). This effectively addresses the concerns related to soil-borne pathogens and salt buildup, while maintaining comparable season extension abilities of HTs.

Primary quality attributes

The pH, titratable acidity (TA) and total soluble solid (TSS) are important in determining the quality of tomato paste. The pH influences the thermal processing conditions for producing safe products by inactivating enzymes and preventing microbial spoilage (De Sio et al., 2018). The ideal pH for processing tomatoes is 4.25, while a pH of 4.4 is the maximum desirable to avoid microbial spoilage. Furthermore, the flavor of tomato fruits relies on the balance between sugar and organic acids (Arroyo-GarcÍA et al., 2006). The TSS/TA ratio is important in defining flavor profile of tomato cultivars (Malundo et al., 1995). Similarly, the average acidity of processing tomatoes falls around 0.35% and the desirable soluble solid content ranges between 4.5 and 6.25 ºBrix. The higher the total soluble solid in the fruit, the fewer number of tomatoes will be required to produce a given amount of paste.

Objectives

Objectives of this trial were to evaluate the physiological, morphological, and productive differences among eight commercially available paste tomato cultivars with regard to CT and OF production systems, and to determine the air and soil temperature differences, and relative humidity differences between CT and OF, as well as what influence these differences have on plant physiology, morphology, and productivity.

Material and methods

Site description

The study was carried out at the NDSU Horticulture Research Farm near Absaraka, ND, during 2022 and 2023 (46°59’10.7” N 97°21’21.8” W, 1070 m elevation). The region falls under plant hardiness zone 4A (USDA-ARS, 2023). This region is classified as continental with an average precipitation range of 380 to 760 mm (Tollerud et al., 2018). The soil profile at the location is a Warsing soil series characterized as moderately well drained fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls (USNRCS, 1983). Based on the historical data from 1991-2020 the average growing season at Absaraka is nearly 138 days with average last and first frost dates falling between May 11-20 and September 20-30, respectively (NOAA, 2024).

Caterpillar tunnel installation

The CT (Farmers friend, Centerville, TN 37033) was installed adjacent to field trial after the field was tilled and before transplanting. The CT dimensions were 30.48 m long, 4.88 m wide, and 2.74 m tall, with a gothic style arch (Appendix Fig. B6 and B10). It was constructed on 3 June 2022, using 2-mm galvanized steel and a single layer 0.15-mm clear polyethylene film, with a north-south orientation. Hoops were firmly secured into the ground by using 1.2 m long rebars that were pounded into the ground approximately 1 m with a 1.2 m spacing. Further, the structure was strengthened by steel center purlins, wind bracing, a lift kit, and cross bracing. Finally, the frame was covered with polyethylene film and was secured with wiggle wire at both ends of the tunnel. The polyethylene film was anchored to the frame with ropes using a zig-zag pattern that gives the tunnel structure resemblance of a caterpillar. A zipper door was installed at one end of the tunnel, and the other end was securely fastened by folding the polyethylene film and tying it to a T-post placed 1.2 m from the end wall during 2022 growing season. However, in 2023, instead of tying the polyethylene film to the T-post, it was oriented vertically, descending perpendicularly, and was tightly held using construction blocks to mitigate potential abrasion of the polyethylene film against heavy wind. The temperature in the CT and OF production system was recorded throughout the growing seasons even though it remained unregulated, and the side walls remained open until late September.

Planting materials

For the indoor CT trials and the outdoor OF trials, eight paste tomato cultivars (Harris Seeds Company, Rochester, NY; Johnny's Selected Seeds, Winslow, ME and W. Atlee Burpee & Co., Warminster, PA) were selected due to disease resistance, average fruit weight and expected days to maturity (Table 1). All cultivars were first generation (F1) hybrids except 'San Marzano' and 'Amish Paste'.

Table 1. Tomato trial cultivars, seed source and days to maturity.

Cultivars	Seed source[y]	Disease resistance[x]	Ave. fruit wt. (gm)	Days to maturity[w]
Pozzano[z]	HS	BER, ToMV (races 0-2), FW (races0-1) and VW (race 0).	113-142	72
Granadero[z]	HS	IR to TSWV and RKN, HR to PW, ToMV races 0 - 2, FW races 0 - 1 and VW race 0.	142	75
Amish Paste	JSS	-	227-340	85
Cauralina[z]	JSS	HR to FW race 1, FC and RR, and ToMV	227-397	72
Big Mama[z]	WAB	-	227-284	80
Gladiator[z]	WAB	-	227	72
Super Sauce[z]	WAB	-	624-907	70
San Marzano	WAB	-	113	80

[z]Refers to F1 hybrids.
[y]HS=Harris Seeds; JSS=Johny's Selected Seeds; WAB= W. Atlee Burpee & Co.
[x]HR= High resistant; IR= Intermediate resistance; BER= Blossom End Rot; FC= Fusarium Crown; FW= Fusarium Wilt races; PW= Powdery Mildew; RKN=Root Knot Nematode; RR: Root Rot; ToMV: Tomato Mosaic Virus; TSWV: Tomato Spotted Wilt Virus; RKN: Root Knot Nematode; VW: Verticillium Wilt.
[w]Days to maturity: Expected number of days from transplanting to first harvesting.

Transplant establishment

In 2022, for the CT production system, seeds were started on 30 March at the Lord and Burnham Greenhouse at North Dakota State University, Fargo, ND (23.9℃, 16:8 L:D) in standard insert 800 series (T.O. Plastics, Clearwater, MN), filled with a planting mix (Pro-Mix BX, Premier Tech, Quebec, Canada) (Table 14). To enhance better root growth, the seedlings were transplanted into 10.16 cm SVD-450 molded plastic pots using the same planting mix on 20 April. For the OF production system, seeds were started on 13 April following similar procedures and using the same planting mix as the CT trial. The seedlings were then transplanted into 10.16 cm SVD-450 molded plastic pots on 11 May. Plants were irrigated every other day until transplanted into soil. A 20:20:20 general purpose water-soluble fertilizer (JR Peters Inc., Allentown, PA) at 100 parts per million (ppm) was injected into the irrigation system. During the seedling establishment phase, aphid and thrips infestation were observed. To address the issue, pyrifluquinazon (SePRO Corporation, Carmel, IN) at 0.71ml/L was applied. The seedlings for the CT and OF trials were exposed to an open environment (between greenhouse ranges) for acclimatization on 6 May and 20 May respectively. The construction of CT extended beyond the anticipated planting date because of construction delays due to snowfall accumulation and rainfall, resulting in over mature seedlings at transplanting on 3 June.

In 2023, seeds were started in one of the North Dakota Agricultural Experiment Station (NDAES) greenhouse rooms to safeguard the seedlings from potential thrips and aphid infestation. The seeds for CT trial were seeded on 15 March in standard insert 800 series and transplanted into 10.16 cm SVD-450 molded plastic pots on 11 April using the same planting mix previously described. For the OF trial, seeds were seeded directly into 10.16 cm SVD-450 molded plastic pots on 17 April. The seedlings were transplanted into the CT on 5 May without acclimation due to the cooler outdoor temperatures. The seedlings for an OF production system were transplanted on 12 June after a week-long acclimation period.

Site preparation and layout

Before transplanting, soil samples were collected from two depths (0 cm to 15 cm and 15 cm to 30 cm) and placed into different soil sampling bags. These samples were submitted to the NDSU Soil Testing lab (Fargo, ND) for soil nutrient test (Appendix Table A10 and A11). Prior to transplanting, beds were tilled using a rotor-tiller (Woods Equipment, Oregon, IL) attached to a tractor. In each production system, three rows were prepared, and a single line of 0.38-mm drip tape with emitters spaced at 20.3 cm on the center with a flow rate of 2.15 x 10-4 m^3s^{-1} was installed beneath black plastic mulch (Wrap Bros, Chicago, IL) using a tractor-mounted plastic mulch layer (Progressive Grower, West Wareham, MA). The NPK was applied as a split application with a total of 134.5: 134.5: 134.5 kg/ha in three split doses during each growing season. A granular 19:19:19 NPK (J.R. Simplot Company, Boise, ID) was broadcasted pre-plant at 67.25: 67.25: 67.25 kg/ha, while the rest was fertigated in two split doses at 33.63: 33.63: 33.63 kg/ha (20:20:20 water-soluble fertilizer) during the flowering and fruiting period at 6-8 weeks interval using drip tape (Toro® Aqua-Traxx, DripWorks, Willits, CA). Irrigation was scheduled on Mondays, Wednesdays, and Fridays, each lasting two hours throughout the growing season. Weeds were removed manually to ensure optimal crop growth and reduced pest infestations.

Weather

Watchdog 1000 series micro station dataloggers (Spectrum Technologies, Inc. Aurora, IL) were installed to monitor air and soil temperatures. Temperature probes were positioned at the center of each production system and data loggers were programmed to collect data at hourly intervals throughout the growing season. Soil temperature readings were recorded at a depth of 30 cm and air temperature readings were taken at 1.5 m height across both environments during both growing seasons. The daily average, maximum and minimum air temperature were calculated and numerically compared between the two-production systems. During the 2023 growing season, WaterScout SMEC 300 soil moisture sensors (Spectrum Technologies, Inc. Aurora, IL) were installed to monitor the soil moisture levels throughout the growing season. Further, the accumulated GDD was calculated using the equation:

$$GDD = \frac{daily\ max.\ temperature + daily\ min.\ temperature}{2} - base\ temperature \qquad (1)$$

Where,

above high cutoff temperature= 30 ºC

below base cutoff temperature= 10 ºC

Management practices

Seedlings were transplanted at the spacing of 1.52 m between rows and 0.61 m between plants. Tomatoes were trained to a two-leader system using Tomahooks (Van den Wijngaart, The Netherlands). To suspend these hooks metal wires were run along the length of the CT, serving as rafters. Similarly, in the OF trial, two T-posts were installed on each side of the row with a 1.22 m spacing throughout the length of row and the iron rebar was run through the top of each t-posts to create the rafters to support the trellis wire (Appendix Fig. A7). The leaves below the two main leaders at approximately 30 cm height and suckers were removed using sterilized pruners to improve air flow. During the 2022 growing season, the experiment became infested with herbivorous insects such as aphids, thrips, and leafhoppers. In response, imidacloprid (Admire Pro, Bayer Crop Science LP, NC) at 163 ml/ha was applied to effectively control those insects. The experiment was also heavily infected with TSWV from an incident with another researcher during the seedling growth stage. To reduce the spread of the virus, infected plants were removed as soon as the symptoms were visible. Notable symptoms such as bronzing of upper sides of the young leaves, which later developed into distinct necrotic spots, leaflets curled upward while the midveins curled downward, and tip dieback were visible. Symptoms were noted on approximately 20% of the plants in the CT and all the cultivars except ‘Granadero’ in the OF. In 2022, the experiments were located at the field's east side. However, in 2023 the CT and the OF trial were relocated to the field's west side. The viral infestation was lower in 2023.

Similarly, BER affected many tomato fruits in 2022. Therefore, in 2023, calcium nitrate (Yara North America, Inc, Tampa, FL) at 28.8 gm/L of water was manually sprayed over the foliage to reduce BER.

Data collection

Crop phenology

Phenological, yield and quality data were recorded and compared across two production systems. Phenological data were recorded on the number of days to first flowering, days to first fruiting and days to first harvest from transplanting date based on visual inspections (Table 2). For the phenological data, plants were examined every other day throughout the growing season. The days to first flowering were recorded once the first flower fully opened. Similarly, days to first fruiting were recorded upon the fruit's emergence with complete petal shedding. Fruits were harvested once they reached the pink to red stage (USDA, 2017).

Table 2. Dates for seeding, transplanting and harvest in the caterpillar tunnel and open field production system in 2022 and 2023.

Year	Action	Caterpillar tunnel	Open field
2022	Seeding	30 March	13 April
	Transplant	3 June	3 June
	First harvest	1 August	5 August
	Last harvest	11 October	4 October
2023	Seeding	15 March	17 April
	Transplant	5 May	12 June
	First harvest	24 July	21 August
	Last harvest	23 October	12 October

Note: Seeding and transplanting date depend on outdoor environment and workability of soil.

Crop yield

Fruits were harvested using official tomato visual aids from USDA Agricultural Marketing Service Fruit and Vegetable Division, once they reached the pink to red stage (USDA, 2017). Fruit harvest occurred twice a week during a peak period and once a week other time for approximately 10 and nine weeks in the CT and the OF production systems, respectively, during the 2022 growing season and 13 and seven weeks in the CT and the OF production systems, respectively, during 2023 growing season.

Data were recorded on the total number of fruits per plant, total weight of fruits per plant, number of marketable fruits per plant, and marketable fruit weight per plant. Tomatoes were graded following US grade standards for tomatoes (USDA, 1991) and US consumer standards for tomatoes (USDA, 1948) from the USDA Agricultural Marketing Service. Fruits were graded as very large (≥283.5 g), large (170-283.5 g), medium (85-170 g) and small (<85 g). The marketability of tomatoes was assessed based on shape, size, freshness, and surface defects. Fruits that were deeply bruised, rotten, cracks greater than 1.27 cm, deep scars, catface, or had other defects affecting postharvest life were considered unmarketable. Fruits having minor scars/cracks were considered marketable. Percentage marketability was calculated using the equation:

$$Percentage\ marketability = \frac{number\ of\ marketable\ fruits}{total\ number\ of\ harvested\ fruits} * 100 \qquad (2)$$

Fruit composition/quality

Fruit compositions, including TSS, pH and TA were recorded three times during the fruit ripening stage-early, mid, and late. For each sampling, three fruits were randomly selected from each plant, stored in the cooler at 4 °C temperature overnight and analyzed. Fruits were crushed manually and filtered through cheese cloth to extract the juice. The TSS was measured using a pocket refractometer (Atago Co., Ltd, Tokyo, Japan), pH was measured using pocket pH meter (Atago Co., Ltd, Tokyo, Japan) and TA was assessed using a pocket brix-acidity meter (Atago Co., Ltd, Tokyo, Japan) by diluting 1µl tomato juice to 49µl distilled water (Blakey, 2024).

Final plant height:

Final plant height was recorded at the end of each growing season to evaluate plant growth. Plant height was determined by measuring the distance from the soil line to the growing point of each plant (Lang et al., 2020).

Experimental design and statistical analysis

Within each production system, cultivar trials were set up as randomized complete block design with four replications. Each plot, within a replication consisted of two plants from the same cultivar, resulting in a total plot area of 1.86 m^2. In 2022, TSWV infections were observed in about 20% of plants in the CT and more than 80% in the OF trial. Thus, a comprehensive comparison was made only between the 2022 CT, 2023 CT and 2023 OF production systems. Statistical analyses were performed within each production system due to lack of CT replications. Additionally, the cultivars ‘Amish Paste’ and ‘San Marzano’ were excluded from the statistical analysis in the 2022 CT production system due to infection in all replications.

Statistical Analysis System (SAS) version 9.4 was used for the statistical analysis, using PROC GLIMMIX with the REML estimation method (SAS Institute, SAS Circle, Cary, NC). Cultivars were treated as a fixed effect and the replication within each production system was treated as a random effect. Least squares means was used to separate the means at $\alpha = 0.05$ where appropriate.

Results

The only cultivar that remained unaffected by TSWV in both production systems in 2022 was ‘Granadero’. The statistical analysis and the analysis of variance (ANOVA) for 2022 CT production system is included in the appendix and only the result from 2023 was included in this thesis.

Air and soil temperature 2022

Air temperature

The average daily air temperature throughout the growing season was 0.6 °C higher in the CT compared to the OF production system (Table 3). July had the highest average temperature i.e., 24.5 °C and 24.2 °C for the CT and OF production systems, respectively. Further, June 19 was the hottest day of the year with the average air temperature of 33 °C in both production systems. The minimum temperature recorded was -3.2 °C and -4.8 °C in the CT and the OF production systems, respectively, on 7 October. Comparing the monthly average air temperature between the two production systems, in October, the coldest month of the growing season, the CT had an average air temperature of 15.2 °C while the OF system was 12.2 °C. The greatest diurnal temperature fluctuation of the CT and OF production systems were 36.3 °C and 26.3 °C, respectively. Considering the average daily temperature, 29 out of 126 days (7 June-11 October) in the CT production system deviated from the optimal temperature range of 18 °C-30 °C for growth (Welbaum, 2015). Similarly, 32 out of 126 days in the OF production deviated from the optimal 18 °C-30 °C range. The plants in the OF could not survive the frost event of 5 October which resulted in the end of harvest season seven days earlier in the OF production system compared to the CT production system. The GDD in the CT production system from June 7 to October 11 was 1440, while the OF production system was 1386.

Table 3. Average monthly air temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Months	Avg. air temperature CT[z] (°C)	Avg. air temperature OF (°C)	Max. air temperature CT (°C)	Max. air temperature OF (°C)	Min. air temperature CT (°C)	Min. air temperature OF (°C)
Jun (7-30)	23.7	23.4	41.7	41.7	9.8	9.1
Jul	24.5	24.2	40.7	40.3	11.4	9.8
Aug	22.2	21.9	40.1	39.6	9.6	8.2
Sep	17.1	16.7	35.7	35.6	1.6	-0.6
Oct (1-11)	15.2	12.2	38.4	28.8	-3.2	-4.8

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Soil temperature

The average daily soil temperature throughout the growing season was 1.4 °C higher in the CT compared to the OF production system. July had the highest average soil temperature in the CT and OF production systems at 26 °C and 25 °C, respectively (Table 4). The greatest average soil temperatures in the CT and OF production systems occurred on 18 July at 27.5 °C and 26.4 °C, respectively. The minimum soil temperature in the CT production system was 13.2 °C on 8 October, while the minimum soil temperature of 10.6 °C was recorded on the same day in the OF production system. Comparing the monthly minimum soil temperatures between two production systems showed that in October, the coldest month of the growing season, the CT production system had minimum soil temperature of 11.8 °C, while the minimum soil temperature in the OF system was 10.6 °C. The greatest soil temperature fluctuation of 5.5 °C occurred in the CT production system on 17 July, while the fluctuation of 2.8 °C was recorded in the OF production system.

Table 4. Average monthly soil temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Months	Avg. soil temperature CT[z] (°C)	Avg. soil temperature OF (°C)	Max. soil temperature CT (°C)	Max. soil temperature OF (°C)	Min. soil temperature CT (°C)	Min. soil temperature OF (°C)
Jun (7-10)	23.3	22.1	29.5	27.2	18.6	17.4
Jul	26.0	24.9	30.1	27.9	21.1	21.0
Aug	24.5	23.4	28.6	26.6	20.1	19.4
Sep	20.3	18.6	26.9	23.8	14.7	13.0
Oct (1-11)	16.9	14.0	20.1	17.3	11.8	10.6

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Air and soil temperature 2023

Air temperature

The average daily air temperature in the CT and OF production system were 19.3 °C and 18.7 °C respectively (Table 5). June had the highest average monthly temperature in the CT and OF production systems at 23.5 °C and 23.4 °C, respectively. The hottest day of the season in the CT and OF production systems was 20 June with average air temperatures of 30.7 °C and 30.6 °C, respectively. The coldest day of the growing season for the CT and OF was 10 October with an average air temperature of 7.4 °C and 5.6 °C, respectively. In October, the coldest month of the growing season, the CT had an average air temperature of 12 °C while the temperature in the OF system was 11.2 °C. The greatest air temperature fluctuation of 29.4 °C was recorded in the CT production system on 19 September, while the fluctuation of 26.4 °C was recorded on 16 October in the OF. Considering the average daily temperature, 43 out of 159 days (18 May-23 Oct) in the CT system deviated from the optimal temperature range of 18 °C-30 °C for growth (Welbaum, 2015). In contrast, 53 out of 159 days in the OF production system deviated from the optimal temperature range of 18 °C-30 °C for growth. The plants in the OF could not survive the frost event of 13 October which resulted in the end of harvest season 11 days earlier than the CT production system. The GDD in the CT and OF production systems from 18 May to 23 October were 1653 and 1606, respectively.

Table 5. Average monthly air temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Months	Avg. air temperature CT[z] (°C)	Avg. air temperature OF (°C)	Max. air temperature CT (°C)	Max. air temperature OF (°C)	Min. air temperature CT (°C)	Min. air temperature OF (°C)
May (18-31)	20.7	20.0	37.9	37.1	5.4	4.6
Jun	23.5	23.4	39.1	39.7	10.1	8.9
Jul	21.6	21.2	39.1	39.7	7.9	7.1
Aug	21.2	21.4	38.3	38.7	9.4	8.6
Sep	18.8	17.6	40.8	37.9	4.0	2.4
Oct (1-23)	12.0	11.2	41.2	35.8	-1.4	-2.9

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Soil temperature

The average daily soil temperature throughout the growing season was 1.3 °C higher in the CT compared to the OF production system (Table 6). June had the highest average soil temperature in the CT production system at 23.7 °C and August had the highest average soil temperature in the OF production system at 22.9 °C. The greatest average soil temperatures in the CT and OF production systems occurred on 3 July at 26.5 °C and on 3 September at 26.9 °C, respectively. The minimum soil temperature in the CT production system was 11.1 °C on 16 October, while the minimum soil temperature of 8.7 °C was recorded on the same day in the OF production system. Comparing the average monthly soil temperature between two production systems showed that in October, the coldest month of the growing season, the CT production system had an average monthly soil temperature of 15 °C, while the average soil temperature in the OF system was 11.9 °C. The greatest soil temperature fluctuation of 5.7 °C occurred in the CT production system on 20 May, while the fluctuation of 8.6 °C was recorded in the OF production system on 10 September.

Table 6. Average monthly soil temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Months	Avg. soil temperature CT[z] (°C)	Avg. soil temperature OF (°C)	Max. soil temperature CT (°C)	Max. soil temperature OF (°C)	Min. soil temperature CT (°C)	Min. soil temperature OF (°C)
May (18-31)	19.54	16.3	24.4	21.7	13.2	10.6
Jun	23.7	22.5	27.5	26.7	19.8	19.0
Jul	23.7	22.8	27.9	26.7	19.7	19.1
Aug	23.0	22.9	27.4	30.0	19.9	19.0
Sep	20.4	19.7	26.1	30.9	15.8	13.6
Oct (1-23)	15.0	11.9	24.9	18.5	11.1	8.7

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Crop phenology

The effect of cultivars on the number of days to first flowering was not significant within each production system in 2023 (Table 7). However, when examining the days to first flowering for each production system, all cultivars flowered at least one day earlier in the OF production system. ‘Cauralina’, ‘San Marzano’, and ‘Super Sauce’ on average, had the greatest difference (6 days) in days to first flower between production systems.

A significant difference in days to first fruiting was observed among the cultivars in both production systems in 2023 (Table 7). In the CT production system, ‘Gladiator’ produced the earliest fruit, but this was not significantly earlier than ‘Cauralina’, ‘Granadero’ and ‘Super Sauce’. Similarly, ‘Cauralina’ and ‘San Marzano’ produced fruit significantly earlier than ‘Amish Paste’, ‘Super Sauce’, and ‘Big Mama’ but not earlier than ‘Gladiator’, ‘Granadero’ and ‘Pozzano’ in the OF production system.

No difference was observed in the days to the first harvest among the cultivars in the CT production system in 2023 (Table 7). However, in the OF production system, ‘Cauralina’ was harvested significantly earlier than other cultivars. Cultivars in the CT production system were harvested from 24 July to 23 October, while harvesting in the OF began on 21 August and continued until 12 October in 2023. When comparing the catalogue description with the recorded data, all the cultivars in both production systems were harvested later than the estimated number of days to first harvest, except for 'Amish Paste' (Table 8).

Table 7. Effect of cultivar on phenological stages for paste tomato cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Days to first flowering[x]		Days to first fruiting		Days to first harvest	
	CT[z]	OF	CT	OF	CT	OF
Amish Paste	33a[y]	32a	43a	40a	82a	84ab
Big Mama	34a	31a	41ab	39a	88a	87ab
Cauralina	29a	23a	38bc	31b	83a	74c
Gladiator	30a	29a	35c	36ab	87a	89ab
Granadero	31a	29a	38bc	36ab	86a	85ab
Pozzano	33a	24a	39b	35ab	90a	87ab
San Marzano	30a	24a	40ab	32b	85a	83b
Super Sauce	31a	25a	39bc	39a	88a	90a
P-Value	0.2117	0.0687	0.0207	0.0202	0.1482	0.0047

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represents significant difference at $P<0.05$.
[x]Days to each phenological stage: Number of days from transplant to each phenological stage.

Table 8. Comparison between catalogue description, and the caterpillar tunnel and open field production system for number of days from transplantation to harvest.

Cultivar	Days to harvest[z]		
	Catalogue description	CT[y]	OF
Amish Paste	85	82	84
Big Mama	80	88	87
Cauralina	72	83	74
Gladiator	72	87	89
Granadero	75	86	85
Pozzano	72	90	87
San Marzano	80	85	83
Super Sauce	70	88	90

[z]Days to harvest= Days from transplantation to first harvest
[y]CT= Caterpillar tunnel; OF= Open field.

Crop yield

A significant cultivar response was observed in the total number of fruits per plant in both production systems in 2023 (Table 9). ‘San Marzano’ had the most fruits per plant compared to other cultivars across two production systems. Further, descriptive analysis of each production system showed that each cultivar produced more fruits in the CT compared to the OF production system. The number of fruits increased by 34%-165% in the CT compared to the OF production system.

The total weight of fruits per plant was influenced by the cultivars in both production systems in 2023 (Table 9). ‘Cauralina’ had the greatest total yield per plant in both systems. However, in the CT production system ‘Pozzano’ and ‘Granadero’ performed similarly to ‘Cauralina’. A descriptive comparison across two production systems showed that the total weight of fruits per plant increased by 50%-133% in the CT compared to the OF production system depending on the cultivar.

A significant difference in the number of marketable fruits per plant was observed among the cultivars in both production systems in 2023 (Table 9). In the CT production system, ‘Granadero’ followed by ‘San Marzano’ and ‘Pozzano’ had the greatest number of marketable fruits than other cultivars. Similarly, ‘San Marzano’ had the greatest number of marketable fruits per plant in the OF production system. When examining the number of marketable fruits for each production system, the cultivars produced 45%-438% more fruits in the CT compared to the OF production system.

‘Granadero’, ‘Cauralina’ and ‘Pozzano’ had significantly greater marketable fruit weight per plant compared to other cultivars except ‘Amish Paste’ in the CT production system (Table 9). Similarly, ‘Pozzano’ had the greatest marketable fruit weight per plant, but it was not significantly different from ‘Granadero’, ‘Cauralina’, ‘Super Sauce’ and ‘San Marzano’ in OF production system. A descriptive comparison between the two production systems showed that marketable fruit weight per plant increased by 46%-303% in the CT production system compared to the OF production system.

Table 9. Effect of cultivar on the crop yield for paste tomato cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Total number		Total weight (kg)		Number of marketable		Marketable weight (kg)	
	Fruits/plant							
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Amish Paste	79c[y]	27c	14.29bc	6.87bc	70b	13c	12.30ab	3.05c
Big Mama	51de	29c	9.62e	5.56bc	41cd	19c	8.22cd	4.12bc
Cauralina	64cd	35c	17.22a	10.44a	53bc	18c	14.86a	5.51ab
Gladiator	56cde	20c	12.44cd	4.69c	43cd	12c	9.82bc	2.96c
Granadero	127b	53b	15.50ab	6.64bc	118a	45b	14.90a	5.78ab
Pozzano	138b	52b	15.71ab	7.65b	104a	41b	13.56a	6.46a
San Marzano	163a	81a	8.64e	5.74bc	108a	64a	7.13d	4.89abc
Super Sauce	35e	26c	10.14de	6.84bc	29d	20c	8.44cd	5.05abc
P-Value	<.0001	<.0001	<.0001	0.0036	<.0001	<.0001	<.0001	0.0197

[z]CT= Caterpillar tunnel; OF= Open field.

[y]Means with different alphabets within a column represent significant difference at P<0.05.

‘Granadero’ had the most marketable fruits per plant at 92.72% and 85.55% in the CT and OF production system, respectively, in 2023 (Table 10). In the CT production system ‘Granadero’ had significantly higher marketability than ‘San Marzano’, ‘Pozzano’, ‘Big Mama’ and ‘Gladiator’. Similarly, it had significantly higher marketability compared to ‘Cauralina’, ‘Gladiator’ and ‘Amish Paste’ in the OF production system. When examining the marketability for each production system, all cultivars except for ‘San Marzano’ and ‘Pozzano’ had greater percentage of marketable fruits in the CT production system compared to the OF production system.

The effect of cultivars on the number of BER infected fruit was significant in both production systems in 2023 (Table 10). ‘San Marzano’ had the most BER infected fruits in both production systems. However, it was not different from ‘Big Mama’, ‘Cauralina’, and ‘Pozzano’ in the OF production system. ‘Amish paste’, ‘Gladiator’, ‘Granadero’, and ‘Super Sauce’ did not have any BER infected fruits in the OF production system. A descriptive comparison across the two production systems showed that at least one fruit from each cultivar in the CT production system developed BER.

Table 10. Effect of cultivar on the percentage marketability and the number of blossom end rot infected fruits per plant for paste tomato cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Marketability (%)		BER infected fruits (no.)	
	CT[z]	OF	CT	OF
Amish Paste	87.72ab[y]	48.02d	1c	0b
Big Mama	77.48bcd	68.62abcd	9c	6a
Cauralina	82.82abc	55.86bcd	4c	5ab
Gladiator	77.33bcd	55.19cd	4c	0b
Granadero	92.72a	85.55a	3c	0b
Pozzano	75.99cd	78.70ab	29b	4ab
San Marzano	67.55d	79.69a	46a	9a
Super Sauce	83.08abc	75.32abc	1c	0b
P-Value	0.0037	0.0120	<.0001	0.0110

[z]CT= Caterpillar tunnel; OF= Open field; BER=Blossom end rot.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.

Size classification

‘Cauralina’ had significantly more very-large fruits per plant than other cultivars in both production systems in 2023 (Table 11). In the OF production system, ‘Super Sauce’ had a similar number of very large fruits as ‘Cauralina’. ‘Granadero’ and ‘San Marzano’ did not produce very-large fruits in both production system.

In 2023, ‘Gladiator’ had significantly more large-sized fruits per plant than other cultivars except for ‘Amish Paste’ in the CT production system (Table 11). ‘Big Mama’ had a greater number of large-sized fruits in the OF production system but was not significantly greater than ‘Pozzano’, ‘Gladiator’ and ‘Super Sauce’. ‘San Marzano’ was the only cultivar that did not produce large-sized fruits in both production systems.

‘Granadero’ had significantly more medium sized fruits per plant than other cultivars in both production systems in 2023 (Table 11). ‘Big Mama’, ‘Cauralina’, ‘Gladiator’ and ‘Super Sauce’ had the fewest medium-sized fruits per plant in both production systems.

‘San Marzano’ had the most small-sized fruits per plants in both production systems in 2023 (Table 11). ‘Big Mama’, ‘Gladiator’ and ‘Super Sauce’ did not produce small-sized fruits in either production system.

Table 11. Effect of cultivar on the fruit size for paste tomato cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Very large[x]		Large		Medium		Small	
	Number of fruits/plant							
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Amish Paste	7c[y]	3b	28ab	7bcd	32c	3c	3b	0b
Big Mama	4cd	1bc	25b	16a	11d	3c	0b	0b
Cauralina	23a	10a	21b	6cde	7d	1c	1b	0b
Gladiator	6c	2bc	33a	10abc	5d	0c	0b	0b
Granadero	0d	0c	13c	1de	94a	42a	12b	1b
Pozzano	1d	2bc	22b	14ab	62b	26b	20b	1b
San Marzano	0d	0c	0d	0e	17cd	19b	90a	46a
Super Sauce	15b	7a	11c	9abc	3d	3c	0b	0b
P-Value	<.0001	<.0001	<.0001	0.0008	<.0001	<.0001	<.0001	<.0001

[z]CT= Caterpillar tunnel; OF= Open field.

[y]Means with different alphabets within a column represent significant difference at P<0.05.

[x]Very large, large, medium, small: Categorized according to the United States consumer standards for fresh tomatoes.

Fruit composition/quality

'Gladiator' reported the highest pH value compared to other cultivars in both production systems in 2023 (Table 12). However, in the CT production system, the pH of 'Gladiator' did not differ significantly from 'Pozzano' and 'Big Mama'.

A significant difference on TSS was observed among the cultivars in both production systems in 2023 (Table 12). 'Amish Paste' had the highest TSS content in the fruits but did not differ from 'Cauralina' in both production systems. When examining TSS for each production system, each cultivar in the OF had higher TSS content compared to the CT.

A significant effect of cultivars on TA was observed in the OF production system in 2023 (Table 12). 'San Marzano' had the highest TA compared to other cultivars, except for 'Amish Paste'. However, all the cultivars had similar TA in the CT production system. When examining TA descriptively for each production system, each cultivar in the CT had lower TA content compared to the OF.

In 2023, a significant cultivar response was observed in the TSS/TA ratio in the OF production system (Table 12). 'Super Sauce' had the highest TSS/TA ratio compared to other cultivars. A descriptive comparison between two production systems showed that TSS/TA ratio of each cultivar in the CT production system was higher compared to the OF production system.

Table 12. Effect of cultivar on fruit quality for eight paste tomato cultivars in the open field and caterpillar tunnel production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	pH		TSS (°B)		TA (%)		TSS/TA	
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Amish Paste	4.13bcd[y]	4.15bcd	5.17a	5.72a	0.76a	1.16ab	6.93a	4.92bc
Big Mama	4.25ab	4.19bc	4.50bc	5.31bc	0.63a	1.03cd	7.36a	5.17b
Cauralina	4.10cd	4.08de	5.10a	5.47ab	0.70a	1.06bcd	7.38a	5.22b
Gladiator	4.35a	4.52a	4.09d	5.09bcd	0.60a	0.99de	6.82a	5.28b
Granadero	4.08d	3.97e	4.49bc	4.84de	0.68a	1.13bc	6.60a	4.30cd
Pozzano	4.24ab	4.26b	4.28cd	5.00cde	0.60a	0.90e	7.19a	5.55b
San Marzano	4.20bc	4.19bcd	4.68b	5.23bc	0.85a	1.27a	5.61a	4.12d
Super Sauce	4.14bcd	4.09cd	4.19cd	4.56e	0.74a	0.75f	6.63a	6.20a
P-Value	0.0014	<.0001	<.0001	0.0007	0.2323	<.0001	0.0781	0.0003

[z]CT= Caterpillar tunnel; OF= Open field; TSS= Total soluble solid; TA=Titratable acidity.
yMeans with different alphabets within a column represent significant difference at P<0.05.

Final plant height

A significant difference in the final plant height was observed among the cultivars in both production systems in 2023 (Table 13). ‘Granadero’ was the tallest plant across both systems. However, the height was not significantly different from ‘Amish Paste’, ‘Cauralina’ and ‘Pozzano’ in the CT production system, and ‘Amish Paste’ and ‘Cauralina’ in the OF production system. When comparing two-production systems descriptively, each cultivar in the CT production system was taller compared to the OF production system.

Table 13. Effect of cultivar on the final plant height for paste tomato cultivars in caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Final plant height (cm)	
	CT[z]	OF
Amish Paste	332ab[y]	239a
Big Mama	254c	200b
Cauralina	344a	230a
Gladiator	274bc	204b
Granadero	372a	240a
Pozzano	329ab	200b
San Marzano	212c	171c
Super Sauce	101d	75d
P-Value	<.0001	<.0001

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.

Discussion

A numerical comparison between two production systems showed higher daily average air temperature in the CT than the OF production system by 0.6 °C in both years. The marginal difference in the air temperature can be attributed to the dimensions of the CT. Caterpillar tunnels are smaller and shorter than HTs (Wortman et al., 2016), and under the polyethylene films, air volatility increases as air volume decreases (Lamont, 2005). Results from the current study align with Zhao and Carey (2009), where they reported the increase in average daily temperature by ~0.2-0.3 °C in the single poly HT compared to the OF production system. The difference in maximum air temperature between the two production systems in October was 9.7 °C and 5.4 °C in 2022 and 2023, respectively. The higher maximum temperature in the CT can be attributed to the rapid rise in temperature in the CT during daytime (Wallace et al., 2012; Wien, 2009). The greatest air temperature fluctuation was recorded in the CT compared to the OF production system. The greatest air temperature fluctuation in the CT production system can be attributed to the rapid increase and decrease in air temperature compared to OF during the hot and the cold hours of the day. According to Wien (2009), the minimum air temperature in the tunnel may drop lower than OF temperature depending on the characteristics of polyethylene film. The fluctuation in the temperature was also influenced by the transparency of polyethylene film to IR radiation (Cemek et al., 2006; Wien, 2009). The higher GDD in the CT production system in both years resulted from higher average air temperature in the CT compared to the OF production system (0.6 ºC in both years) (Rho et al., 2020; Wallace et al., 2012).

Comparing the soil temperature across two production systems, the daily average soil temperature in the CT production system was higher by 1.4 °C and 1.3 °C in 2022 and 2023, respectively, than OF production system. The daily average soil temperature in May and October was higher by 3 °C in the CT production system compared to the OF production system. Similar results were recorded by Wien (2009), where soil temperature fluctuated little and was only 2 °C higher in the HT compared to the OF at 10 cm depth during winter months.

In 2022, transplanting overmatured seedlings in the CT production system resulted in early flowering compared to 2023. In 2023, plants in the CT production system took longer to flower than the OF production system, likely due to slower growth and development of the seedlings in the CT during crop establishment phase from early-May to mid-June. However, other phenological stages did not differ. The first date to flowering, fruit development and harvest were 2 June, 5 June, and 24 July, respectively, in the CT production system, while first date to flowering, fruit development and harvest were 3 July, 10 July, and 21 August, respectively, in the OF production system in 2023. Fruit harvest was extended by 11 days and 39 days in the CT production system compared to the OF production system in 2022 and 2023, respectively. Early transplanting and greater GDD in the CT production system facilitated the earlier and extended harvesting in the CT than in OF production system (Maughan et al., 2012; Rho et al., 2020; Sideman, 2020). In addition to protection from wind chill, higher daily average soil temperatures in May by 3 °C facilitated early transplanting in the CT compared to the OF production system by providing warmer conditions for root growth (Rowley et al., 2011; Wien, 2009). Additionally, protection from early fall frost under the CT production system also extended the harvest later in the fall by 11 days compared to the OF harvest in 2023. All the cultivars in both production systems were harvested later than the estimated number of days to first harvest from the transplanting, except for ‘Amish Paste’. According to Loria (2019) catalogue descriptions may not reflect the condition of the particular area. The extended days between the transplanting and first harvesting in the CT can be attributed to the slower growth due to lower air and soil temperature during the seedling establishment phase (May) in the CT compared to the OF production system (June) (Haghighi et al., 2014; Kang and Saltveit, 2002).

The total number of fruits per plant, total weight, number of marketable fruits and marketable fruits weight were significantly different among the cultivars. In 2022, ‘Granadero’ outperformed other cultivars in terms of yield and performance in the CT production system (Appendix Table A2). It was also the cultivar with more fruits infected with blossom end rot compared to other cultivars. However, ‘Granadero’ did not show symptoms of TSWV in either production systems. Therefore, the greater yield of ‘Granadero’ can be attributed to the resistance to TSWV.

In 2023 in both production systems, ‘San Marzano’ had the most total and marketable fruits per plant. ‘Cauralina’ had the greatest total weight of fruits per plant in both production systems. However, ‘Cauralina’, ‘Granadero’ and ‘Pozzano’ had the greatest marketable fruit weight per plant in both production systems. Descriptive analysis of two production systems in 2023 showed increased yield in the CT production system compared to the OF production system. Similar results were reported where earlier transplanting in HTs resulted in earlier harvesting. The earlier and extended fall harvest resulted in higher yields per plant in the HT production system compared to OF system (Hunter et al., 2012; Maughan et al., 2012; Rho et al., 2020).

The greater marketability of ‘Granadero’, ‘Amish paste’, ‘Cauralina’ and ‘Super Sauce’ in the CT production system can be attributed to fewer BER infected fruits. However, ‘San Marzano’ and ‘Pozzano’ showed a greater reduction in marketability in the CT production system, likely due to BER infection. In the OF production system, the reduction in marketability of ‘Amish Paste’, ‘Cauralina’ and ‘Gladiator’ was due to other defects, including catfaces and deep scars at the end of the growing season.

‘San Marzano’ and ‘Pozzano’ developed more BER in the CT than in the OF, however, marketable yield remained higher in the CT production system due to greater number of fruits set per plant. The large diurnal temperature fluctuation and higher maximum temperature during the day may have triggered BER in the CT production system (Rho et al., 2020). Furthermore, erratic watering (Appendix Fig. B1) may have also resulted in BER, as plant’s capabilities of absorbing Ca^{2+} get reduced when plant does not receive adequate water or when there is excess of water in root zone (Masarirambi et al., 2009). Similarly, high relative humidity (RH) inside CT may have played a role in BER (Appendix Fig. B2). Banuelos et al. (1985) reported that fruits exposed to a continuous high relative humidity receive less Ca^{2+} transported from the petiole into the basal portion of the fruits than those not exposed to high RH.

In our study, pH value ranged from 3.69-4.52. The highest pH value (4.52) was observed in 'Gladiator' in OF production system in 2023, exceeding the maximum desirable level of 4.4 for paste tomatoes (Garcia E. and Barrett, 2006). The TSS was in the desirable range of 4.5-6.25 ºBrix except for 'Gladiator', 'Pozzano' and 'Super Sauce' in the CT production system. These TSS values are similar to the values reported by Akbudak (2010), where they attributed the differences to the varietal characteristics. In both production systems, TA was greater than the desirable range of around 0.35%. Cultivars in the CT production system had higher TSS/TA ratio than OF production system. However, the ratio was lower compared to other studies (Bilalis et al., 2018; Pieper and Barrett, 2009; Zhu et al., 2018). The lower TSS/TA ratio can be attributed to high TA. According to Akbudak (2010), TA depends on the maturity of the tomatoes. Further, seasonal variation, diurnal temperature fluctuation and horticultural practices may also affect the fruit composition of tomatoes (Araujo et al., 2014).

Compared to 2023, plants were shorter in 2022 (Appendix Table A4) due to TSWV infection. Descriptive analysis showed the difference between the two production systems in 2023. Compared to the OF production system plants were taller in the CT production system. A study by Rogers and Wszelaki (2012) recorded significantly taller plants in the HTs compared to the OF plots. The taller plants in the CT production system were attributed to the improved microclimate, earlier transplanting, extended growing season and protection from biotic and abiotic stress.

Limitation

The study lacked replication for the production systems. Therefore, a statistical comparison between two production systems was not feasible. Additionally, removal of crops due to severe TSWV infection in the OF production system made it impossible to compare the cultivars in the CT and OF production systems in 2022.

Conclusion

Although severe TSWV infection was recorded in 2022, the study demonstrated the benefit of microenvironment modification with the CT compared to the OF production system. The findings highlight the potential of CT to extend the growing season and protect the crops from biotic and abiotic stresses resulting in greater yield and quality. Compared to the recent studies in in the HT production of tomato in the upper Midwest (Dawson et al., 2017; Splichal, 2020), our trial in 2023 produced higher total and marketable yield per plant. Furthermore, the study reported the performance of different tomato cultivars between two production systems which will aid in cultivar selection for North Dakota environments.

The study also signifies the importance of further research on biotic and abiotic stresses, including temperature fluctuation, TSWV and BER. Also, feasibility and economic analysis of the CT and HT production system is essential for offering practical recommendations to local market and commercial growers in the upper Midwest.

CHAPTER 4

Bell Pepper

Introduction

Bell pepper is a warm-season vegetable crop characterized by many culinary purposes (Maughan et al., 2012). Commercial production of bell pepper in the US has been documented since 1600s (Bosland, 1996). In 2022, approximately 467,000 Mg of bell peppers for fresh market and 53,500 Mg of bell peppers for processing market were produced on 12,800 ha with a crop production value $673 million in the US (USDA, 2023).

Bell peppers are sensitive to light frost and cool temperatures. For summer vegetables like bell pepper, season extension techniques allow earlier transplanting and extend the harvest later into the fall as compared to field-grown crops (Maynard and Calsoyas, 2016). These techniques not only potentially increase the yield per unit area but also improve market accessibility due to an earlier and prolonged harvest season. Having a high tunnel (HT) extends the growing season and also facilitates the production of mature colored fruit, which can be challenging in field conditions when the growing season is short (Sideman, 2020). The increase in temperature allows peppers to be planted four to six weeks earlier (Maughan et al., 2012) and harvested six weeks later under HT compared to the open field (OF) harvestings (Sideman, 2020). A varietal trial conducted by Splichal (2020) in North Dakota reported bell pepper production of 1.24 kg per plant in the HT, with a 10-fruit average per plant, whereas the average yield in the OF was 1.06 kg per plant, with a nine-fruit average per plant. The difference in pepper yields between the HT and OF conditions was attributed to the incidence of biotic and abiotic stressors during the trials. Similarly, a study by Sideman (2020) reported that total yields in HT ranged from 51,559 to 73,976 kg/ha significantly surpassing typical OF pepper yields ranging from 25,779 to 30,263 kg/ha. While some research has been reported on HT and OF production of specialty crops in the upper Midwest (Splichal, 2020), no research focusing on summer vegetable production or varietal trials using low-cost portable caterpillar tunnel (CT) has been reported in the US.

Objectives

Objectives of this trial were to evaluate the physiological, morphological, and productive differences among eight commercially available bell peppers cultivars with regard to CT and OF, and to determine the air and soil temperature differences, and relative humidity differences between CT and OF, as well as what influence these differences have on plant physiology, morphology, and productivity.

Material and methods

Site description

The study was carried out at the NDSU Horticulture Research Farm near Absaraka, ND, during 2022 and 2023 (46°59’10.7” N 97°21’21.8” W, 1070 m elevation). The region falls under plant hardiness zone 4A (USDA-ARS, 2023). This region is classified as continental with an average precipitation range of 380 to 760 mm (Tollerud et al., 2018). The soil profile at the location is a Warsing soil series characterized as moderately well drained fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls (USNRCS, 1983). Based on the historical data from 1991-2020 the average growing season at Absaraka is nearly 138 days with average last and first frost dates falling between May 11-20 and September 20-30, respectively (NOAA, 2024).

Caterpillar tunnel installation

The CT (Farmers friend, Centerville, TN 37033) was installed adjacent to field trial after the field was tilled and before transplanting. The CT dimensions were 30.48 m long, 4.88 m wide, and 2.74 m tall, with a gothic style arch (Appendix Fig. B6 and B10). It was constructed on 3 June 2022, using 2-mm galvanized steel and a single layer 0.15-mm clear polyethylene film, with a north-south orientation. Hoops were firmly secured into the ground by using 1.2 m long rebars that were pounded into the ground approximately 1 m with a 1.2 m spacing. Further, the structure was strengthened by steel center purlins, wind bracing, a lift kit, and cross bracing. Finally, the frame was covered with polyethylene film and was secured with wiggle wire at both ends of the tunnel. The polyethylene film was anchored to the frame with ropes using a zig-zag pattern that gives the tunnel structure resemblance of a caterpillar. A zipper door was installed at one end of the tunnel, and the other end was securely fastened by folding the polyethylene film and tying it to a T-post placed 1.2 m from the end wall during 2022 growing season. However, in 2023, instead of tying the polyethylene film to the T-post, it was oriented vertically, descending perpendicularly, and was tightly held using construction blocks to mitigate potential abrasion of the polyethylene film against heavy wind. The internal temperature of the tunnel was recorded throughout the growing seasons even though it remained unregulated, and the side walls remained open until late September.

Planting materials

For the indoor CT trials and outdoor OF trials, eight bell pepper cultivars (Johnny’s Selected Seeds, Winslow, ME and Harris Seeds Company, Rochester, NY) were selected due to disease resistance, and days to maturity (Table 14). All the cultivars were first generation (F1) hybrids.

Table 14. Bell pepper trial cultivars, seed source and days to maturity.

Cultivars	Seed source[z]	Disease resistance[y]	Days to maturity[x]
Early Sunsation	HS	IR to BLS	70
Intruder	HS	HR to BLS (races 1-3), TEV, and TMV; and IR to PC	75
Orange Blaze	HS	HR to BLS (races 0-3, 7 and 8) and TMV	68
King Arthur	JSS	HR to BLS (races 1–3, 7, and 8) and potato virus Y	59-79
Olympus	JSS	HR to BLS (races 1-3, 7 and 8)	65-85
Ninja	JSS	HR to TMV and IR to BLS (races 1–10)	60-80
X3R Red Knight	JSS	HR to BLS (races 1-3) and PVY	57-77
Classic	JSS	HR to BLS (Races 1–3, 7, and 8) and TMV	63-83

[z] HS=Harris Seeds; JSS=Johny's Selected Seeds.
[y]HR= High resistance; IR= Intermediate resistance; BLS= Bacterial Leaf Spot races; PC= Phytophthora; PVY= Potato Virus Y; TEV= Tomato Etch Virus; TMV= Tobacco Mosaic Virus.
[x]Days to maturity: Number of days from transplanting to varietal color development.

Transplant establishment

In 2022, for the CT production system, seeds were started on 30 March at the Lord and Burnham Greenhouse at North Dakota State University, Fargo, ND (23.9℃, 16:8 L:D) in standard insert 800 series (T.O. Plastics, Clearwater, MN), filled with a planting mix (Pro-Mix BX, Premier Tech, Quebec, Canada) (Table 14). To enhance better root growth, the seedlings were transplanted into 10.16 cm SVD-450 molded plastic pots using the same planting mix on 20 April. For the OF production system, seeds were started on 13 April following similar procedures and using the same planting mix as the CT trial. The seedlings were then transplanted into 10.16 cm SVD-450 molded plastic pots on 11 May. Plants were irrigated every other day until transplanted into soil. A 20:20:20 general purpose water-soluble fertilizer (JR Peters Inc., Allentown, PA) at 100 parts per million (ppm) was injected into the irrigation system. During the seedling establishment phase, aphid and thrips infestation were observed. To address the issue, pyrifluquinazon (SePRO Corporation, Carmel, IN) at 0.71ml/L was applied. The seedlings for the CT and OF trials were exposed to an open environment (between greenhouse ranges) for acclimatization on 6 May and 20 May respectively. The construction of CT extended beyond the anticipated planting date because of construction delays due to snowfall accumulation and rainfall, resulting in over mature seedlings at transplanting on 3 June.

In 2023, seeds were started in one of the North Dakota Agricultural Experiment Station (NDAES) greenhouse rooms to safeguard the seedlings from potential thrips and aphid infestation. The seeds for CT trial were seeded on 15 March in standard insert 800 series and transplanted into 10.16 cm SVD-450 molded plastic pots on 11 April using the same planting mix previously described. For the OF trial, seeds were seeded directly into 10.16 cm SVD-450 molded plastic pots on 17 April. The seedlings were transplanted into the CT on 5 May without acclimation due to the cooler outdoor temperatures. The seedlings for an OF production system were transplanted on 12 June after a week-long acclimation period.

Site preparation and layout

Before transplanting, soil samples were collected from two depths (0 cm to 15 cm and 15 cm to 30 cm) and placed into different soil sampling bags. These samples were submitted to the NDSU Soil Testing lab (Fargo, ND) for soil nutrient test (Appendix Table A10 and A11). Before transplanting, beds were tilled using a rotor-tiller (Woods Equipment, Oregon, IL) attached to a tractor. In each production system, three rows were prepared, and a single line of 0.38-mm drip tape with emitters spaced at 20.3 cm on the center with a flow rate of 2.15 x 10-4 m^3s^{-1} was installed beneath black plastic mulch (Wrap Bros, Chicago, IL) using a tractor-mounted plastic mulch layer (Progressive Grower, West Wareham, MA). The NPK was applied as a split application with a total of 134.5: 134.5: 134.5 kg/ha in three split doses during each growing season. A granular 19:19:19 NPK (J.R. Simplot Company, Boise, ID) was broadcasted pre-plant at 67.25: 67.25: 67.25 kg/ha, while the rest was fertigated in two split doses at 33.63: 33.63: 33.63 kg/ha (20:20:20 water soluble fertilizer) during the flowering and fruiting period at 6-8 weeks interval using drip tape (Toro® Aqua-Traxx, DripWorks, Willits, CA). Irrigation was scheduled on Mondays, Wednesdays, and Fridays, each lasting two hours throughout the growing season.

Weather

Watchdog 1000 series micro station dataloggers (Spectrum Technologies, Inc. Aurora, IL) were installed to monitor air and soil temperatures. Temperature probes were positioned at the center of each production system and data loggers were programmed to collect data at hourly intervals throughout the growing season. Soil temperature readings were recorded at a depth of 30 cm and air temperature readings were taken at 1.5 m height across both environments during both growing seasons. The daily average, maximum and minimum air temperature were calculated and numerically compared between the two-production systems. During the 2023 growing season, WaterScout SMEC 300 soil moisture sensors (Spectrum Technologies, Inc. Aurora, IL) were installed to monitor the soil moisture levels throughout the growing season. Further, the accumulated growing degree day (GDD) was calculated using the equation:

$$GDD = \frac{daily\ max.\ temperature + daily\ min.\ temperature}{2} - base\ temperature \qquad (3)$$

Where,

above high cutoff temperature= 30 ºC

below base cutoff temperature= 10 ºC

Management Practices

Seedlings were transplanted at the spacing of 1.52 m between rows and 0.61 m between plants. Weeds were removed manually to ensure optimal crop growth and reduced pest infestations. During the 2022 growing season, the experiment became infested with herbivorous insects such as aphids, thrips, and leafhoppers. In response, imidacloprid (Admire Pro, Bayer CropScience LP, NC) at the rate of 163 ml/ha was applied to effectively control those insects. The experiment was also heavily infected with TSWV from an incident with another researcher during the seedling growth stage. To reduce the spread of the virus, infected plants were removed as soon as the symptoms were visible. Notable symptoms such as bronzing of upper sides of the young leaves, which later developed into necrotic spots, leaves curled upward while the midveins curled downward, and tip dieback was visible symptoms were noted on approximately 25% of the plants in the CT and about 50% of the plants in the OF. In 2022, the experiments were located at the field's east side. However, in 2023 the CT and the OF trial were relocated to the field's west side. The viral infestation was lower in 2023. Similarly, BER affected some fruits in 2022. Therefore, in 2023, calcium nitrate (Yara North America, Inc, Tampa, FL) at 28.8 gm/l of water was manually sprayed over the foliage to control BER.

Data collection

Crop phenology

Phenological, yield and quality data were recorded and compared across two production systems. Phenological data were recorded on the number of days to first flowering, days to first fruiting and days to first harvest from transplanting date based on visual inspection (Table 14). For the phenological data, plants were examined every other day throughout the growing season. The days to first flowering were recorded once the first flower fully opened. Similarly, days to first fruiting were recorded upon the fruit's emergence with complete petal shedding. Green bell peppers were harvested based on the mature fruit size and ease of separation before any varietal color developed (Quamruzzaman et al., 2022).

Table 15. Dates for seeding, transplanting and harvest in the caterpillar tunnel and open field production system in 2022 and 2023.

Year	Action	Caterpillar tunnel	Open field
2022	Seeding	30 March	13 April
	Transplant	3 June	3 June
	First harvest	25 July	25 July
	Last harvest	11 October	4 October
2023	Seeding	15 March	17 April
	Transplant	5 May	12 June
	First harvest	3 July	14 August
	Last harvest	26 October	9 October

Note: Seeding and transplanting date depend on outdoor environment and workability of soil.

Crop yield

Fruit harvest occurred twice a week during a peak period and once a week other time for approximately 11 and 10 weeks in the CT and OF production systems, respectively, during the 2022 growing season, and 16 and 8 weeks in the CT and OF production systems, respectively, in 2023. Data were recorded on the total number of fruits per plant, total weight of fruits per plant, number of marketable fruits per plant, and marketable fruit weight per plant.

Fruit quality

Bell peppers were graded following sweet peppers grades and standards (USDA, 2005) from USDA Agricultural Marketing Service (USDA, 2016a). The grades were classified as US fancy, US #1 and US#2 based on shape, appearance, and presence of defects. The US fancy consisted of fruits having diameter and length not less than 7.62 cm and 8.89 cm respectively. The US #1 consisted of fruits having diameter and length not less than 6.35 cm. US #2 consisted of fruits having diameter and length less than 6.35 cm. The quality of bell peppers was assessed based on shape, size, freshness, and surface defects. Fruits that were deeply bruised, rotten, had deep scars, catface, or defects that would compromise the postharvest storage life were considered unmarketable. Fruits with minor scars were considered marketable.

Final plant height

Final plant height was recorded at the end of each growing season to evaluate plant growth. Plant height was determined by measuring the distance from the soil line to the growing point of each plant (Lang et al., 2020).

Experimental design and statistical analysis

Within each production system, cultivar trials were laid out in a randomized complete block design with four replications. Each plot within a replication consisted of two plants from the same cultivar, resulting in a total plot area of 1.86 m^2. In 2022, TSWV infections were observed in about 25% of plants in the CT and about 50% in the OF trial. Thus, a comprehensive comparison was made only between the 2022 CT, 2023 CT and 2023 OF production systems due to severity of TSWV in the OF production system in 2022. Statistical analyses were performed within each production system due to lack of CT replication. Additionally, the Cultivars 'Classic' and 'Orange Blaze' were excluded from the statistical analysis in the 2022 CT production system due to infection in all replications.

Statistical Analysis System (SAS) version 9.4 was used for the statistical analysis, using PROC GLIMMIX with the REML estimation method (SAS Institute, SAS Circle, Cary, NC). Cultivars were treated as a fixed effect and the replication within each production system was treated as a random effect. Least squares means was used to separate the means at $\alpha = 0.05$ where appropriate.

Results

In 2022, OF trial was excluded due to the severity of TSWV among all the replications in the trial. The statistical analysis and the analysis of variance (ANOVA) for 2022 CT production system is included in the appendix and only the results from 2023 were included in this thesis.

Air and soil temperature 2022

Air temperature

The average daily air temperature throughout the growing season was 0.6 °C higher in the CT compared to the OF production system (Table 16). July had the highest average temperature i.e., 24.5 °C and 24.2 °C for the CT and OF production systems, respectively. Further, June 19 was the hottest day of the year with the average air temperature of 33 °C in both production systems. The minimum temperature recorded was -3.2 °C and -4.8 °C in the CT and the OF production systems, respectively, on 7 October. Comparing the monthly average air temperature between the two production systems, in October, the coldest month of the growing season, the CT had an average air temperature of 15.2 °C while the OF system was 12.2 °C. The greatest diurnal temperature fluctuation of the CT and OF production systems were 36.3 °C and 26.3 °C, respectively. Considering the average daily temperature, 29 out of 126 days (7 June-11 October) in the CT production system deviated from the optimal temperature range of 18 °C-30 °C for growth (Welbaum, 2015). Similarly, 32 out of 126 days in the OF production deviated from the optimal 18 °C-30 °C range. The plants in the OF could not survive the frost event of 5 October which resulted in the end of harvest season seven days earlier in the OF production system compared to CT production system. The GDD in the CT production system from June 7 to October 11 was 1440, while the OF production system was 1386.

Table 16. Average air temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Months	Avg. air temperature CT[z] (°C)	Avg. air temperature OF (°C)	Max. air temperature CT (°C)	Max. air temperature OF (°C)	Min. air temperature CT (°C)	Min. air temperature OF (°C)
Jun (7-30)	23.7	23.4	41.7	41.7	9.8	9.1
Jul	24.5	24.2	40.7	40.3	11.4	9.8
Aug	22.2	21.9	40.1	39.6	9.6	8.2
Sep	17.1	16.7	35.7	35.6	1.6	-0.6
Oct (1-11)	15.2	12.2	38.4	28.8	-3.2	-4.8

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Soil temperature

The average daily soil temperature throughout the growing season was 1.4 °C higher in the CT compared to the OF production system. July had the highest average soil temperature in the CT and OF production systems at 26 °C and 25 °C, respectively (Table 17). The greatest average soil temperatures in the CT and OF production systems occurred on 18 July at 27.5 °C and 26.4 °C, respectively. The minimum soil temperature in the CT production system was 13.2 °C on 8 October, while the minimum soil temperature of 10.6 °C was recorded on the same day in the OF. Comparing the average monthly soil temperatures between two production systems showed that in October, the coldest month of the growing season, the CT production system had average soil temperature of 16.9 °C, while the average soil temperature in the OF system was 14 °C. The greatest soil temperature fluctuation of 5.5 °C occurred in the CT production system on 17 July, while the fluctuation of 2.8 °C was recorded in the OF production system.

Table 17. Average soil temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Months	Avg. soil temperature CT[z](°C)	Avg. soil temperature OF (°C)	Max. soil temperature CT (°C)	Max. soil temperature OF (°C)	Min. soil temperature CT (°C)	Min. soil temperature OF (°C)
Jun (7-30)	23.3	22.1	29.5	27.2	18.6	17.4
Jul	26.0	24.9	30.1	27.9	21.1	21.0
Aug	24.5	23.4	28.6	26.6	20.1	19.4
Sep	20.3	18.6	26.9	23.8	14.7	13.0
Oct (1-11)	16.9	14.0	20.1	17.3	11.8	10.6

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Air and soil temperature 2023

Air Temperature

The average daily air temperature in the CT and OF production system were 19.3 °C and 18.7 °C respectively (Table 18). June had the highest average monthly temperature in the CT and OF production systems at 23.5 °C and 23.4 °C, respectively. The hottest day of the season in the CT and OF production systems was 20 June with average air temperatures of 30.7 °C and 30.6 °C, respectively. The coldest day of the growing season for the CT and OF was 26 October with an average air temperature of 3.4 °C and 1.1 °C, respectively. In October, the coldest month of the growing season, the CT had an average air temperature of 10.1 °C while the temperature in the OF system was 8.5 °C. The greatest air temperature fluctuation of 29.4 °C was recorded in the CT production system on 19 September, while the fluctuation of 26.4 °C was recorded on 16 October in the OF. Considering the average daily temperature, 46 out of 162 days (18 May-26 Oct) in the CT system deviated from the optimal temperature range of 18 °C-30 °C for growth (Welbaum, 2015). In contrast, 56 out of 162 days in the OF production system deviated from the optimal temperature range of 18 °C-30 °C for growth. The plants in the OF could not survive the frost event of 11 October which resulted in the end of harvest season 17 days earlier than the CT production system. The GDD in the CT and OF production systems from 18 May to 26 October were 1658 and 1608, respectively.

Table 18. Average air temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Months	Avg. air temperature CT[z] (°C)	Avg. air temperature OF (°C)	Max. air temperature CT (°C)	Max. air temperature OF (°C)	Min. air temperature CT (°C)	Min. air temperature OF (°C)
May (18-31)	20.7	20.0	37.9	37.1	5.4	4.6
Jun	23.5	23.4	39.1	39.7	10.1	8.9
Jul	21.6	21.2	39.1	39.7	7.9	7.1
Aug	21.2	21.4	38.3	38.7	9.4	8.6
Sep	18.8	17.6	40.8	37.9	4.0	2.4
Oct (1-26)	10.1	8.5	41.2	35.8	-1.4	-2.9

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Soil temperature

The average daily soil temperature throughout the growing season was 1.3 °C higher in the CT compared to the OF production system (Table 19). June had the highest average soil temperature in the CT production system at 23.7 °C and August had the highest average soil temperature in the OF production system at 22.9 °C. The greatest average soil temperatures in the CT and OF production systems occurred on 3 July at 26.5 °C and on 3 September at 26.9 °C, respectively. The minimum soil temperature in the CT production system was 9.8 °C on 26 October, while the minimum soil temperature of 6.8 °C was recorded on the same day in the OF production system. Comparing the average monthly soil temperature between two production systems showed that in October, the coldest month of the growing season, the CT production system had an average monthly soil temperature of 14.6 °C, while the minimum soil temperature in the OF system was 11.6 °C. The greatest soil temperature fluctuation of 5.7 °C occurred in the CT production system on 20 May, while the fluctuation of 8.6 °C was recorded in the OF production system on 10 September.

Table 19. Average soil temperatures for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Months	Avg. soil temperature CT[z] (°C)	Avg. soil temperature OF (°C)	Max. soil temperature CT (°C)	Max. soil temperature OF (°C)	Min. soil temperature CT (°C)	Min. soil temperature OF (°C)
May (18-31)	18.8	15.7	24.4	21.7	13.2	10.6
Jun	23.7	22.5	27.5	26.7	19.8	19.0
Jul	23.7	22.8	27.9	26.7	19.7	19.1
Aug	23.0	22.9	27.4	30.0	19.9	19.0
Sep	20.4	19.7	26.1	30.9	15.8	13.6
Oct (1-26)	14.6	11.6	24.9	18.5	9.8	6.8

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Crop phenology

A significant difference in days to first flowering was observed among the cultivars in both production systems in 2023 (Table 20). In the CT production system, ‘Orange Blaze’ flowered significantly earlier than other cultivars. However, in the OF production system, ‘Early Sunsation’ flowered significantly earlier than other cultivars but not earlier than ‘Ninja’ and ‘Orange Blaze’.

In the CT production system, ‘Orange Blaze’ produced fruits significantly earlier than other cultivars in 2023 (Table 20). However, in the OF production system, ‘Early Sunsation’ produced fruits significantly earlier than ‘Classic’, ‘Intruder’ and ‘Olympus’ but not earlier than ‘Orange Blaze’, ‘King Arthur’, ‘Ninja’ and ‘X3R Red Knight’.

The effect of cultivars on the number of days to first harvest was not significant within each production system in 2023 (Table 20). However, when examining the days to first harvest for each production system descriptively, all the cultivars harvested at least one day earlier in the CT production system. ‘Olympus’ had the greatest difference in days to first harvest (4 days) between production systems. Cultivars in the CT production system were harvested from 3 July to 26 October, while harvesting in the OF began on 14 August and continued until 9 October.

Table 20. Effect of cultivar on phenological stages for bell pepper cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Days to first flowering[x]		Days to first fruiting		Days to first harvest	
	CT[z]	OF	CT	OF	CT	OF
Classic	35a[y]	39a	39a	43a	63a	65a
Early Sunsation	30bc	27c	35bc	35d	62a	63a
Intruder	33a	38a	37ab	43ab	62a	64a
King Arthur	34a	32b	38ab	38cd	62a	64a
Ninja	30bc	30bc	35bc	38bcd	62a	63a
Olympus	30c	33ab	33c	40abc	60a	64a
Orange Blaze	26d	30bc	29d	38cd	62a	64a
X3R Red Knight	33ab	34ab	37ab	39bcd	61a	63a
P-Value	<.0001	0.0020	<.0001	0.0231	0.1713	0.1882

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.
[x]Days to each phenological stage: Number of days from transplant to each phenological stage.

Crop yield

A significant cultivar response was observed for the total number of fruits per plant in both production systems in 2023 (Table 21). ‘Orange Blaze’ had the most fruits per plant in both production systems. Furthermore, when examining the cultivars across the two production systems descriptively, all the cultivars produced more fruits per plant in the CT production system. The production increased by 50%-158% depending on cultivars in the CT compared to the OF production system.

No difference was observed in the total weight of fruits per plant among the cultivars in the CT production system in 2023 (Table 21). However, in the OF production system, ‘Orange Blaze’ had the greatest total fruit weight per plant but was not significantly different from ‘Classic’ and ‘Early Sunsation’. A descriptive comparison within each cultivar across the two production systems showed an increased total weight of fruits per plant by 71%-50% in the CT production system compared to the OF production system.

A significant cultivar response was observed in the number of marketable fruits per plant in both production systems in 2023 (Table 21). ‘Orange Blaze’ had the most marketable fruits per plant in both production systems. Furthermore, when examining the cultivars across the two production systems descriptively, all the cultivars had more marketable fruits per plant in the CT production system. The number of marketable fruits increased by 50%-158% depending on cultivars in the CT compared to the OF production system.

There was no significant difference in the marketable fruit weight per plant in the CT production system in 2023 (Table 21). However, a significant difference was observed among the cultivars in the OF production system. ‘Orange Blaze’ had the greatest marketable fruit weight per plant at 3.63 kg/plant but was not statistically greater than ‘Classic’ and ‘Early Sunsation’. Furthermore, when examining the cultivars across the two production systems descriptively, all the cultivars had greater marketable fruit weight per plant in the CT production system compared to the OF production system. Marketable fruit weight increased by 73%-150% depending on cultivars in the CT compared to the OF production system.

Table 21. Effect of cultivar on the crop yield for bell pepper cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Total number		Total weight (kg)		Number of marketable		Marketable weight (kg)	
	Fruits/plant							
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Classic	43b[y]	25bc	5.75a	3.31abc	42b	25b	5.60a	3.23ab
Early Sunsation	47b	26b	5.93a	3.46ab	44b	24b	5.63a	3.19ab
Intruder	44b	17c	6.29a	2.51d	42b	17b	6.09a	2.44c
King Arthur	42b	21bc	5.32a	2.92bcd	39b	20b	5.03a	2.81bc
Ninja	45b	18c	5.36a	2.70cd	41b	17b	4.93a	2.63bc
Olympus	46b	20bc	6.07a	2.84bcd	43b	18b	5.66a	2.67bc
Orange Blaze	89a	59a	6.13a	3.65a	88a	58a	6.07a	3.63a
X3R Red Knight	37b	20bc	5.26a	2.88bcd	34b	20b	4.87a	2.80bc
P-Value	0.0001	<.0001	0.9029	0.0243	<.0001	<.0001	0.7724	0.0165

[z]CT= Caterpillar tunnel; OF= Open field.

[y]Means with different alphabets within a column represent significant difference at $P<0.05$.

Grades

Cultivar differences were present in the number of US fancy fruits per plant in both production systems in 2023 (Table 22). In the CT production system, all the cultivars except ‘Orange Blaze’ had a similar number of US fancy fruits per plant. However, in the OF production system, ‘Ninja’ had more US fancy fruits per plant but was not different from ‘King Arthur’, and ‘X3R Red Knight’. ‘Orange Blaze’ did not produce US fancy fruits.

A significant cultivar response was observed in the number of US #1 fruits per plant in both production systems in 2023 (Table 22). In the CT production system, the number of US #1 fruits was similar among all the cultivars except ‘Orange Blaze’, which had the fewest US #1 fruits per plant. However, in the OF production system, ‘Classic’ had the greatest number of US #1 fruits but was not significantly greater than ‘Early Sunsation’ and ‘X3R Red Knight’.

‘Orange Blaze’ had a significantly more US #2 fruits per plant compared to other cultivars in both production systems in 2023 (Table 22). None of the cultivars except ‘Orange Blaze’ had more than 15 and five US #2 fruits per plant in the CT and OF production system, respectively.

Table 22. Effect of cultivar on bell pepper grades in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	US fancy[x]		US #1		US #2	
	Number of fruits/plant					
	CT[z]	OF	CT	OF	CT	OF
Classic	5a[y]	3c	26a	17a	10b	5b
Early Sunsation	7a	5bc	22a	16ab	15b	3b
Intruder	8a	4bc	27a	11c	7b	2b
King Arthur	5a	6ab	25a	11c	8b	2b
Ninja	5a	7a	25a	12bc	11b	1b
Olympus	8a	4bc	25a	11c	9b	3b
Orange Blaze	1b	0d	10b	1d	78a	53a
X3R Red Knight	6a	5abc	20a	13abc	7b	1b
P-Value	0.0391	0.0002	0.0477	<.0001	<.0001	<.0001

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.
[x]US fancy, US #1, US #2: Categorized according to the United States standards for grades of sweet peppers.

Final plant height

A cultivar response was not observed in the final height of plants in the OF production system in 2023 (Table 23). However, in the CT production system ‘Olympus’ were significantly taller than other cultivars. When examining the height of each cultivar across the production systems descriptively, all the cultivars were taller in the CT compared to the OF production system.

Table 23. Effect of cultivar on the final plant height for bell pepper cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Plant height (cm)	
	CT[z]	OF
Classic	81.28b[y]	58.67a
Early Sunsation	70.70bc	48.01a
Intruder	78.10bc	51.44a
King Arthur	79.76bc	53.53a
Ninja	80.92b	55.73a
Olympus	94.62a	60.58a
Orange Blaze	72.71bc	54.48a
X3R Red Knight	68.22c	52.01a
P-Value	0.0021	0.0919

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.

Discussion

A numerical comparison between two production systems showed higher daily average air temperature in the CT than the OF production system by 0.6 °C in both years. The marginal difference in the air temperature can be attributed to the dimensions of the CT. Caterpillar tunnels are smaller and shorter than HTs (Wortman et al., 2016), and under the polyethylene films, air volatility increases as air volume decreases (Lamont, 2005). Results from the current study align with Zhao and Carey (2009), where they reported the increase in average daily temperature by ~0.2-0.3 °C in the single poly HT compared to the OF production system. The difference in maximum air temperature between the two production systems in October was 9.7 °C and 5.4 °C in 2022 and 2023, respectively. The higher maximum temperature in the CT can be attributed to the rapid rise in temperature in the CT during daytime (Wallace et al., 2012; Wien, 2009). The greatest air temperature fluctuation was recorded in the CT compared to the OF production system. The greatest air temperature fluctuation in the CT production system can be attributed to the rapid increase and decrease in air temperature compared to OF during the hot and the cold hours of the day. According to Wien (2009), the minimum air temperature in the tunnel may drop lower than OF temperature depending on the characteristics of polyethylene film. The fluctuation in the temperature was also influenced by the transparency of polyethylene film to IR radiation (Cemek et al., 2006; Wien, 2009). The higher GDD in the CT production system in both years resulted from higher average air temperature in the CT compared to the OF production system (0.6 ºC in both years) (Rho et al., 2020; Wallace et al., 2012).

Comparing the soil temperature across two production systems, the daily average soil temperature in the CT production system was higher by 1.4 °C and 1.3 °C in 2022 and 2023, respectively, than OF production system. The daily average soil temperature in May and October was higher by 3 °C in the CT production system compared to the OF production system. Similar results were recorded by Wien (2009), where soil temperature fluctuated little and was only 2 °C higher in the HT compared to the OF at 10 cm depth during winter months.

Transplanting overmatured seedlings in 2022 CT production system resulted in early flowering, fruiting and harvest compared to 2023 (Appendix Table A5). The first day to flower, fruit and harvest were 30 May, 2 June and 3 July respectively in the CT production system, while first day to flower, fruit and harvest were 3 July, 10 July and 14 August, respectively, in the OF production system in 2023. Fruit harvest was extended by 59 days in the CT production system compared to the OF production system in 2023 growing season. Early transplanting and greater GDD in the CT production system facilitated the earlier and extended harvesting than in OF production system (Maughan et al., 2012; Rho et al., 2020; Sideman, 2020). In addition to protection from wind chill, higher daily average soil temperatures in May by 3 °C facilitated early transplanting in the CT compared to the OF production system by providing warmer conditions for root growth (Rowley et al., 2011; Wien, 2009). Additionally, protection from early fall frost in the CT production system also extended the harvest later in the fall by 17 days compared to the OF harvest.

The total number of fruits per plant, total weight, number of marketable fruits and marketable fruit weight were significantly different among the cultivars. In the CT production system in 2022, all the cultivars performed similar in terms of yield parameters (Appendix Table A6). However, in 2023, ‘Orange Blaze’ had more total and marketable fruits per plant in both production systems. In the OF production system in 2023, total and marketable weight differs among the cultivars, which can be attributed to the difference in size of the fruits (grade) among the cultivars. However, in the CT production system the total and marketable yield did not differ significantly among the cultivars. The similarities can be attributed to the similar number of US fancy, US #1 and US #2 fruits per plant among the cultivars, except for ‘Orange Blaze’ which had a significantly greater number of US #2 fruits per plant.

Descriptive analysis of two production systems in 2023 showed increased yield in the CT production system compared to the OF production system. Similar results have been reported, where earlier transplanting in HTs resulted in earlier harvesting (Hunter et al., 2012; Maughan et al., 2012; O’Connell et al., 2012; Rho et al., 2020). The earlier and extended harvest resulted in higher yields per plant in the HT production system compared to the OF system.

Compared to the OF production system, plants were taller in the CT production system. The results align with Singh et al. (2013), where they attributed increased plant height and plant spread to earlier transplantation, extended season, improved microclimate, and protection from biotic and abiotic stresses in the low poly-tunnel. The shorter plant height under the CT production system in 2022 was due to the TSWV and aphid pressure that resulted in reduced growth and vigor of plants.

Limitation

The study lacked replication for the production systems. Therefore, a statistical comparison between two production systems was not feasible. Additionally, removal of crops due to severe TSWV infection in the OF production system made it impossible to compare the cultivars in the Ct and OF production systems in 2022.

Conclusion

The study demonstrated the potential of the CT to accelerate growth, improve yield and quality, and provide protection against pest pressure compared to the OF production system. The number of fruits per plants, total weight, marketable number of fruits and marketable fruit weight in our study were greater compared to other recent study from the upper Midwest and northern HTs and OF production system study (Jokela and Nair, 2016; Lang et al., 2020; Sideman, 2020; Splichal, 2020; Warren et al., 2015). This comparison showed that the CT has potential to produce fruits like or more than high tunnels.

The study also highlighted cultivar performance differences between the two production systems, offering valuable insights for cultivar selection in North Dakota environments. Our study observed that ‘Classic’ and ‘Early Sunsation’ performed well in both production systems and did not differ significantly in yield, US fancy and US #1 fruits in 2023. However, the limited year of study and severity of disease in 2022 made it difficult to conclude specifically which cultivar would do better.

Additionally, the study signifies the importance of further research on biotic and abiotic stresses management in the CT and OF production system like TSWV and aphids. The economic analysis of CT and HT production system can be important for providing recommendations for local and commercial growers in North Dakota.

CHAPTER 5

Grape

Introduction

Commercial grape production in continental climates may cause substantial economic losses due to winter freeze and spring frost injuries (Dami and Beam, 2004). In North Dakota, commercial grape production and the wine industry began in 2002 (Hatterman-Valenti et al., 2016). However, the extreme cold winters and unpredictable weather conditions have hindered wine grape cultivation. Abrupt temperature fluctuations, late spring and early fall frost threats, short growing seasons, insufficient growing degree days (GDD) and freezing winters have detrimental effects on grape production and consistency in fruit quality in North Dakota.

A study by Hatterman-Valenti et al. (2016) reported that grape cultivars must be able to ripen their berries with as low as 1184 GDDs and growing season of 132 days in North Dakota. Additionally, they also reported that among the 16 cold-hardy interspecific hybrid grape cultivars tested in North Dakota, the cultivars most adapted to North Dakota conditions lacked traits for wine quality such as low TA and medium TSS accumulation. Further, the climatic constraints in the northern climatic region may negatively affect bud break, flowering, veraison, berry maturity and berry composition (Pedneault et al., 2013).

Grapevines are sensitive to spring frost, as new shoots may get exposed to frost temperatures and result in less-developed shoots and inflorescences leading to partial crops (Freeman et al., 2019). Zabadal et al. (2007) reported a total loss of $63.6 million in the New York wine industry due to a single freeze event in 2004. Similarly, nearly a $1 billion economic loss was reported due to low temperature injury to small fruits including grapes that occurred in 21 states (Warmund et al., 2008). Recent frost events that caused huge economic losses include a frost event on May 17-18, 2023, in New York's Finger Lakes; a late spring-frost event the week of April 10, 2022, in Oregon and California vineyards; and frost events in late April and mid-May of 2020 in North Carolina (Fish and Romano, 2022; Friedlander, 2023; Hoffmann et al., 2021).

The combination of cold hardy hybrids and management practices have potential to produce high-quality grapes for the wine industry in cold climates (Tatar, 2020). Season extension structures such as caterpillar tunnel (CT) may be beneficial to produce grapes in several ways. A tunnel can reduce the risk of frost damage by retaining warm air during the day and moderating drops in night-time temperatures. For instance, during the spring and winter months, a single poly high tunnel (HT) can provide about 2 ℃ protection (Wien H. C. and Pritts, 2009). Kadir et al. (2006) reported that a microclimate within the HT has been observed to accelerate the fruiting season by 35 days and protect strawberries from winter damage. A variety trial conducted by Hernandez (2020) using table grape cultivars grown in HTs reported that a HT production of table grape was productive and feasible in areas where OF production system was costly and unsuitable. Further, a study by Garcia et al. (2016) reported successful fruit harvests from the HT plantings, but not from open field (OF) due to late spring frost in 2013.

Cold climate and primary quality attributes

The GDDs and primary fruit quality attributes such as TSS, pH and TA provide an important guideline for the maturity assessment of cold-climate wine grapes. In colder regions like North Dakota, unpredictable weather patterns have detrimental effects on the consistency of fruit yield and quality (Aipperspach et al., 2020). Furthermore, limited GDDs often leads to insufficient ripening of cold-hardy interspecific hybrid cultivars, resulting in high TA and lower TSS concentration (Pedneault et al., 2013).

Winter survival

In northern regions, the ability of grapevines to overwinter is crucial for vine survival and consistent production (Aipperspach et al., 2020). Carbohydrates play an important role in shoot lignification and serve as energy storage for winter survival. Therefore, inadequate carbohydrate storage adversely affects the growth and overall health of grapevines (Santarius, 1973). Accelerated berry ripening extends the temporal window for post-harvest carbohydrate accumulation before dormancy by shortening the harvesting time (Aipperspach et al., 2020). A study by Gagnon et al. (1990) on the influence of fruiting and nitrogen on carbohydrate accumulation and fall cold-hardening of day neutral strawberries concluded that removal of fruits earlier in the fall stimulated the accumulation of greater amount of starch and increased total non-structural carbohydrates. This enabled the plants to withstand significantly lower temperatures compared to the plants that had retained fruits in the fall. The accumulation of soluble carbohydrates decreases the crystallization of water within cells, reducing the freezing-induced dehydration and providing cryoprotection of cellular constituents, which may prevent the disruption of physiological and biochemical functions of plant cells and freezing point depression (Burke, 1986; Caffrey et al., 1988; Crowe et al., 1988; Jeffrey and Huang, 1990; Koster and Leopold, 1988; Lineberger, 1980; Santarius, 1973). Therefore, it is essential to examine different management strategies that enhance the ripening of cold-hardy cultivars to improve the winter acclimation and cold hardiness of northern perennial fruit crops.

While evidence exists for the potential of season extension in table grape production (Alonso et al., 2021; Li et al., 2023; Çoban, 2004), limited research is available on the season extension of wine grapes and no documented research has been reported on grape production using a CT in the upper Midwest. This signifies the need for further investigation and exploration within the climatic context of the upper Midwest.

Objectives

Objectives of this trial were to evaluate the physiological, morphological and productive differences between two cold hardy wine grape cultivars with regard to a CT and OF; to determine the air and soil temperature differences between the CT and OF and what influence these differences have on plant physiology, morphology, and productivity; and to evaluate the influence of a CT on overwintering of two grape cultivars.

Material and methods

Experimental site

The study was carried out at the NDSU Horticulture Research Farm near Absaraka, ND, during 2022 and 2023 (46°59’27.3” N 97°21’20.6” W, 1070 m elevation). The region falls under plant hardiness zone 4A (USDA-ARS, 2023). This region is classified as continental with an average precipitation range of 380 to 760 mm (Tollerud et al., 2018). The soil profile at the location is a Warsing soil series characterized as moderately well drained fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls (USNRCS, 1983). Based on the historical data from 1991-2020 the average growing season at Absaraka is nearly 138 days with average last and first frost dates falling between May 11-20 and September 20-30, respectively (NOAA, 2024).

Caterpillar tunnel Installation

The CT (Farmers Friend, Centerville, TN 37033) 30.48 m long, 4.88 m wide, and 2.74 m tall, with a gothic style arch was built on 18 May 2022, using 2-mm galvanized steel and a Single layer 0.15-mm clear polyethylene film, with a north-south orientation adjacent to the OF study

(Appendix Fig. B6 and B10). Hoops were firmly secured into the ground by using 1.2 m long rebars that were pounded into the ground approximately 1 m with a 1.2 m spacing. Further, the structure was strengthened by steel center purlins, wind bracing, a lift kit and cross bracing. Finally, the frame was covered with polyethylene film and was secured with wiggle wire at both ends of the tunnel. The polyethylene film was anchored to the frame with ropes using a zig-zag pattern that gives the tunnel structure resemblance of a caterpillar. A zipper door was installed at one end of the tunnel, and the other end was securely fastened by folding the polyethylene film and tying it to a T-post placed 1.2 m from the end wall during 2022 growing season. However, on 9 May 2023, instead of tying the polyethylene film to the T-post, it was oriented vertically, descending perpendicularly, and was tightly held using construction blocks to mitigate potential abrasion of the polyethylene film against heavy wind. The internal temperature of the tunnel was recorded throughout the growing seasons even though it remained unregulated, and the side walls remained open until late September.

Cultivars

'Marquette'

'Marquette' is a cold hardy red wine grape cultivar introduced in 2006 by the University of Minnesota (UMN, 2023). It was developed by crossing 'MN 1094' and French hybrid 'Ravat 262' (Watrelot, 2019). It is one of the most popular grapes adapted to cold climates and can survive winter cold events up to -29 to -34 °C. The cultivar is known for moderate resistance to black rot (*Guignardia bidwellii*), botrytis bunch rot (*Botrytis cinerea*), downy mildew (*Plasmopara viticola*), and powdery mildew (*Erysiphe necator)*. The cultivar has relatively early bud break, thus, it possesses the risk of late spring frost damage. Its fast fruit ripening characteristic allows fruit ripening within 1100 GDDs, which generally escapes early fall frost injuries. With sufficient heat units, it has very good harvest parameters: 22-26 ºBrix; pH= 2.9-3.3, TA= 1.1-1.2%. However, on cooler sites slightly higher TA, lower TSS and lower pH should be expected.

'Petite Pearl'

'Petite Pearl' is a cold hardy red wine grape cultivar released by Tom Plocher at Hugo, MN in 2010 (Watrelot, 2020). It is a cross between 'MN 1094' and 'E.S. 4-7-26'. 'Petite Pearl' can resist temperatures as low as -36 °C. The cultivar is highly resistant to powdery and downy mildew as well as resistance to black rot and bunch rot. With a later bud break in the spring compared to 'Marquette', 'Petite Pearl' may escape late spring freezes (Plocher, 2022). However, there is risk of early fall frost injury as the berries ripen later in the season compared to 'Marquette'. The estimated accumulated GDD requirement for 'Petite Pearl' ranges between 1350 to 1500 from bud break (160 days). With sufficient heat units, it achieves excellent harvest parameters: 22-24 ºBrix; pH= 3.45-3.55, TA= 0.6-0.7%. However, on cooler sites slightly higher TA, lower TSS and lower pH should be expected.

Management practices

Experimental vines were planted in 2016. In spring 2022, two healthy one-year canes were selected and trained in a low wire vertical shoot positioning system (VSP). The fruiting wire was positioned at 0.9 m, and the catch wires were set at 1.5 m height. In spring 2023, the dormant canes were spur pruned, leaving two spurs per node. The vines were fertilized at 56:56:28 kg NPK/ha (J.R. Simplot Company, Boise, ID) during the bloom period. Soil moisture was manually monitored, and plants were irrigated using drip tape (Toro® Aqua-Traxx, DripWorks, Willits, CA). Suckers and weeds were removed manually. Canes were routinely repositioned within catch wires throughout the growing season.

Weather

Air and soil temperature data were recorded using Watchdog 1000 series micro station datalogger (Spectrum Technologies, Inc. Aurora, IL). Temperature probes were positioned at the center of each production system and data loggers were programmed to collect data at hourly intervals throughout the growing season. Soil temperature readings were recorded at a depth of 30 cm and air temperature readings were taken at 1.2 m height across both environments during the 2022 and 2023 growing seasons. The daily average, maximum and minimum air temperature were calculated and numerically compared between the two-production systems. The accumulated GDD from bud break (data loggers' installation the first year) to harvest were calculated using daily maximum and minimum air temperature with 10 °C as the base temperature using the equation:

$$GDD = \frac{daily\ max.\ temperature + daily\ min.\ temperature}{2} - base\ temperature \quad (4)$$

Where,

above high cutoff temperature= 30 ºC

below base cutoff temperature= 10 ºC

Data collection

Phenological data

Phenological stages, including days to bud break (for 2023 only), flowering, fruiting, veraison and harvest were recorded following the BBCH scale (Lorenz et al., 1995) and in Julian days. The vine was considered to have reached bud break stage when the green shoot tips were just visible in at least five buds in a vine (BBCH code 7). Similarly, the vine was in the beginning of flowering when 10% of flower hoods fell from the receptacle of at least five clusters (BBCH code 61). Further, the fruiting stage was recorded when the young fruits began to swell, and the remains of flowers shed from at least five clusters (BBCH code 71). The vines were considered to have reached veraison when berries in at least five clusters began to develop a variety specific color (BBCH code 81). Furthermore, 20 berries were sampled randomly and proportionally from the top, middle, and bottom of five clusters from each vine and TSS content were measured to determine the Harvest maturity for each cultivar.

Berries were randomly selected weekly from each vine within both production systems after veraison to determine the harvest time based on a ºBrix value of 24. In 2022, harvest occurred only after 'Petite Pearl' in the OF production system was ready to be harvested (3 October). However, in 2023, cultivars were considered harvestable once the °Brix value reached 24 regardless of the TA and pH. Therefore, harvesting time was different for each cultivar and the production system in 2023. Berries composition (TSS, pH and TA) was recorded weekly after 'Marquette' in the CT reached ºBrix value of 24 in 2022 and after onset of veraison in 2023.

Yield parameters

Immediately after harvest, the number of clusters per vine and total weight of clusters per vine were recorded using Yamato-DP-6200 digital scale (Yamato Scale, Willich, Germany). Subsequently, five random clusters per vine were selected for further analysis. The length of each cluster was measured using a vernier caliper (Mitutyo Corporation, Sakado, Japan) and average length per cluster was computed. The total number of berries per cluster and the weight of 100 randomly selected berries were recorded (Ohaus- NVT16000/1, Ohaus Corp., Parsippany NJ). Additionally, average cluster weight was computed by dividing total cluster weight per vine by number of clusters.

Berries composition

Randomly selected berries from the five kept clusters were squeezed manually, and juice was filtered through a cheese cloth for analysis. The TSS was measured by using a pocket refractometer (Atago Co., Ltd, Tokyo, Japan), pH was measured using a pocket pH meter (Atago Co., Ltd, Tokyo, Japan) and TA was measured using a pocket brix-acidity meter (Atago Co., Ltd, Tokyo, Japan) by diluting 1µl grape juice to 49 µl distilled water (Blakey, 2024).

Winter survival test

The number of buds left per vine after dormant pruning was inconsistent among the vines because of difference in vine vigor. However, the number of buds retained per vine were purposely kept in close range of 16-21 count buds per vine in 2022 and 22-25 count buds in 2023. The CT 'Marquette' was 19 and 25 count buds, OF 'Marquette' was 21 and 25 count buds, CT 'Petite Pearl' was 19 and 25 count buds, and OF 'Petite Pearl' was 16 and 22 count buds, in 2022 and 2023, respectively. The number of viable buds that developed into fruiting canes were counted and the percentage of viable buds was calculated using the equation:

$$Percentage\ of\ viable\ buds = \frac{number\ of\ viable\ buds}{total\ number\ of\ retained\ buds} * 100 \quad (5)$$

Similarly, during the dormant pruning in 2023, six one-year-old cane cuttings were collected. The number of buds left per cutting was counted, and the cuttings were immersed in 19 L buckets filled with one-fourth water and left at room temperature for three weeks. After three weeks, the number of sprouted buds were recorded, and the percentage of bud survival was calculated using the equation:

$$Percentage\ of\ bud\ survival = \frac{number\ of\ sprouted\ buds}{total\ number\ of\ retained\ buds} * 100 \quad (6)$$

Experimental design and statistical analysis

Within each production system, cultivar study was set up as a randomized complete block design (RCBD) with 12 replications. Each plot within a replication consisted of one non-grafted vine. The experiment consisted of two rows with 12 'Marquette' and 12 'Petite Pearl' vines within the 29.2 m (96 ft) long rows. The experimental site was positioned north to south with 2.4 m (8 ft) spacing between vines and 3.1 m (10 ft) between rows.

Statistical Analysis System (SAS) version 9.4 was used for the statistical analysis, using PROC GLIMMIX with the REML estimation method (SAS Institute, SAS Circle, Cary, NC). Cultivars were treated as a fixed effect and the replication within each production system was treated as a random effect. Least squares means was used to separate the means at $\alpha = 0.05$ where appropriate. Due to the lack of replications for each production system, a descriptive comparison of the two production systems was presented.

Results

Temperature

The soil temperature recordings could not be analyzed because the sensor malfunctioned in both years. Thus, only air temperatures in the CT and OF production system were analyzed. The average daily air temperature throughout the 2022 growing season was 1.3 °C higher in the CT compared to the OF production system (Table 24). July had the highest average temperature i.e., 24.8 °C and 23.3 °C for the CT and OF production systems, respectively. The greatest diurnal temperature fluctuation in the CT and OF production systems were 30.4 °C and 26.9 °C, respectively. The minimum temperature recorded was -0.3 °C and -0.1 °C in the CT and OF production systems, respectively, on 28 September. The total GDD accumulated in the CT production system from 7 June to 3 October was 1365, while the OF production system was 1296.

Table 24. Average monthly air temperatures at the fruit zone (1.2 m from the soil surface) for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Months	Avg. air temperature CT[z] (°C)	Avg. air temperature OF (°C)	Max. air temperature CT (°C)	Max. air temperature OF (°C)	Min. air temperature CT (°C)	Min. air temperature OF (°C)
Jun (7-30)	24.7	23.1	43.8	40.9	8.4	7.9
Jul	24.8	23.3	42.4	37.0	9.9	9.4
Aug	22.1	21.0	40.7	36.9	8.2	7.6
Sep	17.2	16.2	36.7	34.6	-0.3	-0.1
Oct (1-3)	15.7	15.0	26.3	24.0	8.8	8.8

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

In 2023, the average daily air temperature throughout the growing season was 0.7 °C higher for the CT compared to the OF production system (Table 25). June had the highest average temperature at 24.4 °C and 23.7 °C for the CT and OF production systems, respectively. The greatest diurnal temperature fluctuation of the CT and OF production systems were 29.8 °C and 29.6 °C, respectively. The minimum temperature recorded was 3.1 °C and 2.4 °C in the CT and OF production systems, respectively, on 17 September. The accumulated GDD in the CT production system from 18 May to 5 October was 1599, while the field production system was 1531.

Table 25. Average monthly air temperature at the fruit zone (1.2 m from the soil surface) for caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Months	Avg. air temperature CT[z] (°C)	Avg. air temperature OF (°C)	Max. air temperature CT (°C)	Max. air temperature OF (°C)	Min. air temperature CT (°C)	Min. air temperature OF (°C)
May (18-31)	22.2	21.1	39.0	39.6	4.4	3.8
Jun	24.4	23.7	44.7	42.7	8.7	7.3
Jul	22.3	21.7	41.2	40.2	6.7	5.4
Aug	22.0	21.5	39.8	37.7	9.2	8.6
Sep	18.4	17.7	39.1	37.9	3.1	2.4
Oct (1-5)	20.1	18.6	41.2	34.7	6.7	7.2

[z]CT= Caterpillar tunnel; OF= Open field; Max.=Maximum; Min.=Minimum.

Crop phenology

A significant effect of cultivar was observed in the timing of key phenological stages, including days to first flowering, fruiting, veraison, and harvest for both production systems in 2022 and 2023 (Appendix Table A9). 'Marquette' flowered, fruited, developed varietal color, and were harvested earlier compared to 'Petite Pearl' in both years (Table 26 and 27). Descriptive comparison of days to harvest between the two production systems showed that in the CT production system, 'Marquette' were ready for harvest five days earlier in both years when compared to the OF production system. Similarly, 'Petite Pearl' were ready for harvest 12 and 14 days earlier in 2022 and 2023, respectively, when compared to the OF production system.

Table 26. Effect of cultivars in the phenological stages for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Days to flowering[x]		Days to fruiting[w]		Days to veraison[v]		Days to harvest[u]	
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Marquette	167b[y]	168b	174b	176b	211b	214b	251b	256b
Petite Pearl	170a	170a	177a	180a	220a	226a	264a	276a
P-value	0.0002	0.0004	0.0006	0.001	<.0001	<.0001	<.0001	<.0001

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.
[x]The day of the year on which 10% of flower hoods fell from at least five clusters.
[w]The day of the year on which young fruits began to swell and the remains of flower shed from at least five clusters.
[v]The day of the year on which berries began to develop variety specific color in at least five clusters.
[u]The day of the year on which berries accumulated total soluble solid content of 24 °Brix.

Table 27. Effect of cultivar in phenological stages for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Days to flowering[x]		Days to fruiting[w]		Days to veraison[v]		Days to harvest[u]	
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Marquette	158b[y]	158b	167b	167b	207b	212b	243b	248b
Petite Pearl	162a	161a	172a	172a	219a	221a	264a	278a
P-value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0079	<.0001

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.
[x]The day of the year on which 10% of flower hoods fell from at least five clusters.
[w]The day of the year on which young fruits began to swell and the remains of flower shed from at least five clusters.
[v]The day of the year on which berries began to develop variety specific color in at least five clusters.
[u]The day of the year on which berries accumulated total soluble solid content of 24 °Brix.

Yield parameters

There was no significant effect of cultivar on the number of clusters per vine in the CT production system in 2022 (Table 28). However, 'Marquette' had significantly more clusters per vine than 'Petite Pearl' in the OF production system in 2022 and both systems in 2023. Furthermore, cultivar difference was observed on the total weight of clusters per vine only in the OF production system in 2023 where 'Petite Pearl' had significantly greater total yield per vine compared to 'Marquette'.

Table 28. Effect of cultivar on the yield parameters for wine grape cultivars in the caterpillar tunnel and open field production system at the North Dakota State University Horticulture Research Farm near Absaraka, ND in 2022 and 2023.

Cultivar	Number				Total weight (kg)			
	Clusters/vine							
	2022		2023		2022		2023	
	CT[z]	OF	CT	OF	CT	OF	CT	OF
Marquette	18a[y]	22a	47a	46a	1.04a	1.71a	2.37a	2.24b
Petite Pearl	13a	13b	21b	27b	1.69a	1.59a	2.63a	3.06a
P-value	0.0887	0.0069	<.0001	0.0002	0.0739	0.6397	0.3277	0.0474

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.

There was no significant effect of cultivar on the number of clusters per fruiting cane and the cluster length in both production systems in both years (data not shown). However, 'Petite Pearl' consistently produced heavier cluster and more berries per cluster than 'Marquette' in both production systems in 2022 and 2023 (Tables 29 and 30).

Similarly, 'Marquette' had significantly higher 100-berries weight compared to 'Petite Pearl' in the CT and OF production system in 2022 and CT production system in 2023, while no significant difference was observed in 100 berries weight between two cultivars in the OF production system in 2023.

When descriptively examining the yield performance of each cultivar across two production systems in both years, ‘Marquette’ showed inconsistency in yield parameters each year. However, ‘Petite Pearl’ produced at least 2.86 gm heavier cluster, had at least three more berries per cluster and showed lower 100 berries weight by at least 1.14 gm in the CT production system in both years.

Table 29. Effect of cultivar on the yield parameters for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Weight of individual cluster (g)		Number of berries per cluster		100 berries weight (g)	
	CT[z]	CT	CT	CT	CT	CT
Marquette	50.63b[y]	77.33b	67b	76b	141.50a	140.58a
Petite Pearl	121.26a	118.40a	119a	116a	123.25b	124.64b
P-value	<.0001	<.0001	0.0002	0.0001	0.0005	0.0002

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at P<0.05.

Table 30. Effect of cultivar on the yield parameters for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	Weight of individual cluster (g)		Number of berries per cluster		100 berries weight (g)	
	CT[z]	OF	CT	OF	CT	OF
Marquette	50.86b[y]	49.52b	61b	50b	133.84a	129.04a
Petite Pearl	124.72a	114.51a	128a	110a	123.95b	126.09a
P-value	<.0001	<.0001	<.0001	<.0001	0.0097	0.3522

[z]CT= Caterpillar tunnel; OF= Open field.
[y]Means with different alphabets within a column represent significant difference at P<0.05.

Berries composition

In the OF production system, ‘Petite Pearl’ had significantly higher pH compared to ‘Marquette’, while no difference was observed in the CT production system in 2022 (Table 31). In 2023, ‘Marquette’ had higher pH in both production systems (Table 32). Similarly, ‘Marquette’ had higher TA than ‘Petite Pearl’ in both years regardless of the production system.

However, TSS/TA ratio was higher in 'Petite Pearl' compared to 'Marquette' in both production systems in both years. When descriptively comparing each cultivar across two production systems over two years, TA in the CT production system is lower than in the OF production system by at least 0.05%, while TSS/TA ratio was higher in the CT production system than in OF production system by at least 0.4.

Table 31. Effect of cultivar on berries composition for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	pH		TA (%)		TSS/TA	
	CT[z]	OF	CT	OF	CT	OF
Marquette	3.14a[y]	3.05b	1.58a	1.69a	16.64b	15.12b
Petite Pearl	3.12a	3.21a	1.07b	1.36b	23.62a	18.47a
P-Value	0.5642	0.001	<.0001	0.0122	<.0001	0.0159

[z]CT= Caterpillar tunnel; OF= Open field; TA= Titratable acidity; TSS= Total soluble solid.
[y]Means with different alphabets within a column represent significant difference at P<0.05.

Table 32. Effect of cultivar on berries composition for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Cultivar	pH		TA (%)		TSS/TA	
	CT[z]	OF	CT	OF	CT	OF
Marquette	3.27a[y]	3.03a	1.65 a	1.83 a	14.81 b	13.62 b
Petite Pearl	2.73b	2.88b	1.18b	1.23 b	20.33 a	19.93 a
P-value	0.0462	<.0001	<.0001	<.0001	0.0001	0.0003

[z]CT= Caterpillar tunnel; OF= Open field; TA= Titratable acidity; TSS= Total soluble solid.
[y]Means with different alphabets within a column represent significant difference at P<0.05.

Winter survival

In 2022, a significant difference was observed between the cultivars under CT production system, whereas both cultivars showed a similar percentage of viable buds in OF (Table 33). Within the CT production system, 'Marquette' had a greater percentage (55.89%) of viable buds compared to Petite Pearl (46.32%). In 2023, 'Marquette' had a greater percentage (83%) of viable buds compared to 'Petite Pearl' (72.33%) within the CT production system. However, both cultivars showed a similar percentage of viable buds within the OF production system. Similarly, a greater percentage of ‘Marquette’ buds (87.94%) sprouted than ‘Petite pearl’ (79.86%) in the CT, while no significant difference was observed in the percentage of sprouted buds between the two cultivars in the OF.

When comparing the percentage of viable and sprouted buds across two production system in 2023, ‘Marquette’ had 2.33% and 3.59% more viable and sprouted buds, respectively, in the CT production system compared to OF production system. However, ‘Petite Pearl’ showed a reduction in percentage of viable and sprouted buds by 1.87% and 5.87%, respectively, in the CT compared to OF production system in 2023.

Table 33. Effect of cultivars on winter survival for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022 and 2023.

Cultivar	Percentage of viable buds				Percentage of sprouted buds	
	2022		2023		2023	
	CT[z]	OF	CT	OF	CT	OF
Marquette	55.89a[y]	59.27a	83.00a	80.67a	87.94a	84.70a
Petite Pearl	46.32b	58.69a	72.33b	74.20a	79.86b	86.23a
P-value	0.0439	0.8804	0.0155	0.2029	0.0159	0.8165

[z]CT= Caterpillar tunnel; OF= Open field; TA= Titratable acidity; TSS= Total soluble solid.
[y]Means with different alphabets within a column represent significant difference at P<0.05.

Discussion

Temperature

A numerical comparison between two production systems showed higher daily average air temperature in the CT than the OF production system by 1.3 °C and 0.7 °C in 2022 and 2023, respectively. The marginal difference in the air temperature can be attributed to the dimensions of the CT. Caterpillar tunnels are smaller and shorter than HTs (Wortman et al., 2016), and under the polyethylene films, air volatility increases as air volume decreases (Lamont, 2005). Results from the current study align with Zhao and Carey (2009), where they reported the increase in average daily temperature by ~0.2-0.3 °C in the single poly HT compared to the OF production system. The greatest air temperature fluctuation was recorded in the CT compared to the OF production system. The greatest air temperature fluctuation in the CT production system can be attributed to the rapid increase and decrease in air temperature compared to OF during the hot and the cold hours of the day. According to Wien (2009), the minimum air temperature in the tunnel may drop lower than OF temperature depending on the characteristics of polyethylene film. The fluctuation in the temperature was also influenced by the transparency of polyethylene film to IR radiation (Cemek et al., 2006; Wien, 2009). The higher GDD in the CT production system in both years resulted from higher daily average air temperature in the CT compared to the OF production system (Rho et al., 2020; Wallace et al., 2012).

Phenology

In both 2022 and 2023, significant differences in the timing of key phenological stages were observed between 'Marquette' and 'Petite Pearl'. In the CT production system, 'Marquette' flowered three and four days earlier than 'Petite Pearl' in 2022 and 2023, respectively. Similarly, In the OF production system, 'Marquette' flowered two and three days earlier in 2022 and 2023, respectively. These results align with the findings by Tatar (2020), where they found 'Marquette' flowered earlier than 'Petite Pearl' in field conditions, likely influenced by genetic factors (UMN, 2023; Watrelot, 2020).

The days to fruiting, veraison and harvest followed a similar pattern to the days to flowering, with 'Marquette' reaching these phenological stages significantly earlier than 'Petite Pearl' in both years. When examining two years, both cultivars completed their phenological stages later in 2022 than 2023. Tatar (2020) also recorded a similar result in OF production system, where delayed bud break, bloom and veraison was recorded in 2019 compared to 2017 and 2018. The delayed flowering in 2022 was attributed to lower minimum daily temperatures from May to mid-June compared to 2023 (NDAWN, 2024). The last spring freeze event occurred on 21 May in 2022 and 3 May in 2023. Further, lower GDD (292) was recorded in 2022 compared to 2023 (429) during the same period.

A descriptive comparison between two production systems showed that 'Marquette' in the CT was ready for harvest five days earlier when compared to the OF production system in both years. Similarly, 'Petite Pearl' in the CT was ready for harvest 12 and 14 days earlier when compared to the OF production system in 2022 and 2023, respectively. This difference can be attributed to the higher average daily air temperature and increased GDD in the CT than the OF production system. A study by Çoban (2004) on production of table grapes under Ultraviolet+ Infra-red (UV+IR) plastic covering reported accelerated phenological stages with 26-33 days earliness in the ripening of different table grape cultivars compared to the OF production system. They attributed the accelerated phenological stages to the increase in temperature and accumulated GDD under polyethylene covering (Kamiloglu et al., 2011; Çoban, 2004).

Yield

The greater number of clusters per vine in 'Marquette' compared to 'Petite Pearl' can be attributed to more viable buds in 'Marquette' than in 'Petite Pearl' in both years. Furthermore, 'Petite Pearl' had heavier clusters and more berries per cluster than 'Marquette' across both production systems. These differences can be attributed to the compactness and the size of berries within the cluster. Our study found that 'Petite Pearl' berries were more tightly packed within the cluster and were smaller in size compared to 'Marquette'. Therefore, the total weight of clusters per vine in both cultivars remains similar.

The 100-berries weight of ‘Marquette’ was greater than that of ‘Petite Pearl’ in both production systems in 2022 and CT production system in 2023. This is expected as ‘Marquette’ produces larger berries than ‘Petite Pearl’ berries.

The numerical differences among yield components between the two production systems were inconsistent. For instance, ‘Marquette’ had more berries per cluster in the OF compared to CT in 2022, while the opposite occurred in 2023. In our study, harvesting time was determined based on TSS content of 24 ºBrix, however berries were harvested on 3 October regardless of the cultivar and production system in 2022. Therefore, the delayed harvesting in 2022 resulted in loss of over-ripened ‘Marquette’ berries in the CT production system due to wasp (*Vespula* spp.) attack. Similarly, shriveling of over-ripened ‘Marquette’ berries may have resulted in lower individual cluster weight in the CT than in the OF production system in 2022. Unlike, 2022, in 2023 cultivars were harvested once berries attained TSS content of 24 ºBrix.

Berries composition

The harvest date was determined by TSS content; therefore, it was not included in the analysis. Over two years inconsistent cultivar response was observed in pH. ‘Petite Pearl’ had lower TA compared to ‘Marquette’ in both 2022 and 2023, regardless of the production system, resulting in a higher TSS/TA ratio for ‘Petite Pearl’ during harvesting. ‘Marquette’ recorded extremely high TA compared to ‘Petite Pearl’ in both years. Although, both cultivars reached the desirable TSS content at 24 ºBrix, the desired pH (3.3-3.5) and TA (0.6-0.9%) for red wine were not achieved (Dami, 2014; Mansfield, 2006; Schrader et al., 2019).

The pH for ‘Marquette’ ranged between 3.03-3.27, falling within the harvest parameters (2.9-3.3) of ‘Marquette’ (UMN, 2023). However, compared to the desirable acidity for Marquette (1.1-1.2%), TA in our study was comparatively higher (1.58-1.83%) regardless of the production systems. Similarly, the desirable pH (3.45-3.55) and TA (0.6-0.7%) for 'Petite Pearl' could not be achieved in our study in both production systems (Plocher, 2022). However, a marginal reduction in TA and 5-14 days earlier accumulation of desirable TSS was observed in the CT production system compared to OF production system.

A marginal difference in berries composition across two production systems can be attributed to the greater temperature fluctuation and the minimum air temperature, where the internal temperature of the tunnel sometimes dropped below the OF air temperature (Li et al., 2023; Novello and Palma, 2008). Similar results were recorded by Çoban (2004) and Kamiloglu (2011), where the differences were observed among the cultivars but not across the production systems. Furthermore, Hatterman-Valenti et al. (2016) reported that grape varieties developed from *V. riparia* consistently showed higher TA values regardless of extended growing season and higher GDD. Li et al. (2023) reported that, compared to the OF production system, the quality of the berries can be lower in tunnel production system due to the inability of the growers to control the changes in the weather condition based on crop demands.

Winter survival

A significant effect of cultivars was observed in the percentage of viable buds in the CT production system in both years, but not in the OF production system. When comparing the two years descriptively, 2023 had a higher percentage of viable buds compared to 2022. The lower survivability of buds in 2022 can be attributed to the winter temperatures and the last freeze event on 21 May, compared to 2023, which occurred on 3 May. The minimum temperature recorded in the 2021-2022 winter was -37.8ºC, while the minimum temperature recorded in the 2022-2023 winter was -32.2ºC. Additionally, vine management practices in 2022 growing season, compared to 2021, may have contributed to the concentration of structural carbohydrates.

These carbohydrates may have played an important role in cell wall lignification and supercooling, resulting in greater winter survival in 2023 compared to 2022 (Willwerth et al., 2014; Zabadal et al., 2007). A study by Kaya (2020) reported a negative correlation between soluble carbohydrates and bud death rate.

A significant difference was recorded between cultivars in the percentage of sprouted buds in the CT production system. However, no significant difference was observed between cultivars in the OF production system. While comparing the percentage of viable and sprouted buds, ‘Marquette’ showed greater survival rate compared to ‘Petite Pearl’, but the limited duration of this study may not be sufficient to substantiate these results for perennial crops.

Data on the percentage of viable buds and sprouted buds as well as low temperature exotherm in spring 2024 may provide a clear picture of the impact of harvesting time on cold hardiness, as cultivars were harvested at different times based on TSS content in 2023. Further analysis of soluble carbohydrates and water content of buds during spring pruning in the following years could provide clear insight into the relationship between harvesting time, soluble carbohydrate accumulation, and cold hardiness (Wample and Bary, 1992).

Limitation

The study lacked replication for the production systems. Therefore, statistical comparison between two production systems was not feasible making it difficult to compare the results with marginal differences between two production systems.

Conclusion

As mentioned by Tatar (2020), viticulturists in North Dakota should consider the effects of freezing and weather constraints to achieve fruit maturity, yield, fruit composition, and vine longevity. Our study examined the performance of two cold-hardy wine grape cultivars ‘Marquette’ and ‘Petite Pearl’ in two production systems to understand the impact on yield, quality, earliness, and winter survivability. ‘Marquette’ was superior in terms of survivability and earliness in harvesting.

While statistical comparisons between the two production systems were not feasible, the CT production system showed potential to accelerate the phenological stages by improving the GDD. Future studies with the CT replications and temperature management according to the crop requirement in the tunnel, along with study on relationship between harvest timing and carbohydrate and water content in buds after winter months, will provide an important insight into winter survival. Additionally, exploring the impact of temperature fluctuations on berry quality could be another interesting area of study.

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APPENDIX A: TABLES

Table A1. Effect of cultivar on phenological stages for paste tomato cultivars in the systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Days to first flowering[y]	Days to first fruiting	Days to first harvest
Big Mama	16a[z]	40a	79a
Cauralina	16a	49a	75a
Gladiator	18a	47a	88a
Granadero	17a	43a	80a
Pozzano	17a	43a	74a
Super Sauce	16a	47a	83a
P-Value	0.5948	0.4934	0.2634

[z]Means with different alphabets within a column represent significant difference at P<0.05.
[y]Days to each phenological stage is the days from transplant to each phenological stage.

Table A2. Effect of cultivar on the crop yield for paste tomato cultivars in the caterpillar tunnel systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Total number	Total weight (kg)	Number of marketable	Marketable weight (kg)	Marketability (%)	Number of BER infected
	Fruits/plant					
Big Mama	36b[z]	2.93b	8b	0.88b	27.01a	24ab
Cauralina	29b	5.29ab	11b	2.39b	30.66a	9b
Gladiator	29b	4.86b	15b	2.73b	50.74a	4b
Granadero	88a	8.51a	40a	5.00a	45.01a	37a
Pozzano	41b	2.19b	10b	0.91b	21.54a	15b
Super Sauce	24b	3.50b	12b	2.05b	45.48a	3b
P-Value	0.0012	0.0079	0.0004	0.0081	0.3465	0.0257

[z]Means with different alphabets within a column represent significant difference at P<0.05.

Table A3. Effect of cultivar on the fruit size for paste tomato cultivars in the systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Very large[y]	Large	Medium	Small
	Number of fruits/plant			
Big Mama	0a[z]	1a	2b	3a
Cauralina	3a	4a	3b	1a
Gladiator	3a	6a	4b	1a
Granadero	0a	4a	28a	4a
Pozzano	0a	1a	2b	4a
Super Sauce	1a	3a	5b	1a
P-Value	0.4138	0.2055	<.0001	0.0962

[z]Means with different alphabets within a column represent significant difference at $P<0.05$.
[y]Very large, large, medium, small: Categorized according to the United States consumer standards for fresh tomatoes.

Table A4. Effect of cultivar on berries composition and final plant height for paste tomato cultivars in the systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	pH	TSS[z] (ºBrix)	TA (%)	TSS/TA	Final plant height (cm)
Big Mama	3.98a[y]	5.13a	0.80a	6.71a	194b
Cauralina	3.98a	4.90a	1.00a	5.78a	264b
Gladiator	3.89a	5.53a	0.71a	7.83a	196b
Granadero	3.69a	4.79a	0.72a	6.92a	362a
Pozzano	3.96a	5.91a	0.67a	9.36a	201b
Super Sauce	3.79a	5.67a	0.69a	8.37a	105c
P-Value	0.1023	0.6313	0.5306	0.4415	<.0001

[z]TSS= Total soluble solid; TA=Titratable acidity.
[y]Means with different alphabets within a column represent significant difference at $P<0.05$.

Table A5. Effect of cultivar on phenological stages for bell pepper cultivars in the caterpillar production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Days to first flowering[y]	Days to first fruiting	Days to first harvest
Early Sunsation	14a[z]	16a	54a
Intruder	15a	21a	63a
King Arthur	15a	23a	58a
Ninja	15a	18a	62a
Olympus	15a	18a	58a
X3R Red Knight	15a	21a	56a
P-Value	0.7354	0.0636	0.4091

[z]Means with different alphabets within a column represent significant difference at $P<0.05$.
[y]Days to each phenological stage is the days from transplant to each phenological stage.

Table A6. Effect of cultivar on the crop yield for bell pepper cultivars in the caterpillar tunnel systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Total number	Total weight (kg)	Number of Marketable	Marketable weight (kg)
	Fruits/plant			
Early Sunsation	10a[z]	1.52a	9a	1.40a
Intruder	7a	0.96a	6a	0.90a
King Arthur	5a	0.64a	4a	0.55a
Ninja	9a	1.26a	7a	0.94a
Olympus	11a	1.55a	8a	1.30a
X3R Red Knight	6a	0.87a	4a	0.65a
P-Value	0.0901	0.1992	0.2414	0.1735

[z]Means with different alphabets within a column represent significant difference at $P<0.05$.

Table A7. Effect of cultivars on bell pepper grades in the systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	US fancy[y]	US #1	US #2	Height (cm)
	Number of fruits/plant			
Early Sunsation	1a[z]	6a	2a	43.69a
Intruder	2a	3a	1a	48.01a
King Arthur	2a	1a	1a	41.91a
Ninja	2a	3a	2a	61.91a
Olympus	2a	4a	2a	51.31a
X3R Red Knight	2a	2a	1a	43.60a
P-Value	0.9240	0.2244	0.5377	0.0666

[z]Means with different alphabets within a column represent significant difference at $P<0.05$.
[y]US fancy, US #1, US #2: Categorized according to the United States standards for grades of sweet peppers.

Table A8. Effect of cultivars in the days to bud break for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Cultivar	Days to bud break	
	CT[y]	OF
Marquette	139b[Z]	139b
Petite Pearl	150a	146a
P-value	<.0001	<.0001

[z]Means with different alphabets within a column represent significant difference at $P<0.05$.
[y]CT=Caterpillar tunnel; OF=Open field.

Table A9. Source of variation, F-value and P-value for key phenological stages for wine grape cultivars in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022 and 2023.

Variables	year	Production system[z]	Source of variance	Num DF	F Value	P-value
Days to flowering	2022	CT	Cultivar	1	30.06	0.0002
	2022	OF	Cultivar	1	27.99	0.0004
	2023	CT	Cultivar	1	70.05	<.0001
	2023	OF	Cultivar	1	123.1	<.0001
Days to fruiting	2022	CT	Cultivar	1	22.62	0.0006
	2022	OF	Cultivar	1	21.06	0.001
	2023	CT	Cultivar	1	170.88	<.0001
	2023	OF	Cultivar	1	161.44	<.0001
Days to veraison	2022	CT	Cultivar	1	126.31	<.0001
	2022	OF	Cultivar	1	132.95	<.0001
	2023	CT	Cultivar	1	252.27	<.0001
	2023	OF	Cultivar	1	97.22	<.0001
Days to harvest	2022	CT	Cultivar	1	279.51	<.0001
	2022	OF	Cultivar	1	132.95	<.0001
	2023	CT	Cultivar	1	10.48	0.0079
	2023	OF	Cultivar	1	692.78	<.0001

[z]CT=Caterpillar tunnel; OF=Open field.

Table A10. Soil test results for tomato and bell pepper before transplanting in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.

Production system	Soil depth (cm)	NO_3-N lb/a	P ppm	K ppm	pH	EC mmhos/cm	OM %
CT[z]	0-15	54	16	196	6.1	0.37	2.1
CT	15-30	1	7	148	6.1	0.18	1.9
OF	0-15	41	15	185	6.4	0.45	1.9
OF	15-30	5	5	120	6.6	0.24	1.9

[z]CT=Caterpillar tunnel; OF= Open field; NO_3-N= Nitrate nitrogen; P= Phosphorus; K=Potassium; EC=Electrical conductivity; OM=Organic matter.

Table A11. Soil test results for tomato and bell pepper before transplanting in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.

Production system[z]	Soil depth (cm)	NO_3-N lb/a	P ppm	K ppm	pH	EC mmhos/cm	OM %	Ca PPM	Mg^{2+} ppm	Na ppm
CT	0-15	24	20	168	7.6	0.45	2	2500	290	210
CT	15-30	8	13	106	7.6	0.29	1.6	2900	380	210
OF	0-15	2	31	162	7.3	0.14	2	1650	320	195
OF	15-30	2	24	114	6.8	0.12	1.9	1710	310	190

[z]CT=Caterpillar tunnel; OF= Open field; NO_3-N= Nitrate nitrogen; P= Phosphorus; K=Potassium; EC=Electrical conductivity; OM=Organic matter; Ca= Calcium; Mg^{2+}= Magnesium, Na= Sodium.

Table A12. Soil test results for grapes in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in spring 2022.

Production system[z]	Soil depth(cm)	NO_3-N lb/a	P ppm	K ppm	pH	EC mmhos/cm
CT	0-15	7	26	226	6.6	0.1
CT	15-30	8	19	109	6.7	0.9
OF	0-15	5	25	249	6.8	0.1
OF	15-30	4	20	249	6.9	0.1

[z]CT=Caterpillar tunnel; OF= Open field; NO_3-N= Nitrate nitrogen, P= Phosphorus, K=Potassium, EC=Electrical conductivity.

Table A13. Soil test results for grapes in the caterpillar tunnel and open field production systems at the NDSU Horticulture Research Farm near Absaraka, ND in spring 2023.

Production system[z]	Soil depth (cm)	NO_3-N lb/a	P ppm	K ppm	pH	EC mmhos/cm	OM %
CT	0-15	18	32	228	7.4	0.17	1.7
CT	15-30	14	35	222	7.3	0.12	1.7
OF	0-15	6	23	195	7.5	0.11	1.8
OF	15-30	2	22	139	7.4	0.11	1.8

[z]CT=Caterpillar tunnel; OF= Open field; NO_3-N= Nitrate nitrogen, P= Phosphorus, K=Potassium, EC=Electrical conductivity, OM=Organic matter.

APPENDIX B: FIGURES

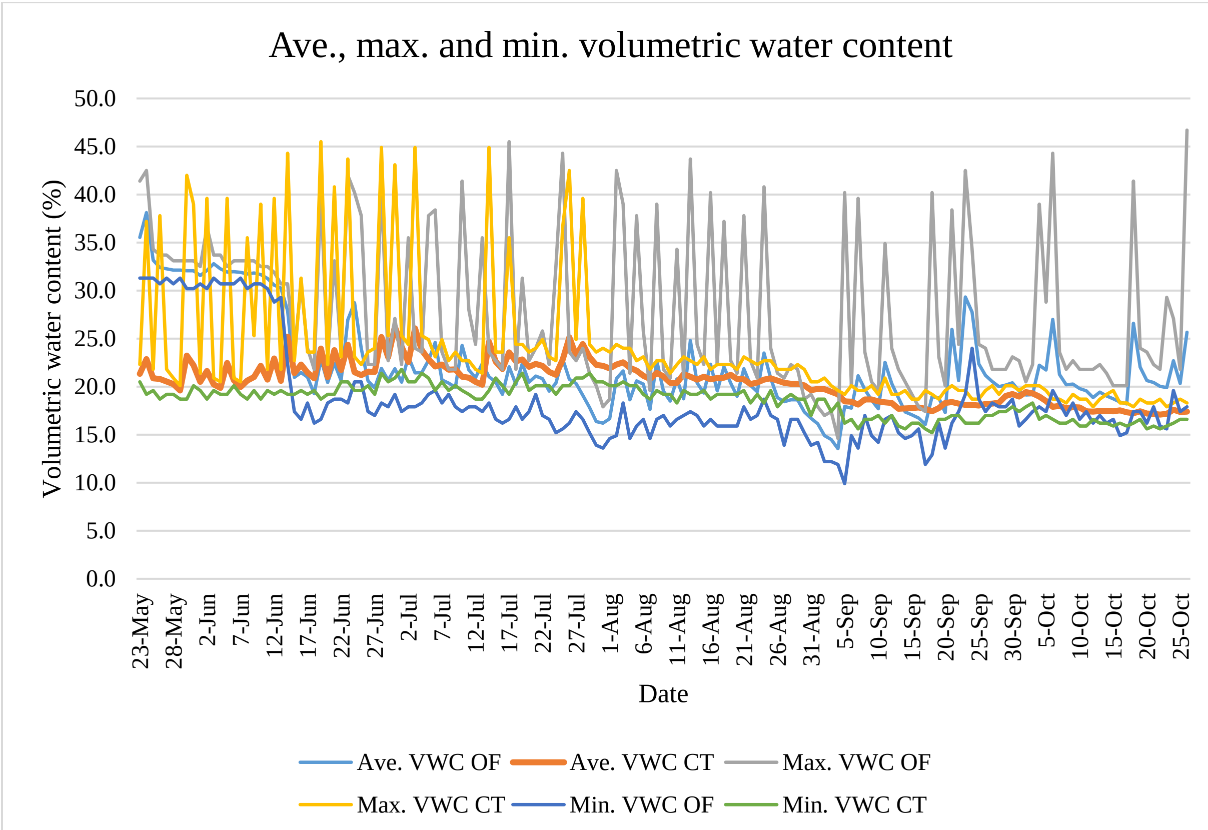

Fig B1. Daily average, maximum, and minimum volumetric water content of soil in the caterpillar tunnel and open field production systems for tomato and bell pepper at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.
Note: VWC= Volumetric water content; CT=Caterpillar tunnel; OF=Open field.

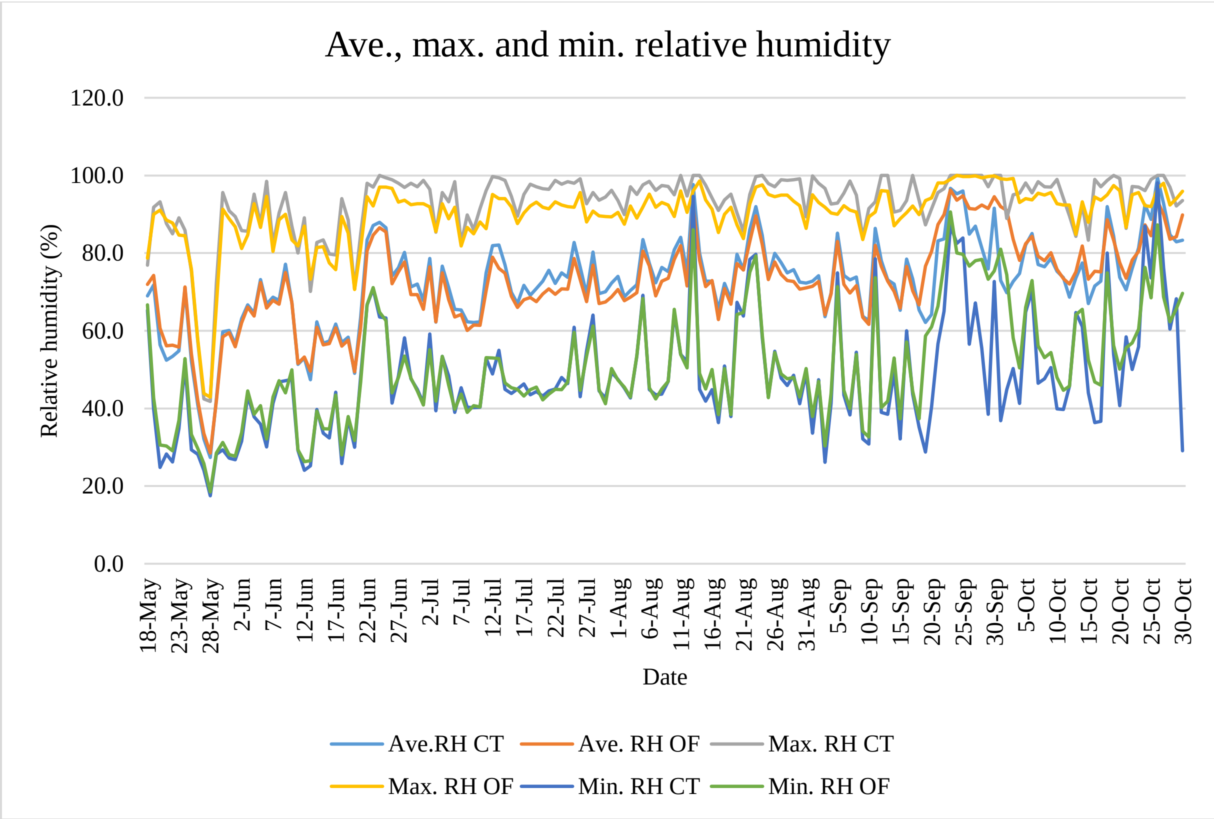

Fig B2. Daily average, maximum, and minimum relative humidity in the caterpillar tunnel and open field production systems for tomato and bell pepper at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.
Note: RH= Relative humidity; CT=Caterpillar tunnel; OF=Open field.

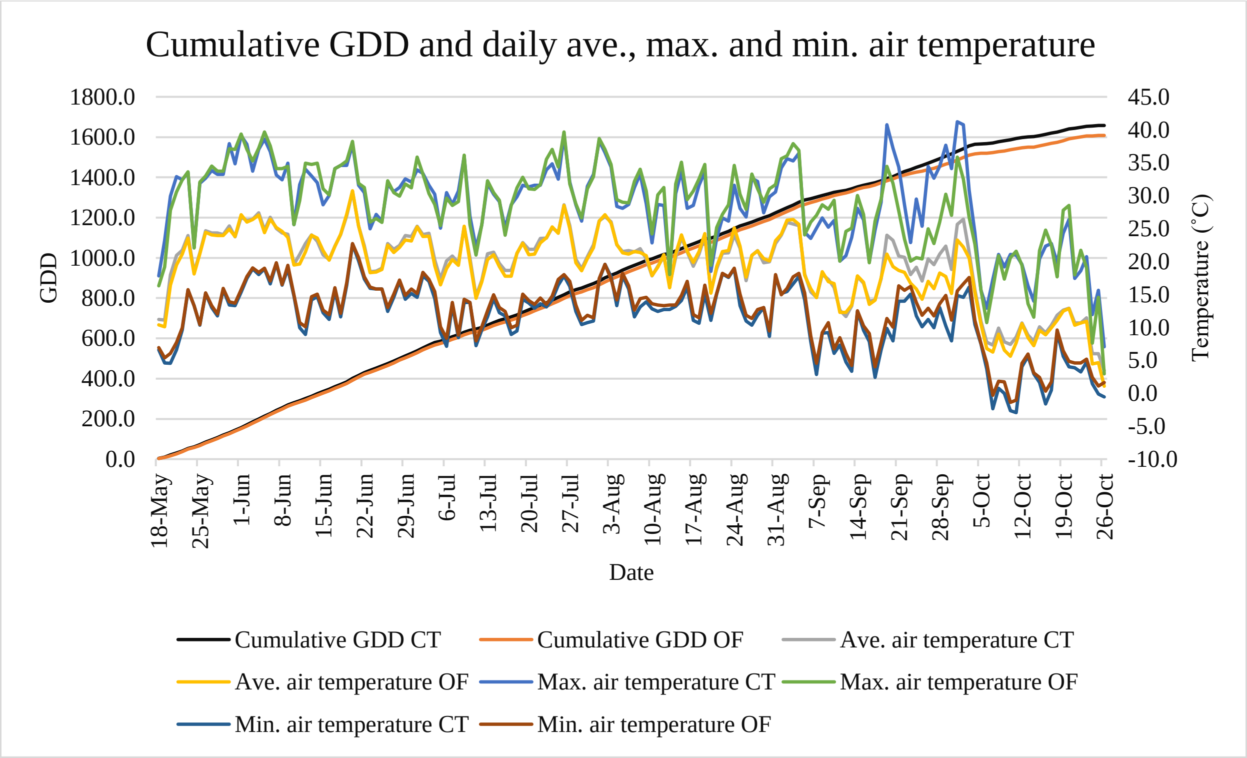

Fig B3. Cumulative GDD and daily average, maximum, and minimum air temperature in the caterpillar tunnel and open field production systems for tomato and bell pepper at NDSU Horticulture Research Farm near Absaraka, ND in 2023.
Note: GDD= Growing degree days; CT=Caterpillar tunnel; OF=Open field.

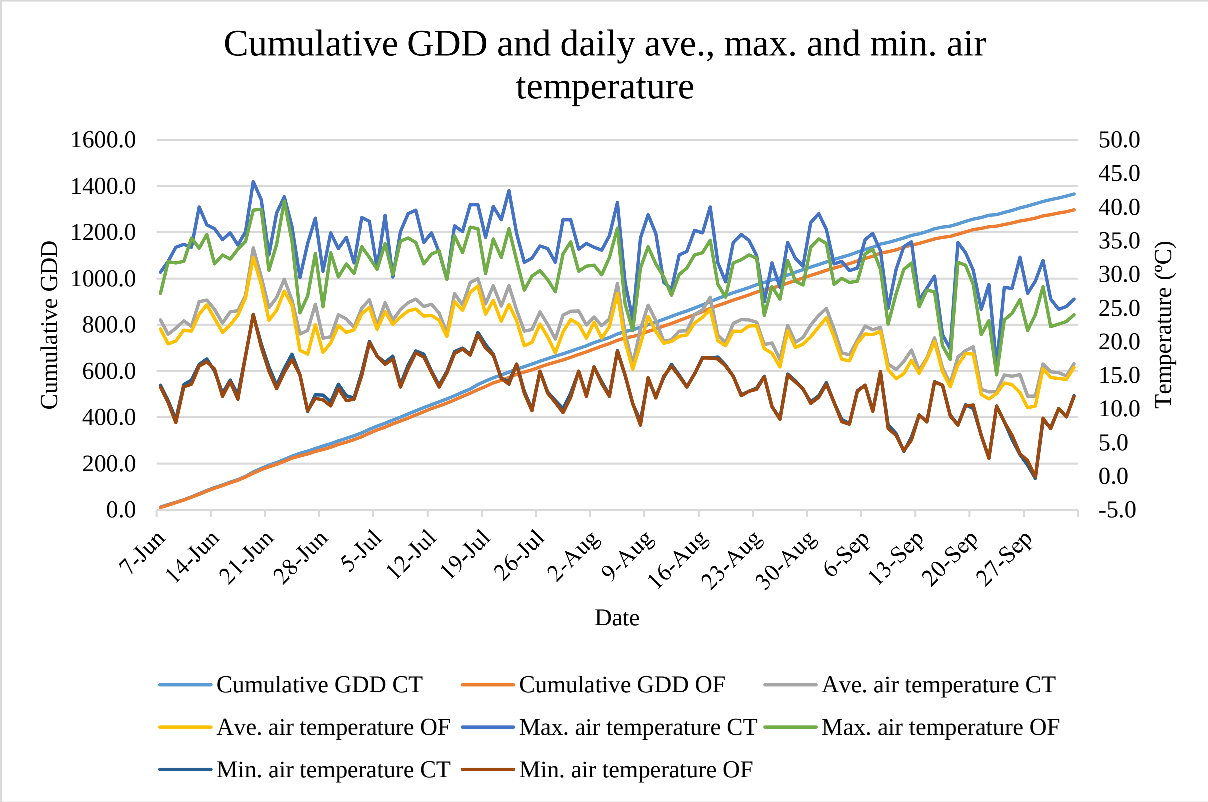

Fig B4. Cumulative GDD and daily average, maximum, and minimum air temperature in the caterpillar tunnel and open field production systems for grapes at the NDSU Horticulture Research Farm near Absaraka, ND in 2022.
Note: GDD= Growing degree days; CT=Caterpillar tunnel; OF=Open field.

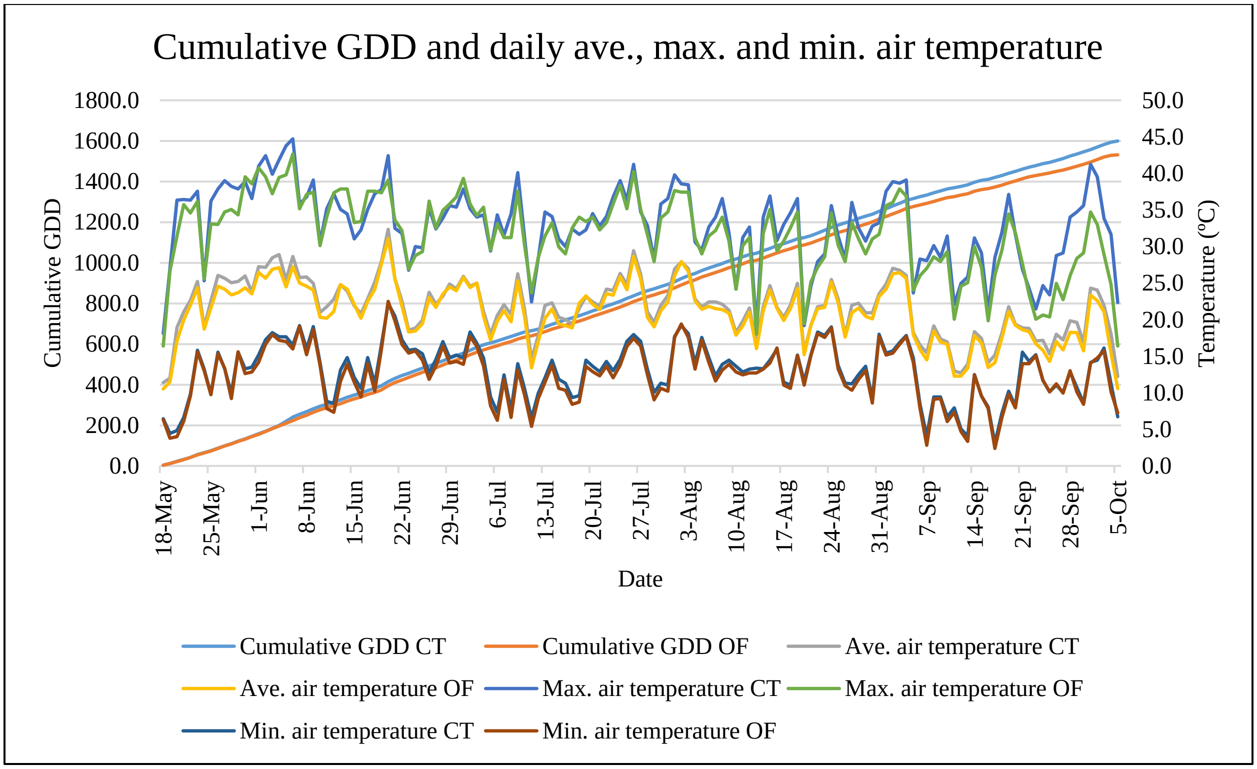

Fig B5. Cumulative GDD and daily average, maximum, and minimum air temperature in the caterpillar tunnel and open field production systems for grapes at the NDSU Horticulture Research Farm near Absaraka, ND in 2023.
Note: GDD= Growing degree days; CT=Caterpillar tunnel; OF=Open field.

Fig B6. Caterpillar tunnel framing.

Fig B7. Trellis system for tomato in the open field production system.

Fig B8. Bell pepper and tomato cultivars in the caterpillar tunnel production system.

Fig B9. Bell pepper and tomato cultivars in the open field production system.

Fig B10. Aerial view of cultivar trials in the caterpillar tunnel and open field production systems.

Fig B11. Wine grape cultivar in the caterpillar tunnel production system.