UTILIZING REMOTE CONTROLLED-SENSORS AND HIGH TUNNELS USE FOR SEASON EXTENSION IN TOMATO AND BELL PEPPER PRODUCTIONS

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Ivymary Goodspeed

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

April 2023

Fargo, North Dakota

North Dakota State University
Graduate School

Title

UTILIZING REMOTE CONTROLLED-SENSORS AND HIGH TUNNELS USE FOR SEASON EXTENSION IN TOMATO AND BELL PEPPER PRODUCTIONS

By

Ivymary Goodspeed

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

SUPERVISORY COMMITTEE:

Dr. Harlene Hatterman-Valenti
Chair

Dr. Edward Deckard

Dr. Xinhua Jia

Approved:

05/06/2024
Date

Dr. Richard Horsley
Department Chair

ABSTRACT

High tunnels are used to modify the environment by trapping solar energy, offer protection for unfavorable weather events and extend the growing season. This study evaluated yield and quality of eight paste tomatoes (*Solanum lycopersicum L.*) and bell peppers (*Capsicum annuum L.*) in a high tunnel and open field. Total yields for high tunnel peppers in both years were 2 times higher than open field. Tomato's highest total yields from the high tunnel and open field were comparable to each other at 13.8 and 10.26 kg plant^{-1} respectively. In both years, crops were planted in high tunnel 1 month earlier than the open field. Incidence of Tomato Spotted Wilt Virus (TSWV) was lower in the high tunnel compared with the open field in 2022. Results of this study showed potential of high tunnel for season extension, optimizing yields and increasing fruit quality for high value crops in North Dakota.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my advisor, Dr. Harlene Hatterman-Valenti for giving me this opportunity to pursue my degree under her supervision. Her expertise, constructive feedback, and dedication have not only enhanced the quality of this thesis but have also inspired me to push the boundaries of my potential. Thank you, Harlene, for believing in me and I couldn’t have asked for a better advisor. Thank you to both my committee members Dr. Edward Deckard and Dr. Xinhua Jia for their invaluable guidance, unwavering support, and mentorship throughout the course of my research.

I would also like to extend my gratitude to Collin Auwarter for his technical expertise and support, which has significantly contributed to the successful completion of my research project. I also want to thank the entire High Value Crops (HVC) team for their help with data collection, their collaborative spirit and friendship that made the graduate experience immensely rewarding. Special thanks to Dr. Jawahar Jyoti, Avery Shikanai and Phabian Makokha for their help with data analysis. Big thanks to the North Dakota State Specialty Block Grant for funding this research.

Finally, I would like to thank my family, Elijah Mbugua, Esther Mbugua, Luke Goodspeed and Brian Mbugua who encouraged me through this journey and kept me going during my lowest moments. The excess produce from these trials was donated to local food banks in both Cass County.

DEDICATION

This paper is dedicated to my loving family, whose unwavering support, encouragement, and sacrifices have been the foundation of my journey through academia. Their belief in me, even during the most challenging times, has inspired and motivated me to pursue excellence.

This achievement is as much theirs as it is mine.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF APPENDIX TABLES

CHAPTER 1: INTRODUCTION

Today, growers are faced by challenges of producing more food and dealing with unpredictable and extreme weather patterns. In North Dakota, commercial production of warm season crops is limited due to the chilling temperatures and reduced number of days from the first to the last frost. Therefore, adopting upcoming farming technologies is key for better crop growth. Many vegetable growers are taking advantage of high tunnels (HTs), which are structures categorized as protected agriculture structures. High tunnels have emerged as a strategic solution to counter this region’s harsh climatic conditions.

High tunnels are also referred to as hoop houses and are not the same as greenhouses although the greenhouse principle is the basis for the HT function. Greenhouses are permanent structures that are heated and/or cooled using electricity or other fuel sources and are usually top vented, often with automatic systems set to achieve certain temperature ranges within the greenhouse (Janke et al., 2017). On the other hand, HTs are passively heated and cooled. High tunnels are generally made from flexible plastic with rigid plastic used for the end walls and the environment in HTs are less controlled than greenhouses. Unlike in the greenhouse where plants are grown in pots and placed on benches, plants are usually grown directly in the soil in a HT.

High tunnels are being utilized worldwide to protect crops from harsh weather conditions and to extend the crop growing season through climate enhancement (Lamont, 2009; Zhao & Carey, 2009). These enclosed structures modify the inside temperature which lengthens the growing season from 1 to 4 weeks in spring, and 2 to 8 weeks in fall (Wells & Loy, 1993).

Water plays a crucial role in HT vegetable production as a substantial amount is usually used. Therefore, to fully optimize the potential of HTs and address the challenges of chilling temperatures, incorporation of smart irrigation within a HT will not only conserve water but also extend the growing season. The trend in recent years has been the adoption of a more efficient irrigation system and drip irrigation has been considered among the most efficient systems available (Sezen et al., 2006). Additionally, drip irrigation is preferred for its efficiency and labor cost savings and its ability to maintain dry foliage for disease control (Conner et al., 2010).

In a smart irrigation system, drip irrigation scheduling is done with controllers (soil sensors) programmed using evapotranspiration (ET), crop coefficients, or soil moisture, which help to make it an easier and a more reliable method to conserve water (Dukes, 2020). These remote sensors help growers to precisely monitor, and tailor soil moisture based on the specific crop needs therefore ensuring optimal conditions for warm season crops such as tomatoes (*Solanum lycopersicum*) and bell peppers (*Capsicum annum*). The integration of remote-controlled sensors into HT production will play a key role in optimizing growth conditions for vegetables, which consume a significant amount of water (USDA, 2021).

Literature Review

High Tunnels Origin

In the 1600's horticultural crops were protected against the cold by the use of glass lanterns, bell jars, cold frames and hot bed covered with glass (Jensen). Low portable wooden frames covered with an oiled translucent paper were used to warm the plant environment much as plastic rows do (Dalrymple, 1973). In the United States, the first use of polyethylene as a greenhouse cover was by Emory M. Emmert. He couldn't afford a glass greenhouse in 1948 so he designed a crude wooden structure with a stretched cellophane which resembled the glass greenhouse (Wittwer & Castilla, 1995). He used it to grow tomatoes, lettuce (*Lactuca sativa*), cucumbers (*Cucumis sativus*) and bedding plants for commercial purposes. This structure played an important role in the development of plastic covered plant growth structures. Plastic sheeting was then introduced in the early-post World War II period for greenhouses, row covers and soil mulches (Dalrymple, 1973). The first plastic greenhouse was constructed in Kentucky in the winter of 1953-54 because of its low cost (Emmert, 1955).

High tunnels started becoming an important production tool for growers since then but their adoption by fruit, vegetable and flower growers in the United States was not as quick compared to many other countries (Wittwer & Castilla, 1995). Research and extension professionals in the Northeastern United States started reporting about HTs and their potential for vegetable production, especially for production of warm season crops such as tomato in the early 90s (Wells & Loy, 1993).

High tunnels continue to gain popularity after the implementation of the seasonal High Tunnel Initiative (HTI) in 2009 through the Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP)(Bruce et al., 2017). HT construction and use has been increasing in the last ten years and this has been driven by an interest in small scale, local market production systems and the cost share benefits provided by the NRCS EQIP HTI (Bruce et al., 2017; Carey et al., 2009).

Design and Structure of High Tunnels

Most HTs in northern regions consist of a single or double layer of 4-6 mm, greenhouse-grade polyethylene plastic (Lamont et al., 2002; Wells, 1996) with a heat transmittance of 5.7 W m^{-2} K^{-1} (Jett, 2017). The positioning and orientation of the HT is dependent on the site. Maximizing passive ventilation or cross ventilation is key as this will ensure optimum growth conditions for crops and prevent extreme fluctuations in temperature and humidity, which can adversely affect crop yield and quality. For a suitable ventilation, the HT length should be placed perpendicular (at right angles) to prevailing winds (Jett, 2017). North-South facing HTs have the long sides running North to South to maximize solar radiation and also maximize ventilation through sidewalls due to summerly westerly winds (Sethi, 2009).

The common structural designs for HTs are the gothic and Quonset types. Gothic styles have peaked roofs which are better suited for locations that receive snow fall events as they tend to shed snow better than Quonset types (Jett, 2017). Gable vents or peaks can also be added to the gothic structure to facilitate air movement and ventilation. Quonset types have a round roof with slightly shorter and curved sidewalls. Their roof can collect more snow and thus more susceptible to snow load damage than the peaked tunnels.

High tunnels are also available as single bay or multi-bay units. Single bay tunnels have a greater environmental modification (plastic stays on the HT for a year which is permanent) while multi-bay tunnels are more temporary as plastic stays on the tunnel for a maximum of eight months (Jett, 2017). Single bay tunnels are often used in regions with cold climates and used for producing plants that need season extension (Heidenreich et al., 2012). Single bay tunnels are usually stand-alone, while multi-bay HTs consist of a series of interconnected Quonset type frames. They are usually not designed for holding up loads of snow and therefore uncovered during winter. They are mainly used for production of small fruits in the United States and worldwide.

Most of the HTs are stationary and therefore growers rotate crops in between seasons of each year (Biernbaum, 2006). There is an increasing demand for HTs where growers can use the same HT for several crops throughout the year (Jett, 2017). This also helps to reduce accumulation of fertilizer salts in the soil and reduce the buildup of soilborne diseases, which can have a negative effect on the HT crops (Garbos, 2013). With movable HTs, growers can also grow both annual and perennial crops by moving the HT from one plot to the other during the growing season.

Benefits of High Tunnel.

With increasing demand for year round fresh, high-quality and local produce, the number of HTs have increased substantially in the United States (Carey et al., 2009). High tunnels have been successfully used in the temperate regions of the world to extend the growing season as they modify the temperature thus creating a warmer environment for crop growth (Jiang et al., 2004; Wells). A research study on tomato production in HTs in New Hampshire showed that there was more than one month of early season extension (Wells, 1991).

These enclosed structures also accelerate crop growth due to their ability to accrue more daytime heat which results in accumulation of growing degree days (Gent, 1992; O'Connell et al., 2012). The warmer air temperatures in the HTs, reduces the time period needed for crop maturation when compared to conditions that are too cold in the open field (OF) (Both et al., 2007; Waterer & Bantle, 2018). This allows growers to capture a higher market price. High tunnels also increase overall yields. (Kadir et al., 2006) reported that strawberry (*Fragaria × ananassa*) in HTs not only matured earlier but also produced higher yields and superior quality compared to OF plants. Another study done on production of raspberries (*Rubus fruticosus*) in Minnesota showed greater yields as well as extended seasons with a HT (Yao & Rosen, 2011).

High tunnels help reduce incidences of foliar diseases by minimizing the negative effects of rainfall (Orzolek et al.), 2002). Crops within a HT are protected from soil splash which may spread the soil borne diseases (Mills et al., 2002) (Burlakoti et al., 2013) reported that incidences of both botrytis fruit rot mold (*Botrytis cinerea*) and anthracnose fruit rot (*Colletotrichum acutatum*) in strawberries were very low in the HT plots, compared to OF plots (5-fold lower

Botrytis grey mold (BGM) incidence and 5 to 20-fold lower AFR incidence). Increased fruit quality and reduced disease incidence for raspberry HT production was also reported in Michigan (Hanson et al., 2011).

Others have predicted that HTs help to manage leaf infecting pathogens by reducing leaf wetness. According to a study by (Xiao et al., 2001), shorter periods of leaf wetness in the HTs may have contributed to the lower incidence of botrytis fruit rot for strawberry when compared to those in the OF plots. (O’Connell et al., 2012) also reported lower incidence of gray leaf spot (*Stemphylium solani*) on tomatoes in the HTs when compared with the OF.

The plastic covering on HTs have the ability to reduce ultraviolet (UV) radiation thus reducing pressure of some insect species (Costa et al., 2002). Interference with the UV radiation makes it harder for these flying insects to navigate easily, therefore reducing pest populations (Antignus et al., 1996). Crops grown in tunnels covered with UV-absorbing plastic sheets were protected from infestation of sweet potato whitefly (Bemisia *tabaci*), western flower thrips (Frankliniella *Occidetalis*) and cotton aphids (*Aphis gossypii*).

Crops in the HT are also protected from extreme weather events such as wind and hail. This can help improve the survival rate of perennial crops, improve their quality, reduce the number of culls which translates to overall higher marketable produce (Kaiser & Ernst, 2012). A study by (Rho et al., 2020) with Jalapeno peppers (*Capsicum annum*) and tomatoes in the Texas High Plains, showed that crops in the HT required less total water over the growing season compared with those grown in the OF. This was because the crops in the HT were protected from dry high winds.

Limitations of High Tunnels.

Despite HTs providing a wide array of benefits, they still have limitations. Growers who own HTs are faced with the problem of managing time and high labor requirements with HT production (Bruce et al., 2019). This is because HT crops have planting and harvesting schedules that differ from the ones in the field. More labor is also required due to denser plantings, faster crop growth, longer growing seasons and succession plantings. Furthermore, growers are forced to invest in more labor to ensure that the HT is generating enough income to cover its costs.

A survey by (Bruce et al., 2019) with Indiana farmers who owned a HT, reported that the complexity of HT management is one of the biggest challenges. Farmers also added that the complexity of timing and harvesting are limiting factors since the time required for a crop to mature in a HT may vary from year to year depending on weather conditions. Some farmers also reported a lack of winter or off-season markets and reduced frequency of existing winter markets as a big problem.

Due to increased temperatures in the HT, plants tend to require adequate amounts of water due to higher evapotranspiration rates. When plants are not supplied with enough water the low soil moisture content may cause a decrease in nutrient transport from the soil to the roots (Kuchenbuch et al., 1986). In a study by (Shaykewich et al., 1971), the incidence of blossom end rot increased with increasing soil water stress. Other problems that have been reported in HTs include increased soil salinity (Knewtson, Janke, et al., 2010), changes in fertility management (Reeve & Drost, 2012) and increased soil borne disease pressure (Kubota et al., 2008).

Irrigation in High Tunnels

Vegetable production uses a substantial amount of water and an efficient irrigation system is necessary for HT production. Approximately 70% of global and 80% of the U.S. fresh water consumption is for agricultural practices (Evans & Sadler, 2008; Schaible & Aillery, 2012). Common irrigation methods in HTs include drip, sprinkler, and irrigation by hand.

In a survey conducted in Indiana, more than 75 percent of the growers surveyed reported that they use drip irrigation, while approximately 23 percent reported using hand watering and about 2 percent were using sprinklers (Bruce et al., 2018). Drip irrigation has become the common method for protected systems since higher yields, improved water use efficiency, and higher produce quality have been reported for drip irrigation systems compared with other irrigation methods for different vegetable crops, including potato (*Solanum tuberosum)* (Ünlü et al., 2006), bell pepper (Sezen et al., 2006), cucumber (Yuan et al., 2006) and eggplant (*Solanum melongena)* (Aujla et al., 2007; Yuan et al., 2006).

Drip irrigation has also been attributed to reduced water use as compared other irrigation such as furrow without significant yield reduction therefore maximizing profit (Zahid et al., 2020). In addition, with drip irrigation systems, water and nutrients can be applied directly to the crop at the root level, thus providing positive effects on yield and water savings and increasing the irrigation performance (Phene & Howell, 1984). (Üstün, 1993) evaluated the effects of furrow, drip and surface irrigation on bell peppers and showed that the highest yield of 27,900 kg ha^{-1} was achieved with drip irrigation even though amount of irrigation water applied was reduced by 2.4-fold as compared to surface irrigation.

To reap all the benefits of drip irrigation, scheduling the drip irrigation is key. Scheduling allows efficient use of water, as excessive irrigation may reduce yield, while inadequate irrigation may cause water stress and reduced production (Sezen et al., 2006). Bell peppers for example, are classified as susceptible to very susceptible to water stress, with the blossom stage as the most sensitive period (Bruce, 1980). Tomatoes on the other hand are more susceptible to cracking under excess water (O’Connell et al., 2012).Therefore, for higher tomato yields, adequate water supply and relatively moist soils are required during the total growing period.

Vegetable Crops

Tomatoes

The origin of tomato is along the western seaboard of South America, as well as Ecuador and Peru (Hobson & Grierson, 1993). Tomatoes were first cultivated as ornamental or curiosity plants and were thought to be poisonous (Peralta & Spooner, 2006). This is due to its classification within the *Solanaceae* family also known as the nightshade family and therefore believed to be carrying the same toxins as the deadly nightshades (Tang). Due to this myth, tomatoes were slow to gain popularity in North America. Today, tomatoes are among the most popular fruits grown in the world for the essential nutrients they provide in human diets.

Tomato belongs to the *Solanacea* family, which contains more than 3000 species including other plants such as potatoes, eggplants, petunias (*Petunia × hybrida*), tobacco (*Nicotiana tabacum*), chilli and bell peppers (*Capsicum spp.*) (Carey et al., 2009). Tomato is a self-pollinated crop which is grown annually in temperate climates but plants and fruits suffer physiological injury under low non-freezing temperatures (Heuvelink, 2018).

Tomato has a water content of 95% while the other 5% consists mostly of carbohydrates and fiber (Giovanelli & Paradiso, 2002). It’s a good source of phytochemicals such as lycopene, lutein and also nutrients such as vitamin C, folate, iron and potassium (Kumar et al., 2012; Toor et al., 2005). Besides lycopene, tomatoes are also a good source of antioxidants, such as beta-carotene, phenolic compounds such as flavonoids, hydroxycinnamic acid, chlorogenic, homovanillic acid and ferulic acid (Borguini & Ferraz da Silva Torres, 2009; Kumar et al., 2012; Toor et al., 2005).

Tomato can be consumed as either raw or cooked and their nutritive value is maintained even after being cooked (Kumar et al., 2012). (Gärtner et al., 1997) reported that food processing renders lycopene more available in processed tomato products than in raw tomatoes. Besides being consumed raw or cooked due to their desirable nutritional properties, tomatoes are increasingly being used in many tomato products (Pérez-Conesa et al., 2009). More than 80% of the processing tomatoes are consumed as pastes, tomato juice, puree, ketchup, sauce and salsa (Pérez-Conesa et al., 2009).

Bell Pepper

Also known as sweet pepper, bell pepper is a member of the nightshade family (*Solanaceae*). It originated in Mesoamerica (Mexico and Central America) and South America and is now cultivated all over the world (Bosland, 1992). Pepper was discovered as early as 6000 years ago and is considered to be the first spice domesticated and used by humans (Devi et al., 2021). Christopher Columbus encountered pepper in 1493 and thought it was related to black pepper (*Piper nigrum*) which actually belongs to a different genus due to its pungent fruit (Kelley et al., 2009). The pungency in the hot peppers is due to six chemically related compounds known as capsaicinoids (Deepa et al., 2007). Capsaicin (trans-8-metil-N-vanilil-6-nonenamide) and dihydrocapsaicin (8-metil-N-vanillylnonanamide), are the two most abundant capsaicinoids in peppers and together constitute around 90%, with capsaicin accounting for ~71% of the total capsaicinoids most of the pungent varieties (Barbero et al., 2014). Bell pepper fruits are however non-pungent, containing almost negligible amounts of capsaicin ($C_{18}H_{27}NO_3$) and zero Scoville Heat Units (SHU) (González-Zamora et al., 2013).

Bell pepper is a warm season crop sensitive to low temperatures and is characterized by a glossy exterior of different colors. Bell pepper (2n=2x=24), which is the most cultivated pepper species, has a large genome size of 3.48 GB (Kim et al., 2014). There are over 200 common names in use for whole pepper groups thus creating confusion about its various species and cultivars. Some popular names in various countries include bell pepper (USA, Canada), sweet pepper (UK, Ireland, Malaysia), Shimla mirch (India), capsicum (Australia, India, New Zealand, Pakistan), vegetable paprika, or sometimes the term paprika is simply added with fruit color like green pepper or red pepper, yellow pepper, etc. (Devi et al., 2021). It is a self-pollinated crop although considerable cross pollination can occur (Rai et al., 2013). Bell pepper fruits are termed as anti-climacteric, meaning they ripen independently of the phytohormone ethylene which means that after being harvested, they do not continue to ripen even after being exposed to ethylene (Welbaum, 2015).

Bell peppers are consumed as salads, stuffed, baked, in soups and as a stew ingredient, dried, pickled or as culinary seasoning (Devi et al., 2021). (Byrne et al., 2018) summarized the nutritional profile of fresh bell pepper per 100 g as comprising 20 kcal of energy, 4.6 g carbohydrate, 1.7 g fiber, 0.2 g fat, 0.9 g protein, 370 IU vitamin A, 80.4 mg vitamin C, 0.4 mg vitamin E, 7.4 mg vitamin K, 0.1 mg thiamin, 0.5 mg niacin, 0.2 mg vitamin B6, 10 mg folate, 0.3 mg iron, 10 mg magnesium, 20 mg phosphorous, 175 mg potassium, 0.1 mg copper and 0.1 mg manganese. One medium green bell pepper can provide up to 8 % of the recommended daily allowance of vitamin A, 180 % of vitamin C, 2 percent of calcium and 2 % of iron (Kelley et al., 2009). The fruits also contain fibers that help to lower cholesterol levels and lycopene, a carotenoid which reduces the risk of prostate, bladder and pancreatic cancers (Lu et al., 2001).

Cultivar Trials

Cultivar selection is a crucial component to ensure successful vegetable production. Cultivar trials are of a great importance as growers are able to intuitively compare multiple performance traits based on their own preference and local growing conditions thus selecting cultivars that best suit their particular needs (Warren et al., 2015). Total marketable yield, percentage of unmarketable yield, fruit size, total number of fruits and consumer taste preferences are the traits that producers are looking for when selecting which cultivar to grow. Other traits such as physiological disorders and susceptibility to disease are critical and should be included in the overall assessment of cultivar performance (Hutton & Handley, 2006). Cultivar performance can however vary greatly from one region to the other thus making it difficult for growers to make the decision of which cultivars to grow in their farms and how a specific cultivar will perform on their farms (Sánchez et al., 2011).

Pests and Diseases Encountered

Tomato-Spotted Wilt and Thrips

Tomato-spotted wilt (TSW) is caused by the tomato-spotted wilt virus (TSWV) (genus Tospovirus; family Bunyaviridae) and is a major disease affecting tomatoes and peppers (Soler et al., 2015). This virus has also been found in tomatillos (*Physalis philadelphica*), as well as ornamental plants such as blanket flower (*Gaillardia sp.*) and zinnia (*Zinnia elegans*). The western flower thrips (*Frakliniella occidentalis*) which are small yellow/ brown insects measuring less than 1 mm in size are primarily responsible for transmitting this virus, even though TSWV can also be spread by tobacco thrips (*Frankliniella fusca*) and onion thrips (*Thrips tabaci*).

Symptoms exhibited by a plant with TSW vary from one plant to another according to the time or the stage that the plant was infected (Soler et al., 2015). In tomatoes, the leaves possess small brown or necrotic spots and brown ringspots appear on immature green fruit (Nischwitz et al., 2019). In red ripe fruits, there is presence of yellow ringspots while bronzing of tissue on mature green fruits was observed (Olson, 2004). Infected pepper plants also exhibit symptoms almost similar to those in tomatoes. Affected fruits display ringspots or calico patterns appearing from green to red while the foliage shows chlorotic ringspot patterns (Nischwitz et al., 2019). Plants affected in their early stages usually are stunted severely or show severe wilt stress and later die.

Immature thrips (usually in their larval stage), generally acquire the virus from feeding on infected weedy plants or infected vegetables and then transmit it to the healthy plants (Nischwitz et al., 2019). Adult thrips can acquire the virus but are not able to transmit it. Once the immature thrips have acquired the virus, they are able to transmit in for the remainder of their lives and as they mature, the acquired virus replicates within their system thus becoming readily transmittable and making curative control measures mostly ineffective (Ullman et al., 1997). The symptoms in the affected plant usually start to appear in about 7 to 10 days and the virus continues to spread throughout the plant until the whole plant is affected (Nischwitz et al., 2019).

Due to the unique epidemiology and wide host ranges of both thrips and TSWV make TSW disease difficult to control (Yudin et al., 1986). However, some improved techniques that are available today for the control of TSW include the use of resistant cultivars, use of reflective metalized ultra-violet-mulch (UV-mulch) (Awondo et al., 2012) early-season insecticide treatments (Brown & Brown, 1992); (Riley & Pappu, 2000), and host-plant resistance (Krishna-Kumar et al., 1993); (Krishna Kumar et al., 1995). However, (Awondo et al., 2012) stated that the use of reflective metalized mulch to control TSW may also delay maturity in crops such as tomato, potentially affecting price and market window. They further stated that the use of resistant cultivars may limit the horticultural attributes (yield, taste, appearance etc.) available from standard TSWV susceptible hybrids.

A study by Riley & Pappu (2000) demonstrated that early season foliar sprays of effective insecticide targeting the thrips should be applied for a minimum of two consecutive weeks after transplanting in combination with an imidacloprid soil treatment was found to cause significant reduction in incidence of TSW only in years during which the disease incidence was >17%. In another field experiment, fungicide application of acibenzolar-S-methyl (Actigard, Sygenta Inc. Greensboro NC) was the most effective during the years when disease pressure was greatest while on the other hand UV-reflective mulch performed better than black polythene mulch in reducing colonization of thrips, regardless of thrips pressure (Awondo et al., 2012). A combination of UV-reflective mulch, acibenzolar-*S*-methyl and insecticides were found to be the most effective in controlling TSWV incidence in tomato in a study by (Momol et al., 2004).

Aphids

Aphids are a common pest found in HTs. The common types found in HTs are, green peach aphid (*Myzus persicae*), melon aphid (*Aphis gossypii*), potato aphid (*Macrosiphum euphorbiae*) and cabbage aphid (*Brevicoryne brassicae*) (Volesky & Schrumm, 2021). They are pear-shaped, soft-bodied insects and possess a pair of cornicles on the posterior end of their abdomen (Volesky & Schrumm, 2021). Adults can be either winged or unwinged and they cause damage using their mouth parts modified for piercing and sucking. Aphids feed on most plant structures including buds, leaves, stems, fruits and even roots.

Aphids cause damage by feeding and sucking sap (plant juices) from plant cells causing yellowing and curling thus reducing plant vigor (Volesky & Schrumm, 2021). They excrete honeydew (which may grow sooty mold), which is a sugary substance that attracts ants, which can cause further damage to plants. Aphids are also important vectors of plant disease particularly viruses (Drees, 1993) and the cotton aphid is known to transmit over 50 plant viruses while the green peach aphid can transmit over 100 (Kennedy et al., 1962).

Two Spotted Spider Mite

Another common pest in HTs is the two spotted spider mite (TSSM) (*Tetranychus urticae Koch).*This pest puncture the leaf surface using their stylets and suck out all the cell contents while leaving the leaf intact (Tomczyk, 1985). Symptoms observed on leaves that mites have fed on include small, light colored punctures, which develop into irregularly shaped white or grayish color upon prolonged exposure to mites (Škaloudová et al., 2006).

The increased temperatures and sheltered environment in a HT play a crucial role for development of pests. Several researchers have demonstrated that traditional pests of greenhouse crop systems including two-spotted spider mites, aphids, and thrips are more severe under HTs when compared to the open field (Demchak, 2009; Ingwell et al., 2017; Yao & Rosen, 2011). This is because the HT creates a protected environment that stays dry and hot (Wien, 2009; Yao & Rosen, 2011), creating ideal conditions for some of these pests to thrive (White et al., 2003).

High tunnel vegetables should be scouted regularly for aphids, mites, thrips and other pests at least twice per week during the growing season. Application of both biological, cultural and in some instances chemical control methods would be the best approach in managing these pests. In case of thrips such as the western flower thrips, management can be achieved by using reflective mulches or screens to repel (Antignus, 2000); using predatory mites (*Amblyseius cucumeris);* and using predatory bugs (*Orius spp.*) (Weeden, 2002). Additionally, predatory mites in the genus *Feltiella* or *Theridoplosis* have been successfully used in hot and dry environments to manage spider mites (Osborne et al., 2002).

Judicious use of pest control products can be used in combination with biological and chemical control methods. Insecticides with different modes of action should be used to reduce pesticide resistance. In addition, care should be taken when using pesticides as some of them could have a negative effect on the beneficial insects.

Physiological Disorders

Blossom End Rot

Blossom end rot (BER) is a physiological disorder that affects various crops such as eggplant, pepper, tomato and watermelon (*Citrullus lanatus*) and has been shown to cause 50% yield reductions (Sethi, 2009). Symptoms first appear as water soaked area at the blossom end of the fruit which usually develops rapidly, resulting in a blackened, dry, sunken leathery spot (Ho & White, 2005; Topcu et al., 2022). BER can also affect the internal placenta tissue surrounding the locular contents and the outside wall. From the late 1800s, BER was thought to have been caused by a parasitic organism and was originally described as ‘Black rot’ (Taylor & Locascio, 2004). Previous studies have shown that BER is caused by a combination of one or more factors including poor Ca distribution in relation to demand, poor uptake, high salinity, inadequate xylem tissue development, accelerated growth rates, unfavorable moisture relationships (high, low or fluctuating) and high temperature (De Kreij, 1996; Marcelis & Ho, 1999; Saure, 2001). BER can be controlled by use of polyethylene mulch, maintaining adequate soil moisture and avoiding the susceptible cultivars to BER (Elkner & Kaniszewski; Taylor & Locascio, 2004). A greenhouse study (Paiva et al., 1998) showed an increase in fruit transpiration was more effective in increasing fruit Ca concentrations than increasing Ca concentration in the substrate.

Sunscald

Sunscald is a physiological disorder of fruits resulting from exposure to the sun’s ray causing injury to plant tissues and affects many horticultural crops including vegetables (Barber & Sharpe, 1971) and fruits (Racsko & Schrader, 2012). Sunscald affects peppers by creating blemishes which render the peppers unmarketable (Madramootoo & Rigby, 1991) and it can cause important economic losses in pepper production (Barber & Sharpe, 1971). In field produced red bell peppers, 36% of losses were reported (Rylski & Spigelman, 1986) due to sunscald while reported 12% losses in field grown mature green peppers in Sydney and Wellington, Australia (Barber & Sharpe, 1971). (Díaz-Pérez, 2014) reported yellow bell pepper fruit cultivars displayed greater incidence of sunscald than red fruit cultivars. This can be attributed to a likely increase in carotenoids concentration in red pepper cultivars as carotenoids protect leaves and fruit tissues from photo-oxidative processes associated with sunscald disorder. Increased temperature and solar radiation diminish lycopene and β-carotene contents resulting in sunscald induction in tomato (Rosales et al., 2006). Research has demonstrated the use of either forced or natural ventilation (Zheng et al., 2019), whitewashing of the high tunnels and shade cloth (shade netting) as techniques for heat management especially in high tunnels (Díaz-Pérez & Smith, 2017).

Research Objectives

The objectives of this study were to evaluate yield, fruit quality, growth and development of eight tomato paste cultivars and eight bell pepper cultivars grown in a high tunnel and an open field under three irrigation regimes.

CHAPTER 2: TOMATO

Introduction

Tomato, is the primary crop grown in HTs in the United States (Carey et al., 2009). Other crops that can be grown in the HTs include leafy greens, pepper, tree fruits, small fruits and ornamentals. Tomatoes are among the high-value crops that are well adapted to the HT system where economic returns can be higher when compared with outside field production (Orzolek et al.). Additionally, due to their adaptability to trellising techniques, tomatoes with an indeterminate growth habit can be pruned and trained vertically and this maximizes space in a HT(Wittwer & Castilla, 1995).

The demand for local food production and consumption has been steadily increasing in the United States (Nie & Zepeda, 2011; Zumkehr & Campbell, 2015). Generally, local food is defined as food that travels a short distance from production to retail and/ or is sold directly by the producer to the consumer (Watts et al., 2017). The local food consumers perceive that locally produced food has better taste (Feldmann & Hamm, 2015) and is of higher quality (Brown, 2003; Feldmann & Hamm, 2015). To meet the demand for consumers wanting safe, flavorful and nutritious locally grown produce, growers are adopting farming technologies such as HTs. This is mostly for growers in regions such as the upper Midwest, with reduced growing days due to chilling temperatures.

In 2012, local food production in the United States equated to a $1.4 billion industry which is double the amount that was produced in 1992 (US Department of Agriculture (USDA) Marketing Services, 2016). The movement for consuming locally produced food is also depicted by the increase in the number of farmers markets across the country. In 2016, the United States National Farmers Market Directorate (US Department of Agriculture (USDA) Marketing

Services, 2016) recorded 8, 675 farmers' markets, 733 community service agriculture programs, 1,393 on-farm markets, and 170 food hubs. This is a growth of 394% just for the farmers' market alone since the year 1994.

High tunnels are expanding opportunities to increase local food production in the midst of a globalized food system (Foust-Meyer & O'Rourke, 2014) by buffering temperatures to extend the growing season and shelter crops from extreme weather events. High tunnels have made it possible for growers to fulfill consumer demand for fresh market produce at times which are traditionally off-season (Conner et al., 2009).

A survey conducted at three farmers' market in Michigan showed that customers were willing to pay for premium prices for locally grown spinach (*Spinacia oleracea*) and tomatoes late and early in the year (Conner et al., 2009). Previous studies have also shown how HT tomatoes are of greater quality and therefore marketable due to protection from wind damage, injury from insects, diseases, birds and rodents (Rogers & Wszelaki, 2012).

The United States Department of Agriculture (USDA) instituted the Know Your Farmer, Know Your Food initiative to increase the connection between all levels of agricultural production and the consumer (USDA,2013). In support of this initiative, the USDA tasked the Natural Resources Conservation Service (NRCS) with administering the Seasonal High Tunnel (SHT) in 2009. This is a cost-share program that helps farmers own HTs and are able to grow vegetables, berries and other specialty crops in climates and at times of the year which it would not be possible otherwise. Farmers can earn extra income from the produce while the community benefits from availability of fresh, locally grown food (Merrigan, 2010).

High tunnels are a promising technology that continues to contribute to the local food movement (Martinez, 2010). Unfortunately, scientific research into production of tomatoes in the

HT in North Dakota under deficit irrigation is limited. The objectives of this trial were to assess the yield, quality and growth and development of eight paste tomatoes grown in the HT and the OF in the eastern part of the state.

Materials and Methods

Site Description

The research was conducted during the 2022 and 2023 growing seasons in two production systems, a HT and an OF environment. The experiment took place at the NDSU Horticulture Research Farm (46°59’28.2” N 97°21’19.9” W, with an elevation of 1070 m) near Absaraka, ND in Cass County. This region is characterized as continental, that has hot or warm summers and cold winters with an annual precipitation range between 380 and 760 mm (Tollerud et al., 2018). The site soil type is a Warsing soil series; Fine-loamy over sandy or sandy-skeletal, mixed, super active, frigid oxyaquic hapludolls (Soil Survey, 2000). Warsing soils are characterized by moderately well-drained loam alluvium over stratified sand and gravel. This region is in plant hardiness zone 4a with minimum temperature range of 34 ^{o}C to -32 ^{o}C (USDA-ARS, 2012).

The high tunnel trial was conducted in a gothic-style unheated HT (Northpoint, Rimol Greenhouse Systems, Inc. Hooksett, NH) covered with a double air inflated 4 year-rated 6 mil clear polyethylene greenhouse film treated with anti-condensate and ultraviolet features with 13-gauge steel framework for support. The HT housed both the tomatoes and peppers for both years. The length of the HT was oriented north to south with dimensions 29 m long, 9 m wide and 5m tall. The HT was strengthened by nominal lumber-framed end walls, baseboards and hip boards.

Ventilation was accomplished by thermostatically controlled electric roll up sidewalls running the lengths of both sides set to open at 24°C and motorized shutter vents in each gable end wall set to open at 21°C. Three fans were also installed and were manually turned on when needed to allow air circulation during the hot days. Two garage doors on both end walls were manually opened to provide additional ventilation on hot days.

Site Preparation

Prior to planting, the HT and OF plots were cultivated and raised beds formed using a rotor-tiller and bed-shaper equipment. In each HT and OF plots nine beds each measuring 4.6 m in length and 0.69 m in width were established. The beds contained a single row of plants with a spacing of 0.69 m within plants and 1.83 m between rows.

Surface drip irrigation was installed as two lines of 15-mil drip tape (Toro® Aqua-Traxx, DripWorks, 15 Willits, CA) with emitters spaced at 20.3 cm apart. Each plot was covered with a 0.025-millimeter black plastic mulch (Berry Hill Irrigation, Buffalo Junction, VA) to conserve soil moisture and to also reduce weed seed germination.

The drip irrigation system was controlled by a soil potential sensor (Watermark, Irrometer Company, Riverside, CA) using a Wi-Fi enabled controller and solenoid valve (Hunter proC, San Marcos, CA), and a flowmeter (Mid-west Instrument Sterling Heights, Michigan 48314). Three irrigation regimes were used; time-based (which was equivalent to the traditional irrigation system), 10% management allowable depletion (MAD) and 30% MAD for both production systems. The soil potential sensors were used to check the soil moisture status at 09.00 am, 03.00 pm and 09.00 pm daily and irrigation would take place if needed. For the time-based treatment, the irrigation took place at 09.00 am for a duration of 24 minutes every Monday, Wednesday, and Friday regardless of the soil moisture status.

Temperature

Weather data, air temperature and relative humidity were monitored in the field using the North Dakota Agricultural Weather Network (NDAWN) near Prosper, ND with an elevation of 284 m above sea level. The NDAWN station temperature and relative humidity sensors are set at 1.5 m from the soil surface. A Decagon EM50 data logger (Decagon Devices, Inc., Pullman, WA) was set up at the experimental site to monitor inside and outside air temperature readings. Both data loggers were set up to be comparable to the NDAWN stations for air temperature. Growing degree days (GDD) were calculated after transplanting and base temperatures for the calculations were 10 °C as $GDD = [(T_{max} + T_{min},)/2 - T_{base}$, with 10 °C if Tmax or Tmin $< T_{base,}$ and if Tmax> 30 °C its set to be equal to 30°C where T_{max}, and T_{min} are daily maximum and minimum air temperature, respectively, and T_{base} is the base temperature (Pathak & Stoddard, 2018).

Plant Materials

Eight paste tomato cultivars were selected to be used for both the HT and the OF trial for both years. Names of tomato cultivars, disease resistance codes, type of production, average fruit weight and days to maturity are presented in table.

Table 1. Tomato trial cultivar seed source, disease resistance, general production type, average fruit weight, days to maturity and growth type.

Cultivar name	Seed sourcey	Disease resistancex	Production Typew	Average fruit weight (g)	Days to maturityv	Growth typeu
Pozzano F1[z]	JSS	TOMV, F, V	PC and FC	170	72	Indeterminate
Amish Paste (OP)t	JSS	N/A	PC and FC	340	85	Indeterminate
Granadero F1	JSS	F, TOMV, V, N, PM, TSWV	PC	141	75	Indeterminate
Cauralina F1	JSS	F, FOR, TOMV	PC	396	72	Indeterminate
Big Mama F1	BS	N/A	PC	283	80	Indeterminate
Gladiator F1	BS	N/A	N/A	227	72	Indeterminate
Super Sauce	BS	N/A	N/A	623	70	Indeterminate
San Marzano (OP)[t]	BS	N/A	NA	142	70	Indeterminate

[z] Refers to F_1 hybrid.

[y] JSS= Johnny's Selected Seeds, BS= Burpee

[x] TOMV= Tomato Mosaic Virus, F= Fusarium Wilt, V= Verticillium wilt, N= Nematodes PM= Powdery Mildew, TSWV= Tomato Spotted Wilt Virus, FOR= Fusarium Crown and Root Rot

[w] Production type PC= Protected Culture FC= Field Culture

[v] Days to maturity= the average number of days from transplant to first harvestable fruit

[u] Growth type is the habit or form of the plant

[t] Refers to open pollinated

Crop Seeding and Transplanting

In 2022 tomatoes for the HT trial were seeded on 17 March in Lord and Burnham Greenhouse in Fargo, ND (23.9°C, 16:8 L:D, RH=40-65%) in standard insert 800 series (T.O. Plastics, Clearwater, MN) containing a peat-based growing medium (PRO-MIX BX, Premier Tech, Quebec, Canada). Seedlings were then transplanted on 20 April into SVD-450 molded plastic pots (T.O. Plastics, Clearwater, MN) filled with the same growing media.

Tomato seeds for the OF plots were started on 15 April in the same greenhouse using the same media that was used for the HT experiment plants. They were then transplanted into SVD-450 pots on 11 May. Plants were irrigated every other day until transplanted. A 20:20:20 general-purpose water-soluble fertilizer (JR Peters Inc., Allentown, PA) at 100 parts per million (ppm) was administered through a fertilizer injector (Dosatron International, Clearwater, FL).

In 2023, tomato seeds were started in the North Dakota Agricultural Experiment Station (NDAES) since the greenhouse used for year 2022 was connected to the room that had the thrips and aphids which resulted in TSWV infected seedlings. Seeds for the HT tomatoes were sown on 15 March in standard insert 800 series (T.O. Plastics, Clearwater, MN) and transplanted into SVD-450 molded plastic pots on 11 April in a soilless growing media (PRO-MIX BX, Premier Tech, Quebec, Canada). The OF plots seeds were sown directly in SVD-450 molded plastic pots on 17 April using the same growing media that was used for the HT trial. The same fertilization procedure for 2022 was used for 2023 production year.

In both years, seedlings meant for the OF were placed in a protected outdoor condition approximately one week to begin to expose them to the ambient conditions of wind. Transplanting was done by hand in both years. Transplanting dates in the HT were on 5 May 2022 and 1 May 2023, whereas transplanting dates in the OF took place on 1 June 2022 and 12 June 2023 which was a month after transplanting in the HT.

Management Practices

For both years cultural management practices were tailored to each production system to maximize the production capacity of the respective system. The HT tomato apical meristems were pinched early in the growing season to encourage formation of two main leaders. The double leaders were trellised using Roller hooks® (Paskal Technologies Agriculture, Maalot-

Tarshihs, Israel) that hung from the HT rafters. Tomato vines were attached to the strings using plastic trellis clips (Johnny’s Selected Seeds Inc, Winslow, ME), at every 20 cm.

Suckers were removed regularly during the season to maintain a proper ratio between the vegetative and the reproductive parts (Maboko, 2006). The basal leaves were pruned at one leaf below the first fruit cluster to allow light penetration, providing better aeration between plants and consequently decreasing incidence and transmission of pests and diseases (Alvarenga, 2004). Weeds around the plants and in the beds were removed manually by hand. A mechanical hoe was used to remove the weeds between the rows and around the HT and the OF plots.

Scouting for the two production systems took place weekly in both 2022 and 2023 and pest management decisions were based on scouting. In the summer of 2022, the HT crops were infested with the green peach aphid (*Myzus persicae*). One application of malathion 50% E.C. (Ortho Group, Marysville, OH) was applied but was discontinued due to the plants showing burn symptoms after the application. In 2023, the HT crops were infested again with green peach aphids and one application of imidacloprid (Admire Pro, Bayer Crop science Inc.) was made and it successfully controlled the pests. All the pesticides were applied at rates according to label directions.

For the OF trial, the pruning and removal of suckers followed the same procedure that was used for the HT trial. Metal posts were pounded into the ground between every other plant and a horizontal metal pole were placed on top of the vertical poles with strings to hold the strings supporting the plants. Strings were wrapped around the horizontal posts and pulled downwards vertically and pinned to the ground using some metal hooks. The tomato vines were supported using the same trellis clips that were used in the HT.

Fertilization

During the growing season, NPK fertilizer 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. This was applied at the base of each plant under the plastic mulch. In 2023, micronutrient deficiency symptoms were observed in some tomato plants in the HT and OF. In response, a foliar application of the multi-purpose micronutrients (Agro.K Inc., Fridley, MN) was made at intervals of 14 days. The foliar application was discontinued after four applications because the temperatures were too high, and the tomato leaves were showing signs of burning.

Experimental Design

This two-year study was a split plot with irrigation as the whole plot factor and cultivar as the sub-plot. Irrigation treatments, (time-based which is equivalent to the traditional irrigation method, where irrigation took place based on hot, windy, or dry days,10% management allowable depletion (MAD) and 30% (MAD) were applied in the HT and OF trials for both years. Within each irrigation treatment, there were eight paste tomato cultivars. There were three randomized complete blocks with each treatment replicated three times.

Harvesting and Data Collection

Harvesting of fruits took place throughout the season until the tomato plants were severely damaged by cold temperatures. Fruit harvesting in the HT was conducted twice per week from 10 July to 30 Sept. in 2022 and from 21 July to 25 October in 2023. For the OF trials, harvesting took place once a week in 2022 from 5 August to 22 September 2022 and twice per week from 24 August to 17 October 2023.

Tomatoes were picked from the “pink to red” stages classified according to USDA maturity standards (7 CFR § 51.1904) and the unofficial visual aid from the USDA Marketing

Service Fruit and Vegetable Division and the United Fresh Fruit and Vegetable Association (USDA, 1975). Total, marketable, and cull fruit yields were measured. Fruits were sorted into both marketable and non-marketable categories based on their appearance. Fruits were categorized as non-marketable based on these types of defects: cat-facing, blossom end rot, insect damage, fruit cracking, TSWV, and “other”. Fruits with minor cracks or scars were however considered marketable.

The percentage of marketable fruit was calculated as the total number of marketable fruits divided by the total number of harvested fruits, multiplied by 100. The weight of the marketable yield per plot was calculated by subtracting the weight of the unmarketable yield from the total weight of fruits per plot. Yield components including average number of total and marketable fruit per plant, average single fruit weight and average number of fruits per plant were also reported.

In 2023, several measurements were taken during the growing season to assess plant growth. This includes plant height, stem diameter and number of leaves. Plant height was measured from the soil line to the growing point of each plant. Plant leaf counts were collected by selecting a representative plant from each treatment per replication. These measurements were only taken for 2023.

In 2023, samples of tomato fruits were also collected for titratable acidity (TA), pH, and total soluble solids (TSS) analysis. Representative fruits from each treatment per replication were picked randomly from the plant at breaker stage during the early, mid, and late growing season to be used for analysis. The fruit samples were stored in the cooler at 4°C awaiting analysis. Tomato juice was extracted by squeezing the fruit and the juice filtered through a cheesecloth to remove seeds and any large particles. The pH was measured with using a hand-held pH meter

(Atago Co., Ltd, Tokyo, Japan) and recalibrated using buffer solutions of pH 7 regularly. TA was obtained by titrating 10 ml of tomato juice to pH 8.2 with .01 N NaOH manually then expressed as percentage citric acid. To determine TSS, a pocket refractometer (Model: PR-32 α, Atago Co., Ltd, Tokyo, Japan) with juice at room temperature 21°C was used. A drop of the juice was placed on the refractometer prism and readings taken directly and expressed as a Brix value. Between samples the prism of the refractometer was washed with distilled water and dried before use. The refractometer was standardized against distilled water (0 °Brix TSS).

Statistical Analysis

Data was analyzed using linear mixed model as implemented in SAS PROC MIXED (version 9.4; Statistical Analysis Software (SAS) Institute, Cary, NC). Data were analyzed for the presence of significant main effects and interactions. When interactions among factors were present, the main effects for those factors were not considered for further analysis but analysis focused on the interactions. Least-square means comparisons were performed using the Fisher's least significant difference test ($P < 0.05$) where appropriate. Main effects of irrigation and cultivar were considered fixed while year and replications were considered as random effects. Due to a virus outbreak in 2022 open field environment that caused mortality to our plants, the years were analyzed separately.

Results

Temperature Trend in High Tunnel and Open Field 2022

In May, the average HT daily maximum air temperature recorded was 32.2°C, the average daily air temperature was 18.2°C, and the average minimum temperature was 3.6°C. The OF average, minimum and maximum daily temperatures were not available due to the data logger malfunction during this time. In June, the average OF daily maximum air temperature recorded was 38.5°C, the average daily air temperature was 21.2°C, and the average daily minimum temperature was 3.4°C. In June, the average, maximum and minimum daily temperatures were 1.9°C, 1.1°C and 4°C higher inside the HT than in the OF, respectively. In July, the average OF daily maximum air temperature recorded was 36.6°C, the average daily air temperature was 22.8°C, and the average daily minimum temperature was 10.6°C. In July, the average, maximum and minimum daily temperatures were 2.3°C, 1.9°C and 2.9°C higher inside the HT than in the OF, respectively. In August, the average OF daily maximum air temperature recorded was 35.9°C, the average daily air temperature was 20.8°C, and the average daily minimum temperature was 8.3°C. In this same month, the average, maximum and minimum daily temperatures were 2.4°C, 2.7°C and 3.8°C higher inside the HT than in the OF, respectively (Table 2). The hottest month of this growing season was in June (39.6°C) in the HT while the lowest temperature was recorded in June (3.4°C) in the OF.

Table 2. Mean maximum (Max.), average (Avg.) and minimum (Min.) air temperature (°C) for the open field and high tunnel at the Horticulture Research Farm near Absaraka, ND during 2022.

	High tunnel[z]			Open field[y]		
Month	Avg	Max	Min	Avg	Max	Min
May	18.2	32.2	3.6	-	-	-
June	23.1	39.6	7.4	21.2	38.5	3.4
July	25.1	38.5	13.5	22.8	36.6	10.6
August	23.2	38.6	12.1	20.8	35.9	8.3

[y] Open field data represents data from 1 June to 25 August.

[z] High tunnel data is from 11 May to 26 August.

Temperature Trend in Open Field and High Tunnel 2023

In June, the average OF daily maximum air temperature recorded was 35.9°C, the average daily air temperature was 21.8°C, and the average daily minimum temperature was 9.6°C. In June, the average, maximum and minimum daily temperatures were 2.6°C, 2.3°C and

5.2°C higher inside the HT than in the OF, respectively. In July, the average OF daily maximum air temperature recorded was 36.4°C, the average daily air temperature was 20.6°C, and the average daily minimum temperature was 7.1°C. In July, the average, maximum and minimum daily temperatures were 3.1°C, 4.3°C and 4.5°C higher inside the HT than in the OF, respectively. In August, the average OF daily maximum air temperature recorded was 34.6°C, the average daily air temperature was 20.9°C, and the average daily minimum temperature was 9.8°C. In August, the average, maximum and minimum daily temperatures were 2.4°C, 3.5°C and 3.9°C higher inside the HT than in the OF, respectively. In September, the average OF daily maximum air temperature recorded was 35.6°C, the average daily air temperature was 17.5°C, and the average daily minimum temperature was 3.7°C. In September, the average, maximum and minimum daily temperatures were 2.3°C, 1.8°C and 4.1°C higher in the HT than in the OF, respectively. In October, the average OF daily maximum air temperature recorded was 34.1°C, the average daily air temperature was 10.0°C, and the average daily minimum temperature was -3.8°C. In October, the average daily temperatures were 2.4°C, 0.5°C and -0.8°C higher inside the HT than the OF, respectively. In October, the average HT daily maximum air temperature recorded was 20.6°C, the average daily air temperature was 3.9°C, and the average daily minimum temperature was -2.1°C. Open field average, minimum and maximum daily temperatures are not shown due to the data logger malfunction. The lowest average daily temperature recorded for the 2023 growing season was in October (-4.6°C) in the HT while highest temperature was recorded in July (40.7°C) in the high tunnel as well (Table 3).

Table 3. Mean maximum (Max.), average (Avg.) and minimum (Min.) air temperature (°C) for the open field and high tunnel at the Horticulture Research Farm near Absaraka, ND during 2023.

	High tunnel[z]			Open field[y]		
Month	Avg	Max	Min	Avg	Max	Min
June	24.4	38.2	14.8	21.8	35.9	9.6
July	23.7	40.7	11.6	20.6	36.4	7.1
August	23.3	38.1	13.7	20.9	34.6	9.8
September	19.8	37.4	7.8	17.5	35.6	3.7
October	12.4	34.6	-4.6	10.0	34.1	-3.8
November	3.9	20.6	-2.1	-	-	-

[z] High tunnel data represents data from 15 June to 2 November

[y] Open field data represents data from 15 June to 27 October

In 2022 the HT accumulated 365 more growing degree days (°GDD) than in the OF before the number of days between transplanting and 50% harvest (T50) period was reached (Table 4). In contrast, in 2023 the °GDD in the OF was 118 more than those in the HT. In both seasons the HT accumulated more °GDD over the entire season when compared with the OF system. The HT accumulated 596 and 342 more °GDD than the OF in 2022 and 2023 respectively (Table 4).

Table 4. Growing degree-days (GDD) and the number of days between transplanting and 50% harvest (T50) for the high tunnel and field system, at the Horticulture Research Farm near Absaraka, ND during 2022 and 2023.

	Transplant date		T50(d)[z]		°GDD to T50[y]		°GDD for entire season[x]	
Year	High tunnel	Field	High tunnel	Field	High tunnel	Field	High tunnel	Field
2022	5 May	7 June	148	125	2004	1639	2382	1786
2023	1 May	12 June	116	80	1591	1709	2690	2348

[z] T50 represents the number of days between transplanting and when 50% of fruit was harvested.

[y] Growing degree-days (°GDD) until 50% of fruit was harvested.

[x] Growing degree-days (°GDD) from transplanting until end of growing season (high tunnel season was 10 and 20 days longer than the field system in 2022 and 2023 respectively).

Open Field Trial 2022

The 2022 OF trial was abandoned due to severe disease incidence of Tomato Spotted Wilt Virus that caused plant mortality among all the replications in the trial. Therefore, only three environments were used in the statistical analysis: high tunnel 2022, high tunnel 2023 and open field 2023.

High Tunnel Trial 2022

Marketable Yield

There was no interaction between cultivar and irrigation but there was a cultivar effect on marketable yield, number of fruits per plant and the average weight of individual fruits per plant (Appendix Table A.1). The mean marketable yield per plant ranged from 3.7 to 8.8 kg per plant (Table 5). Although 'Granadero' recorded the highest marketable weight (8.8) kg per plant, this yield was similar to the marketable yields from 'Cauralina', 'Amish Paste' and 'Pozzano' which weighed 7.2, 6.5 and 6.8 kg per plant, respectively. 'Big Mama' recorded the lowest marketable yield at 3.7 kg per plant, but this yield was similar to the marketable yield from 'Gladiator', 'San Marzano', and 'Super Sauce', which weighed 5.1, 5.7 and 5.2 kg per plant, respectively. 'Granadero' also had the highest number of marketable fruits, (99) fruits per plant which was similar to the number of fruits produced by 'San Marzano' at 96 fruits per plant. 'Pozzano' was also among the top producers at 70 fruits per plant while the rest of the cultivars produced significantly lower number of fruits with 'Super Sauce' producing the least number of fruits at 19 fruits per plant which was similar to the number of fruits produced by 'Gladiator' and 'Big Mama' at 30.4 and 29 fruits per plant, respectively. 'Super Sauce' produced the heaviest individual fruit which weighed 280 g and was statistically greater than the individual fruit weight from the rest of the cultivars. ‘San Marzano’ had the lightest individual fruit which weighed 60 g and was significantly less than the individual fruit weight from the rest of the cultivars.

Table 5. Total marketable yield, total number of marketable fruit and average weight of individual fruit produced per plant in the high tunnel at the Horticulture Research Farm near Absaraka, ND during 2022.

	Marketable fruit		
Cultivar	Yield (kg/plant)	No. of fruit/plant	Avg fruit weight (g)
Amish Paste	6.5 ab[z]	42.8 c	150 b
Big Mama	3.7 c	29.0 cd	130 c
Cauralina	7.2 ab	39.4 c	170 b
Gladiator	5.1 bc	30.4 cd	170 b
Granadero	8.8 a	99.6 a	90 d
Pozzano	6.8 ab	70.0 b	90 d
San Marzano	5.7 bc	96.7 a	60 e
Super Sauce	5.2 bc	19.4 d	280 a

[z] Means followed by the same letter in the same column are not significantly different on least significant difference (LSD) test at $P< 0.05$

Total and Unmarketable Yield

Irrigation did not affect the total yield or the unmarketable yield and no cultivar by irrigation interaction was observed (Appendix Table A.6). However, cultivar had a significant influence on the total yield, the unmarketable yield, and the percentage of cracks. ‘Cauralina’ had the highest total yield, (10.8) kg per plant although not significantly higher than ‘Granadero’, ‘Amish Paste’ and ‘Pozzano’ which produced 9.9, 8.5 and 8.1 kg per plant respectively (Table 6). ‘Big Mama’ had the lowest total yield at 5.3 kg per plant although not significantly less than ‘San Marzano’, ‘Gladiator’, ‘Amish Paste’, ‘Super Sauce’, ‘Pozzanno’ and ‘Amish Paste’, which produced 6.6, 7.2, 7.5, 8.1 and 8.5 kg per plant respectively. The weight of the unmarketable yield ranged from 0.9 to 3.5 kg per plant. ‘Cauralina’ had the highest unmarketable weight of fruits at 3.5 kg per plant, which was greater than the unmarketable fruit weight from any other cultivar. ‘San Marzano’ had the lowest unmarketable yield at 0.9 kg per plant, which was like the unmarketable yield from ‘Big Mamma’, Granadero’, ‘Pozzano’ and ‘Amish Paste’. Fruit cracks were the main cause for unmarketable fruit with ‘Amish Paste’, ‘Super Sauce’ and ‘Cauralina’ (19.1, 15.8 and 14%, respectively) having a higher percentage of fruit cracks compared to the remaining cultivars. ‘San Marzano’ had the lowest percentage of fruit cracks at 0.2 % per plant, which was similar to the fruit cracks with ‘Granadero’, ‘Pozzano’. ‘Big Mama’ and ‘Gladiator’ at 1.1, 1.7, 4.1 and 4.7% per plant, respectively.

Table 6. Tomato total yield, unmarketable yield and percentage of fruit growth cracks produced per plant in the high tunnel trial at the Horticulture Research Farm near Absaraka, ND during 2022.

		Unmarketable	
Cultivar	Total yield (kg plant^{-1})	Yield (kg plant^{-1})	% Cracks
Cauralina	10.8 a^{z}	3.5 a	14.0 a
Granadero	9.9 ab	1.2 bc	1.1 b
Amish Paste	8.5 abc	2.0 bc	19.1 a
Pozzano	8.1 abc	1.4 bc	1.7 b
Super Sauce	7.5 bc	2.3 b	15.8 a
Gladiator	7.2 bc	2.0 b	4.6 b
San Marzano	6.6 bc	0.9 c	0.2 b
Big Mama	5.3 c	1.7 bc	4.1 b

^{z}Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at P< 0.05.

High Tunnel Trial 2023

Marketable Yield

No cultivar by irrigation interaction influenced marketable yield but the main effects of irrigation and cultivar had a significant influence on the marketable yield of tomatoes (Appendix Table A.3). Cultivars under the 30% MAD irrigation treatment resulted in the highest marketable yields (8.1) kg plant^{-1} but wasn’t significantly higher than the marketable yields under the 10% MAD regime that resulted in 7.8 kg plant^{-1} (Table 7). The time-based treatment resulted in the lowest weight of marketable yield at 6.9 kg plant^{-1} and was significantly different from the other two treatments.

Table 7. Effect of irrigation on the marketable yield produced per plant in the high tunnel trial at the Horticulture Research Farm near Absaraka, ND during 2023.

Irrigation	Marketable yield
	-------------kg plant^{-1}--------------
30% MAD	8.1 a^{z}
10% MAD	7.8 a
Time-Based	6.9 b

^{z}Means followed by the same letter in the same column are not significantly different on least significant difference (LSD) test at $P < 0.05$.

Marketable Yield and Average Fruit Size

In the HT trial, ‘Pozzano’ produced the highest marketable yield at 12.1 kg plant^{-1}, but this wasn’t significantly higher than ‘Granadero’ at 9.8 kg plant^{-1} (Table 8). ‘San Marzano’ had the lowest marketable yield at 4.5 kg plant^{-1}, but this was not significantly lower than ‘Amish Paste’, ‘Big Mama’, ‘Cauralina’, or ‘Super Sauce’ at 6.8, 6.0, 6.8, and 7.1 kg plant^{-1}, respectively.

‘Pozzano’ had the highest number of fruit plant^{-1} at 103 fruits plant^{-1} which was significantly higher than fruit produced by any other cultivar. ‘Granadero’ and ‘San Marzano’ produced the second highest number of fruits plant^{-1} which was similar at 79 and 63 fruits plant^{-1} respectively. The rest of the cultivars produced lower numbers of fruits plant^{-1} with ‘Super Sauce’ having the least number of fruits at 22 fruits plant^{-1}.

‘Super Sauce’ had the heaviest individual fruit at 310 g which was statistically greater than the rest of the other cultivars (Table 8). ‘Cauralina’ and ‘Gladiator’ had the second heaviest with an individual fruit weight of 220 and 190 g, respectively. ‘San Marzano’ had the lightest individual fruit at 70 g.

Table 8. Tomato marketable yield, total number of marketable fruit and average weight of individual fruit produced per plant for high tunnel cultivar trial at the Horticulture Research Farm near Absaraka, ND during 2023.

	Marketable yield		
Cultivar	Yield (kg plant^{-1})	No. of fruit/plant	Avg fruit wt (kg)
Amish Paste	6.8 cd^{z}	41.1 cd	170 c
Big Mama	6.0 cd	32.1 d	180 c
Cauralina	6.8 cd	30.7 d	220 b
Gladiator	7.7 bc	42.0 cd	190 bc
Granadero	9.8 ab	79.2 b	130 d
Pozzano	12.1 a	103.0 a	120 d
San Marzano	4.5 d	63.0 bc	70 e
Super Sauce	7.1 bcd	22.9 d	310 a

^{z}Means followed by the same letter in the same column are not significantly different on least significant difference (LSD) test at $P < 0.05$

Total and Unmarketable Yield (Cracks and Yellow Shoulder)

No interaction of cultivar by irrigation nor the main effect of irrigation influenced the total yield and unmarketable yield, however there was a significant cultivar response (Appendix Table A.4). ‘Cauralina’ recorded the highest weight of marketable yield at 13.8 kg plant^{-1} but wasn’t statistically higher than ‘Granadero’, ‘Amish Paste’ and ‘Pozzano’ (Table 9). ‘San Marzano’ had the lowest total yield at 5.1 Kg plant^{-1} but did not differ from the total yield of ‘Big Mama’, or ‘Super Sauce’. ‘Cauralina’ and ‘Amish Paste’ had the highest percentage of cracks at 16.8 and 16.0 % respectively. ‘Cauralina’ also had the highest percentage yellow shoulder disorder at 4.6 %. This resulted in ‘Cauralina’ having significantly higher unmarketable yield at 7.04 kg plant^{-1} than any other cultivar.

Table 9. Tomato total yield, unmarketable yield, percentage of cracks and yellow shoulder disorder produced per plant in the high tunnel trial at the Horticulture Research Farm near Absaraka, ND during 2023.

		Unmarketable		
Cultivar	Total yield (kg)	Yield (kg)	% Cracks	% Yellow Shoulder
Cauralina	13.8 a[z]	7.04 a	16.8 a	4.6 a
Granadero	10.4 abc	0.6 c	1.9 c	0.2 c
Amish Paste	10.4 abc	4.2 b	16.0 a	1.9 b
Pozzano	12.24 ab	0.04 c	0.4 c	0.05 c
Super Sauce	7.34 e	1.0 c	2.2 c	0.04 c
Gladiator	9.1 bd	1.4 c	7.7 b	0.5 c
San Marzano	5.1 e	0.7 c	0.3 c	0.6 c
Big Mama	6.4 e	0.7 c	1.6 c	0.1 c

[z] Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at P< 0.05

Blossom End Rot

There was no interaction of the main effects, nor did irrigation alone influence blossom end rot (Appendix Table A.5). However, cultivar influenced the weight of fruits with blossom end rot. Numerically, ‘Granadero’ had the highest weight of blossom end rot at 2.05 kg plant^{-1} but similar to ‘Big Mama’, ‘Gladiator’ and ‘Cauralina’ and ‘Pozzano’ (Table 10). ‘Amish Paste’ and ‘Super Sauce’ had the lowest weights of blossom end rot.

Table 10. Tomato total weight of blossom end rot produced per plant in the high tunnel trial at the Horticulture Research Farm near Absaraka, ND during 2023.

	Blossom end rot
Cultivar	--------------------kg plant-^{1}-------------------
Amish Paste	0.33 c^{z}
Big Mama	1.48 ab
Cauralina	1.46 ab
Gladiator	1.54 ab
Granadero	2.05 a
Pozzano	1.85 ab
San Marzano	1.00 bc
Super Sauce	0.28 c

^{z}Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at P< 0.05.

Fruit Quality

For fruit quality measurements, there were no significant interaction of cultivar by irrigation and the effect of irrigation was not significant (Appendix Table A.6). Only cultivar influenced SSC and TA fruit quality measurements while pH was not influenced by any factor. The SSC of fruit from the cultivars ranged from 4.31 to 5.45 °Brix. ‘Cauralina’ had the highest fruit SSC which was significantly higher than fruit SSC from all the other cultivars (Table 11). ‘San Marzano’ and Amish Paste’ had had the next highest fruit SSC although not significantly higher than fruit SSC from ‘Big Mama’ and ‘Pozzano’. The rest of the cultivars had statistically similar fruit SSC. ‘Granadero’ had the highest fruit TA numerically, but the fruit TA did not differ from the rest of the cultivars except for ‘Gladiator’ and ‘Pozzano’ with TA of 0.10 and 0.12 %, respectively (Table 11). There were no significant differences in the pH of fruits among the cultivars.

Table 11. Soluble solids content (SSC), titratable acidity (TA), and pH of high tunnel tomatoes at the Horticulture Research Farm near Absaraka, ND during 2023.

Cultivar	SSC (°Brix)	Titratable Acidity (%)	pH
Big Mama	4.58 bcd [z,y]	0.16 abc	4.22
San Marzano	4.72 bc	0.19 abc	4.04
Amish Paste	4.78 b	0.44 ab	3.92
Cauralina	5.45 a	0.55 a	3.9
Gladiator	4.33 cde	0.10 c	3.87
Pozzano	4.46 bcde	0.12 bc	3.84
Granadero	4.15 e	0.56 a	3.8
Super Sauce	4.31 e	0.14 abc	3.73
F-test[x]	<.0001	0.0469	NS[x]

[z] Values represent the least significant means of fruit harvested at the red ripeness stage from three harvests in 2023 in the high tunnel.

[y] Least significant means followed by the same letters are not significantly different at LSD test ($P < 0.05$).

[x] Probability value for the overall ANOVA *F*-test using the type III hypothesis test ($P \leq 0.05$. NS= Not significant).

Open Field Trial 2023

Average Fruit Size

In the OF trial, the cultivar by irrigation interaction and the main effect of cultivar were not significant but there was a significant influence of the main effect irrigation on the average fruit weight produced plant^{-1} (Appendix Table A.7). Plants in the time-based irrigation produced the heaviest fruit weighing 190g but not statistically greater than fruit from the 10% MAD irrigation regime at 180 g (Table 12). The irrigation treatment of 30% MAD resulted in the lightest fruit at 130 g which was statistically less when compared to average fruit weight from the other two treatments.

Table 12. Effect of irrigation on tomato average fruit weight produced per plant in the open field trial at the Horticulture Research Farm near Absaraka, ND during 2023.

Irrigation	Average fruit weight
	---------- kg plant-1 ----------
10% MAD	180 a[z]
30% MAD	130 b
Time-Based	190 a

[z]Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at $P < 0.05$.

Marketable Yield

No cultivar by irrigation interaction nor irrigation main effect affected the marketable yield plant^{-1} but cultivar was significant (Appendix Table A.7). ‘Pozzano’ produced the highest marketable yield at 4.2 kg plant^{-1} but this was not statistically higher than ‘Granadero’ or ‘Gladiator’ at 3.7 and 2.5 kg plant^{-1}, respectively (Table 13). ‘San Marzano’ produced the lowest marketable yield at 1.5 kg plant^{-1} but this was not statistically less than ‘Big Mama’, ‘Amish Paste’, ‘Cauralina’, ‘Gladiator’ or ‘Super Sauce’.

Marketable Number of Fruits

‘Granadero’ produced the highest number of fruits at 32 fruits plant^{-1}, but this was not statistically higher than ‘Pozzano’ and ‘San Marzano’ that produced 30 and 27 fruits plant^{-1}, respectively (Table 13). The rest of the cultivars produced lower fruit numbers ranging from 8 to 11 fruits plant^{-1} with ‘Cauralina’ having the lowest fruit number plant^{-1}. In contrast with the lowest fruit number plant^{-1}, ‘Cauralina’ had the highest average fruit weight plant^{-1} measuring 240 g. ‘Amish Paste’, ‘Super Sauce’ and ‘Big Mama’ were statistically similar in fruit weight with weights of 220, 220 and 180 g, respectively.’Granadero’, and ‘San Marzano’ had significantly lower individual fruit weights with ‘San Marzano’ having the lightest individual fruit at 60 g.

Table 13. Tomato marketable yield, total number of marketable fruit and average weight of individual fruit produced per plant for the open field trial at the Horticulture Research Farm near Absaraka, ND during 2023.

	Marketable yield		
Cultivar	Yield (kg $plant^{-1}$)	No. of fruit/plant	Avg fruit wt (kg)
Amish Paste	2.1 bc^z	8.53 c	220 ab
Big Mama	1.8 c	11.2 c	180 bc
Cauralina	2.0 bc	8.2 c	240 a
Gladiator	2.5 abc	11.9 bc	180 abc
Granadero	3.7 ab	32.2 a	100 de
Pozzano	4.2 a	30.0 a	120 d
San Marzano	1.5 c	27.7 ab	60 e
Super Sauce	2.5 bc	10.4 c	220 ab

^{z}Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at P< 0.05.

Total Yield

There was a cultivar and a cultivar by irrigation interaction effect on the total yield as shown in (Appendix Table A.8). ‘Big Mama’ and ‘San Marzano’ produced consistently similar yields across the irrigation regimes (Table 14 a). ‘Cauralina’ and ‘Pozzano’ produced significantly different yields across the three different irrigation regimes.

Table 14a. Effect of interaction effect of irrigation and cultivar across the irrigation regimes on tomato total yield harvested per plant (kg) in the open field at the Horticulture Research Farm near Absaraka, ND during 2023.

	Total Yield		
Cultivar	10% MAD	30% MAD	Time based
	----------------------kg plant^{-1}-------------------------		
Amish Paste	7.35 a[z]	3.37 b	7.81 a
Big Mama	2.08 a	3.17 a	2.09 a
Cauralina	10.26 a	1.48 c	7.00 b
Gladiator	3.01 b	4.35 b	8.74 a
Granadero	5.67 a	2.70 b	4.94 a
Pozzano	5.37 b	1.81 c	7.18 a
San Marzano	3.14 a	3.35 a	1.71 a
Super Sauce	4.31 a	2.32 b	5.73 a

[z] Means followed by the same letter across different irrigation regimes are not significantly different on least significant difference (LSD) test at P< 0.05.

‘Cauralina’ and ‘Amish Paste’ had the highest total yields under 10% MAD regime while ‘Big Mama’ had the lowest yields (Table 14b). The Irrigation regime 30% MAD didn’t affect the weight of total yields. Gladiator’ and ‘Amish Paste’ yielded the highest under the time-based irrigation regime while ‘San Marzano’ and ‘Big Mama’ yielded the lowest under time-based regime.

Table 14b. Effect of interaction effect of irrigation and cultivar within the irrigation regimes on tomato total yield harvested per plant (kg) in the open field at the Horticulture Research Farm near Absaraka, ND during 2023.

	Total Yield		
Cultivar	10% MAD	30% MAD	Time based
	----------------------------kg $plant^{-1}$	--------------------------	
Amish Paste	7.35 ab[z]	3.37 a	7.81 a
Big Mama	2.08 c	3.17 a	2.09 bc
Cauralina	10.26 a	1.48 a	7.00 a
Gladiator	3.01 c	4.35 a	8.74 a
Granadero	5.67 bc	2.70 a	4.94 abc
Pozzano	5.37 bc	1.81 a	7.18 a
San Marzano	3.14 c	3.35 a	1.71 c
Super Sauce	4.31 bc	2.32 a	5.73 ab

[z] Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at $P< 0.05$

Unmarketable Yield (Cracks and Yellow Shoulder Disorder).

There was a cultivar by irrigation interaction effect on the unmarketable yield as shown in (Appendix Table A.8). ‘Cauralina’ and ‘Amish Paste’ had significantly higher weights of unmarketable yield when compared to the rest of the cultivars (Table 15). ‘Cauralina’ and ‘Amish Paste’ cultivars were the ones with the largest percentages of cracks and yellow shoulder disorder as shown on (Table 15). For ‘Cauralina’, cracks and yellow shoulder accounted for 51.2 and 77.5 % respectively of the unmarketable yield while cracks and yellow shoulder accounted for 55.5 and 66.9% respectively of the unmarketable portion in cultivar ‘Amish Paste’ (Table 15). For cultivar ‘Gladiator’ and ‘Big Mama’ cracks and yellow shoulder also contributed to a bigger percentage of the unmarketable yield but the percentages of the disorders for both the cultivars were not statistically different from each other (Table 15). ‘Granadero’ and ‘Pozzano’ exhibited considerably lower percentages of the disorders (Table 15).

Table 15. Tomato unmarketable yield, percentage of cracks and yellow shoulder disorder produced per plant in the open field trial at the Horticulture Research Farm near Absaraka, ND during 2023.

	Unmarketable yield	
Cultivar	% Cracks	% Yellow shoulder
Cauralina	51.2 a^z	77.5 a
Amish Paste	55.5 a	66.9 ab
Gladiator	23.3 bc	45.4 c
Super Sauce	11.6 bc	34.4 c
San Marzano	4.6 c	51.1 bc
Pozzano	3.2 c	10.8 d
Big Mama	28.7 b	42.9 c
Granadero	3.7 c	13.7 d

^{z}Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at P< 0.05.

Unmarketable Yield

A significant effect was observed on cultivar by irrigation interaction for the unmarketable yield (Appendix Table A.8). Therefore, analysis will focus on the interaction. ‘Cauralina’ recorded significantly higher unmarketable yields across all the irrigation treatments as shown on (Table 16a). ‘Pozzano’, ‘Big Mama’ and ‘San Marzano’ had similar weights of unmarketable yield across the three irrigation regimes.’Granadero’ had lower unmarketable weights but this varied across the different irrigation regimes. ‘Amish Paste’ and ‘Cauralina’ produced higher weights of unmarketable yield across the different irrigation treatments, but this varied among the treatments.

Table 16a. Effect of interaction effect of irrigation and cultivar across the irrigation regimes on tomato unmarketable yield harvested per plant (kg) in the open field at the Horticulture Research Farm near Absaraka, ND during 2023.

	Unmarketable yield		
Cultivar	10% MAD	30% MAD	Time based
	----------------------------kg plant^{-1}------------------------		
Amish Paste	4.32 b[z]	2.28 c	5.45 a
Big Mama	0.94 a	0.52 a	1.02 a
Cauralina	8.07 a	1.18 c	4.52 b
Gladiator	0.42 c	2.56 b	5.31 a
Granadero	0.72 b	0.39 b	1.63 a
Pozzano	0.99 a	0.8 a	0.92 a
San Marzano	0.85 a	1.12 a	1.42 a
Super Sauce	1.64 b	0.36 c	2.71 a

[z] Means followed by the same letter across different irrigation regimes are not significantly different on least significant difference (LSD) test at P< 0.05.

‘Cauralina’ had the highest weight of unmarketable yield under 10% MAD regime and differed from the rest of the cultivars (Table 16b). The rest of the cultivars produced lower weights of unmarketable yield and didn’t differ from each other except for ‘Amish Paste’ with 4.32 kg plant^{-1}. Irrigation regime 30% MAD didn’t affect the weight of unmarketable yield. ‘Gladiator’ had the highest weight of unmarketable yield under time-based irrigation while ‘Pozzano’ produced the least unmarketable weight under time-based irrigation.

Table 16b. Effect of interaction effect of irrigation and cultivar within the irrigation regimes on tomato unmarketable yield harvested per plant (kg) in the open field at the Horticulture Research Farm near Absaraka, ND during 2023.

	Unmarketable yield		
Cultivar	10% MAD	30% MAD	Time based
	---------------------------------(kg plant^{-1})	-------------------------	
Amish Paste	4.32 b[z]	2.28 a	5.45 a
Big Mama	0.94 c	0.52 a	1.02 c
Cauralina	8.07 a	1.18 a	4.52 ab
Gladiator	0.42 c	2.56 a	5.31 a
Granadero	0.72 c	0.39 a	1.63 c
Pozzano	0.99 c	0.8 a	0.92 c
San Marzano	0.85 c	1.12 a	1.42 c
Super Sauce	1.64 c	0.36 a	2.71 bc

[z] Means followed by the same letter within the same column are not significantly different on least significant difference (LSD) test at P< 0.05.

Fruit Quality

For the OF, no significant differences were observed on irrigation, irrigation by cultivar interaction on the fruit quality measurements, therefore only the effect of cultivar is discussed (Table A.9). Numerically, ‘Pozzano’ was leading with a pH of 4.0 but it didn’t differ statistically from all the other cultivars except for ‘Granadero’ with a pH of 3.25 (Table 17). No significant differences were observed among cultivars for Titratable Acidity (TA) and SSC (°Brix).

Table 17. Soluble solids content (SSC), titratable acidity (TA), and pH of open field tomatoes at the Horticulture Research Farm near Absaraka, ND during 2023.

Cultivar	pH	Titratable Acidity (TA)	SSC (°Brix)
Big Mama	3.51 ab ^{z,y}	1.37	4.77
San Marzano	4.01 a	1.27	5.27
Amish Paste	3.74 ab	1.11	5.02
Cauralina	3.61 ab	1.11	5.17
Gladiator	3.94 a	1.34	4.66
Pozzano	4.00 a	1.03	4.98
Granadero	3.25 b	0.84	4.97
Super Sauce	3.91 a	0.68	4.55
F-testx	0.0365	NS	NS

^{z}Probability value for the overall ANOVA *F*-test using he type III hypothesis test ($P < 0.05$. NS= Not significant

^{y}Least significant means followed by the same letters are not significantly different at LSD test ($P < 0.05$).

^{z}Values represent the least significant means of fruit harvested at the red ripeness stage from three harvests in 2023 in the high tunnel.

Discussion

Tomato offers a unique connection between growers and consumers especially in a direct-market context, due to its economic and cultural importance (Warren et al., 2015). Therefore, cultivar selection still remains one of the most important decisions that growers have to make (Williams & Roberts, 2002). Variations in growth, disease resistance and other traits among the various cultivars require growers to make decisions based on their willingness to accept trade-offs in performance between cultivars.

From our results, greater marketable yields by weight per plant were harvested in 2023 than year 2022 ‘Pozzano, that produced 12.1 kg of weight per plant. Despite, lower marketable yields in the HT 2022, ‘Cauralina’ and ‘San Marzano’ yielded best in 2022. The lower HT marketable yields in 2022 were attributed to an outbreak of tomato spotted wilt virus primarily for the OF plants that were located only a few meters away from the HT. For ‘Cauralina’ and

‘San Marzano’ s to do as well as they did, regardless of the disease, shows that they can be able to tolerate the disease outbreak and therefore a good choice for OF growers. In both years, ‘Super Sauce’ had the lowest number of fruits, and this is due to its large size and therefore fewer fruits produced per plant, but it was the largest in terms of the individual fruit weight. This was the same case for ‘San Marzano’ which produced a considerably high fruit numbers per plant due to its small size and had the lowest individual fruit weight.

As for the production systems (HT and OF), the yield difference between the production systems was evident. The HT produced almost three times higher yield than the open field. Our results are in concordance with (O’Connell et al., 2012; Rho et al., 2020) where HT produced higher marketable yields than the OF. This higher yield suggests greater profit as (Galinato & Miles, 2013) showed in an economic analysis concluded HT grown tomatoes were three times more profitable than the OF tomato production. This can be explained by the ability of HTs to accumulate more Growing Degree Days (GDD) thus increasing the air temperature which allowed for season extension and facilitated early crop establishment thus increasing yield. Season extension for HTs will however vary based on year by year weather patterns and crop species (Rho et al., 2020). Trellising in the HTs can also be attributed to higher yields. Trellising can improve sunlight penetration in the low parts of the canopy layers of tomatoes in HT, which can increase overall photosynthesis and biomass gain of the plants (Rho et al., 2020), even though the current study used similar trellising in the HT and OF.

In the current study, transplanting in the HT was possible ≈ 4 and 6 weeks earlier compared with that of the OF for the 2022 and 2023 growing seasons, respectively. The earlier planting in the HT compared with the OF enabled earlier harvesting of the crops. Similar results were found by (Rho et al., 2020) where 1-3 weeks earlier planting and harvesting was possible in the HT. The ability to harvest crops earlier in the HT has the potential to increase premiums for growers (Bruce et al., 2019; Galinato & Miles, 2013).

The different irrigation treatments used also had varying individual fruit weights in both years. Plants under time-based irrigation and the 10% MAD irrigation treatments produced heavier fruit than plants under the 30% MAD irrigation treatment. This indicates that in general, water limitation (30% MAD) for the cultivars in the current study reduced the individual fruit weight. In contrast, the 30% MAD produced the highest marketable yield while the time based had the lowest number of marketable yields.

There was also an interaction of cultivar by irrigation that was observed on the total yields for the HT 2022 and OF 2023 environments. For growers this could mean that they need to make the right decision concerning the choice of cultivar and irrigation method to use, as some cultivars perform better than others under specific irrigation conditions. As for the unmarketable yield, a cultivar by irrigation effect was also present. This means that the susceptibility of some cultivars to produce unmarketable yield can be influenced by irrigation. Growers ought to select the right irrigation method and right cultivars to avoid quality loss.

The top three causes of physiological disorders during these two growing seasons were cracking, yellow shoulder and blossom end rot. However, while cracking was prevalent in both years yellow shoulder and blossom end rot were only observed in the year 2023. Cultivar ‘Cauralina’ and ‘Amish Paste’ were the most susceptible to cracking. Several factors are thought to affect fruit cracking and they include, rapid fruit growth, high humidity, genetic susceptibility, fluctuations in plant water status and/or diurnal temperatures and fruit subjected to high light intensity (Peet, 1992). From our results, the open field recorded the greatest percentages of cracks. Although this data wasn’t analyzed statistically, in 2023 high tunnels had lower percentages of cracks in ‘Cauralina’ and ‘Amish Paste’ fruit by 24.7 and 22.4 %. Our results are in concordance with (Frey et al., 2020) where high tunnel reduced the cracks in grafted organic tomatoes in the subtropics region. In the OF during rainfall events, water penetrates the fruit through minute cracks or through the corky tissue around the stem scar causing an increase in hydrostatic pressure of the pulp of the skin and causes cracks. According to (Peet, 1992), anatomical characteristics of cracking for susceptible cultivars are identified as large fruit sizes, low skin tensile strength , thin skin and pericarp. ‘Cauralina’ and ‘Amish Paste’ are generally large in size and therefore this could have contributed to their cracking. It is important for growers to gain understanding on the susceptible cultivars to this disorder and the factors that exacerbate these disorders so that they can avoid quality loss.

Yellow shoulder disorder was shown to be at higher percentages for plants in the OF than plants in the HTs in 2022. This disagreed with a study by (Martin, 2013) where they reported higher percentages of yellow shoulder in the high tunnel than in the open field for organically grown tomatoes. The cause of this disorder is complex, but several studies have shown that weather, plant genetics, plant nutritional status and their interactions are possible influencing factors (Dumas et al., 2003; Jarquín-Enríquez et al., 2013; Maynard et al., 2017; Sacks & Francis, 2001; Shaheen et al., 2016). High percentages of this disorder in the OF in our study could be linked to the tomatoes being exposed to direct sun rays in the OF. (Suzuki et al., 2013) indicated that high temperature and direct sunlight affects the development of plastids, reducing the lycopene content and causing the yellowing most often on the shoulders of the tomato. (Helyes et al.) (2008) also reported a similar effect of direct solar radiance that caused exposed fruits to overheat and reach temperatures +10 °C higher than the foliage shaded fruits which results in lycopene degradation. In this context, growers should consider fruit shading when planning to grow these more susceptible cultivars. This disorder also occurs due to low potassium levels in the fruit (Madakadze & Kwaramba, 2004). Therefore, cultivar selection may be an important factor for growers to consider reducing the yield impact of this unmarketable trait.

Blossom end rot was another major defect that occurred during the 2023 growing season. This disorder is attributed to a calcium deficiency in the fruit, correlated with root zone salinity, soil water stress, excessive N fertilization and/or rapid fruit growth (Dorais et al., 2002; Saure, 2001). All these factors can result in an increase in reactive oxygen species that caused high oxidative stress and finally cell death. The BER incidence in the HT was high compared to the OF although the data for the two production systems wasn't statistically analyzed. This is similar to what was reported by (Martin, 2013) where HTs increased the BER occurrence compared with the OF system. The elevated temperatures in the HT can be linked to the occurrence of BER. The incidence of BER also varied among the cultivars with some cultivars exhibiting a higher number of BER than others. This can be attributed to the genetic differences among these cultivars. Lower incidence of BER can be achieved by selecting the less susceptible cultivars as well as modifying cultural practices including irrigation, fertilization, pruning and training.

The fruit quality attributes of tomato vary among cultivars, in terms of pH value which determines the fruit ripeness stage but also post-harvest fruit quality (Savić et al., 2024). From our findings, the HT and OF plants had fruit that exhibited a similar pH range of 3.7 to 4.2 although this data from these two production systems were not analyzed statistically due to lack of replication. This agrees with a study by (Rho et al., 2020) where no significant differences were observed between the pH of fruits grown in the HT and the ones grown in the OF conditions. The pH of tomatoes can influence their taste, as tomatoes with higher pH values are linked to a less sour and grassy flavor perception (Maul et al., 2000). Additionally, ripe tomato fruits with high pH values tend to receive better ratings for sweetness and odor in sensory analysis. However, a high pH value is less desirable for tomatoes used for processing as low acid food with a pH > 4.6 requires rigorous heat treatments to prevent spoilage and guarantee the safety of tomato products (Maul et al., 2000). Producers ought to make the right choice of cultivars to grow based on their consumers preferences.

Soluble solids content (SSC) is an indicator of sweetness since fructose and glucose are the main components (Malundo et al., 1995). It's the sum of sugars, acids and other minor components in the tomato fruit and is measured in °Brix (Balibrea et al., 2006). From our results, sugar content for HT tomatoes ranged from 4.2 to 5.5 while the OF ones ranged from 4.5 to 5.2 °Brix. Tomatoes intended for industrial purposes typically have a SSC level of at least 5 °Brix (Peixoto et al., 2018). In this context, all of our OF cultivars and more than half of the HT cultivars qualified for industrial use due to their high SSC content. Tomato SSC mainly comprises of reducing sugar and therefore any factor including seasonal climatic variation and horticultural practices that alters sucrose synthesis (photosynthetic activity) affects glucose and fructose accumulation in the fruits and SSC. From our study it is evident that SSC is cultivar dependent.

Titratable acidity (TA) determines the estimation of the acids that are available in the fruit and as the TA in the tomato fruit decreases, its maturity increases (Anthon et al., 2011; Mngoma et al., 2022). For this study fruit from plants in the HT had lower values of TA and this can be attributed to the elevated temperatures in the HT which in turn increased the organic acid metabolism (Cowan et al., 2014) and therefore higher TA in the OF can be attributed to lower air temperatures than in the HT thus reduced organic metabolism. (Mngoma et al., 2022) reported that that large-sized tomato fruits had higher acidity than the small-sized fruit. This was however not the case for our study because the TA didn’t seem to have been affected by the fruit sizes. This could be explained by the cultivar genetic differences that caused this difference in the TA (Tigist et al., 2013). Additionally, tomatoes with a high SSC:TA value, consumers would perceive its taste as bland rather than tasty and therefore a certain level of acidity is essential for sensory perception of good tomato taste (Savić et al., 2024).

Conclusions and Further Research

Cold temperature protection, earlier planting and harvests and higher yields were the main advantages of the high tunnel in this study. The high tunnel ability to modify the microenvironment enabled season extension by up to 4 weeks. The eight cultivars varied in fruit yield components and fruit quality variables (SSC, TA and pH). Irrigation treatments affected fruit yield components as well but varied among the cultivars. Irrigation treatment 30% MAD produced the highest marketable yields in the high tunnel. However, the limited number of trial years and inconsistent results across the two production systems highlight the need for additional research. Further studies are necessary to identify a paste cultivar that consistently produced high yields suitable to meet consumer demand.

CHAPTER 3: PEPPERS

Introduction

Internationally, pepper is the second most important HT crop after tomato (Lamont, 2009). It is also the among the top five most common crops grown in the Midwest HTs (Knewtson, Carey, et al., 2010). High tunnels are used to improve the yield and fruit quality of bell peppers while protecting crops from wind, rain, freeze events and insect damage (Torres-Quezada et al., 2021).

Based on the growth habit, bell peppers can be classified as determinate or indeterminate. Determinate bell peppers are genetically programmed to stop growing when flower buds start developing (Santos, 2012). On the other hand, indeterminate cultivars are not predetermined in their growth. They have overlapping flowering and fruit with steady plant growth if resources allowed. Generally, these cultivars can grow throughout the season unless killed by frost. Indeterminate cultivars are mainly used in protected cultures such as the HT, which allows growers to maximize their profits by extending the growing season.

The optimum temperature range for peppers ranges between 20 and 25°C and peppers are sensitive to high temperatures (Saha et al., 2010).Therefore, when the temperature falls below 15°C or exceeds 32°F, growth is usually retarded and yield decreases.

With the HT, air temperature can be modified in the structure helping to reduce sunscald damage on pepper fruits (Lamont, 2009) which is caused by high temperatures. High tunnels also reduce physiological disorders in flowers caused by high air temperature (Gerber et al., 1988; Saha et al., 2010; Wien, 1990). This includes abnormal development of male and female organs in flowers, which can lead to fruit set reduction (Erickson & Markhart, 2001), flowers dropping and reduced marketable yield (Hartz et al., 2008).

Previous research conducted on bell pepper production in the HT has shown a positive effect on pepper yields. (Sideman, 2020) recorded higher number of marketable pepper cultivars from a HT when compared to those grown in an OF. Total and average fruit counts were higher in HT peppers compared to those in the OF in a study by (Rho et al., 2020) . Additionally, the total yields were 62.3 % higher in the HT than in the OF (Fitzgerald & Hutton, 2012).

Unfortunately, scientific research into production of bell peppers in the HT in North Dakota using automated irrigation system is limited. The objective of this study was to evaluate the yield and quality of eight bell pepper cultivars grown in the HT and the OF using an automated irrigation system at two levels of allowable depletion compared to a time-based system.

Materials and Methods

Site Description

The research was conducted during the 2022 and 2023 growing seasons in two production systems, a HT and an OF environment. The experiment took place at the NDSU Dale E. Herman Horticulture Research and Arboretum (46°59’28.2” N 97°21’19.9” W, with an elevation of 1070 m) near Absaraka, North Dakota in Cass County. This region is characterized as continental, that has hot or warm summers and cold winters with an annual precipitation range between 380 and 760 mm (Tollerud et al., 2018). The site is on Warsing soil series; Fine-loamy over sandy or sandy-skeletal, mixed, super active, frigid oxyaquic hapludolls. Warsing soils are characterized by moderately well-drained loam alluvium over stratified sand and gravel (Soil Survey Staff, 2000). This region is in plant hardiness zone 4a with minimum temperature range of -30^{o} F to -25^{o}F (USDA-ARS, 2012).

The high tunnel trial was conducted in a gothic-style unheated HT (Northpoint, Rimol Greenhouse Systems, Inc. Hooksett, NH) covered with a double air inflated 4 year-rated 6 mil clear polyethylene greenhouse film treated with anti-condensate and ultraviolet features with 13-gauge steel framework for support. The length of the HT was oriented north to south with dimensions 29 m long, 9 m wide and 5 m tall. The high tunnel was strengthened by nominal lumber-framed end walls, baseboards, and hip boards.

Ventilation was accomplished by thermostatically controlled electric roll up sidewalls running the lengths of both sides set to open at 25°C and motorized shutter vents in each gable end wall set to open at 21 °C. Three fans were also installed and were manually turned on when needed to allow air circulation during the hot days. Two garage doors on both end walls were manually opened to provide additional ventilation on hot days.

Site Preparation

Prior to planting, the HT and OF plots were tilled and raised beds formed using a rotor-tiller and bed-shaper equipment. In each HT and OF plots, nine beds each measuring 4.6 m in length and 0.69 m in width were made. The beds contained a single row of plants with a spacing of 0.69 m within plants and 1.83 m between rows. Surface drip irrigation was installed with two lines of 15-mil drip tape (Toro® Aqua-Traxx, DripWorks, 15 Willits, CA) with emitters spaced at 20.3 cm apart. Each plot was covered with a 0.025- millimeter black plastic mulch (Berry Hill Irrigation, Buffalo Junction, VA) to conserve soil moisture and to also smother weeds.

The drip irrigation system was controlled by a Watermark soil potential sensor (Irrometer Company, Riverside, CA) using a Wi-Fi enabled controller and solenoid valve (Hunter proC, San Marcos, CA), and a flowmeter (Mid-west Instrument Sterling Heights, Michigan 48314). Three irrigation regimes were used; time-based (which is equivalent to the traditional irrigation system where irrigation would take place based on either hot or dry days), 10% management allowable depletion (MAD) and 30% MAD for both locations. A watermark sensor installed at 15 cm soil depth in each irrigation treatment for each crop was connected to the controller to trigger the irrigation system based on the output from the sensor displayed on the soil click. For the 10% MAD, when the soil moisture level reaches 10% below the field capacity, irrigation will be triggered. For the 30% MAD irrigation was triggered when the soil moisture level reached 30% below the field capacity. For the time-based treatment, the irrigation took place at 09.00 am for a duration of 24 minutes every Monday, Wednesday, and Friday regardless of the soil moisture status. The soil potential sensors were used to check the soil moisture status at 09.00 am, 03.00 pm and 09.00 pm daily and irrigation would take place if needed. The corresponding levels in Soil-Click (Hunter Industries, San Marcos, CA, USA) to automate the irrigation system based on the soil water potential sensor reading installed in the soil at a depth of 15 cm were found based on the manufacturer's manual.

Temperature

Weather data, air temperature and relative humidity were monitored in the field using the North Dakota Agricultural Weather Network (NDAWN) near Prosper, ND with an elevation of 284 m above sea level. The NDAWN station temperature and relative humidity sensors are set at 1.5 m from the soil surface. A Decagon EM50 data logger (Decagon Devices, Inc., Pullman, WA) was set up at the experimental site to monitor inside and outside air temperature readings. Both data loggers were set up to be comparable to the NDAWN stations for air temperature. Growing degree days (GDD) were calculated after transplanting and base temperatures for the calculations were 10 °C as GDD = $[(T_{max} + T_{min},)/2 - T_{base}$, with 10 °C if Tmax or Tmin $< T_{base,}$ and if Tmax> 30 °C its set to be equal to 30 °C where T_{max}, and T_{min} are daily maximum and minimum air temperature, respectively, and T_{base} is the base temperature (Pathak & Stoddard, 2018).

Plant Materials

Eight bell peppers cultivars from (Johnny's Selected Seeds Winslow, ME and Harris Seeds, Rochester, NY) were selected to be used for both the HT and the OF trial for both years. Names of pepper cultivars, seed sources, disease resistance codes, fruit color, average fruit weight and days to maturity are presented in table the below.

Table 18. Pepper trial cultivar, seed source, days to maturity, color and fruit size according to Johnny's Selected Seed.

Cultivar	Seed source^{y}	Disease resistance^{x}	Days to initial/ripe^{w}	Color	Fruit size
Olympus F_1 ^{z}	JSS	BLS	65/75	Green/Red	Medium
Ninja F_1	JSS	TOMV, BLS	60/80	Green/Red	Large
X3RRed Knight F_1	JSS	BLS, PVY	57/77	Green/Red	Large
Classic F_1	JSS	BLS, TOMV	63/83	Green/Red	Large/Extra large
King Arthur F_1	JSS	BLS, PVY	59/79	Green/Red	Large
Early Sunsation F_1	HRS	BLS	65	Green/Yellow	Large
Intruder F_1	HRS	BLS, TOMV	60/72	Green/Red	Large
Orange Blaze F_1	HRS	BLS	65/80	Green/Orange	Medium

^{z}Refers to F_1 hybrid.
^{y}TOMV= Tomato Mosaic Virus, BLS=Bacterial Leaf Spot, PVY=Potato Virus Y
^{x}JSS= Johnny's Selected Seeds, HRS= Harris Seeds
^{w}Initial green/ ripe.

Crop Seeding and Transplanting

In 2022 peppers for the HT trial were seeded on 17 March in Lord and Burnham Greenhouse in Fargo, ND (23.9℃, 16:8 L:D, RH=40-65%) in standard insert 800 series (T.O. Plastics, Clearwater, MN) containing a peat-based growing medium (PRO-MIX BX, Premier

Tech, Quebec, Canada). Seedlings were then transplanted on 20 April into SVD-450 molded plastic pots (T.O. Plastics, Clearwater, MN) filled with the same growing media.

Pepper seeds for the OF plots were started on 15 April in the same greenhouse using the same media that was used for the HT experiment plants. They were then transplanted into SVD-450 pots on 11 May. The seedlings were fertigated with supplemental water-soluble fertilizer 20N:20P:20K (J.R. Peters, Inc Allentown, PA) at a recommended rate of 134 $kg \cdot ha^{-1}$. Seedlings were fertigated weekly at the rate of 100 ppm administered through a fertilizer injector (Dosatron International, Clearwater, FL). This achieved half of the recommended rate for the plants. The remaining half of the fertilizer 67 $kg \cdot ha^{-1}$ was applied post-transplanting in splits.

In 2023, pepper seeds were started in the North Dakota Agricultural Experiment Station (NDAES) since the greenhouse used for year 2022 was connected to the room that had the thrips and aphids which resulted in TSWV infected seedlings. Seeds for the HT peppers were sown on 15 March in standard insert 800 series (T.O. Plastics, Clearwater, MN) and transplanted into SVD-450 molded plastic pots on 11 April in Pro-Mix growing medium (PRO-MIX BX, Premier Tech, Quebec, Canada). The OF plots seeds were sown directly in SVD-450 molded plastic pots on 17 April using the same growing media that was used for the HT trial crops. The same fertilization procedure for 2022 was used for 2023 production year.

In both years, seedlings were placed in outdoor conditions approximately one week to expose them to the ambient conditions of wind and cool mornings so that they would acclimate. Transplanting was done by hand in both years. Transplanting dates in the HT system were on 5 May 2022 and 1 May 2023, whereas transplanting dates in the OF took place on 7 June 2022 and 12 June 2023 which was a month later after transplanting in the HT.

Management Practices

For both years cultural management practices were tailored to each production system to maximize the production capacity of the respective system. For bell peppers, no pinching or pruning took place during the season. However, some metal posts were pounded in the ground then the pepper main stem was attached to these poles by use of trellis clips from (Johnny's Selected Seeds Winslow, ME.). This was to provide support and prevent the breakage of the heavy pepper plants during events of high wind. Weeds around the plants and in the beds were controlled manually by hand. A mechanical hoe was used to remove the weeds between the rows and around the HT and the OF plots.

Scouting for the two production systems took place weekly in both 2022 and 2023 and pest management decisions were based on scouting. In the summer of 2022, the HT peppers were infested with green peach aphid. One application of malathion 50% E.C. (Ortho Group, Marysville, OH) was applied and then discontinued due to the plants showing burn symptoms after the application. In 2023, the HT crops were infested with green peach aphids and one application of imidacloprid (Admire Pro, Bayer Crop Science Inc. St. Louis, MO) was made to successfully control the pests. All the pesticides were applied at rates according to label directions.

Fertilization

In both years, the remaining half of 6.78 kg/ha of the 20N:20P:20K was applied to peppers during the growing season in three splits until the total recommended rate for the season was met. This was applied at the base of each plant under the plastic mulch. Calcium Nitrate (15.5-0-0-19Ca) at the rate of 0.12 kg/ha was also applied during the growing season in split applications to boost calcium level when fruits were beginning to form and expand.

Experimental Design

This two-year study was a randomized complete block design with a split-plot arrangement where irrigation was the whole plot factor and cultivar was the sub-plot. Irrigation treatments, (time-based which is equivalent to the traditional irrigation method, where irrigation took place based on hot, windy or dry days,10% management allowable depletion (MAD) and 30% MAD were applied in the HT and OF trials for both years. Within each irrigation treatment, there were eight paste tomato cultivars. There were three randomized complete blocks with each treatment replicated three times.

Harvest and Data Collection

Harvesting of fruits took place throughout the season until the plants were killed by frost. Fruit harvesting was conducted twice per week in the HT from 10 July to 30 Sept. in 2022 and from 21 July to 25 October in 2023. For the OF trials, harvesting took place once a week in 2022 from 5 August to 22 September 2022 and twice per week from 24 August to 17 October 2023. Marketable and culled fruit from each plant were counted and weighed. Cull fruits were the unmarketable ones since they either showed signs of blossom end rot or sunscald and this was determined based on the observations of mechanical or biological defects on fruit surfaces. Culled fruits were the unmarketable ones since they either showed signs of blossom end rot or sunscald. Other yield parameters including total fruit count, total yield and fruit size were determined.

Statistical Analysis

Data was analyzed using linear mixed model as implemented in SAS PROC MIXED (version 9.4; SAS Institute, Cary, NC). Data were analyzed for the presence of significant main effects and interactions. When interactions among factors were present, the main effects for those factors were not considered for further analysis but analysis focused on the interactions. Least-square means comparisons were performed using the Fisher’s least significant difference test ($P < 0.05$). Main effects of irrigation and cultivar were considered fixed while year and replications were considered as random effects. Homogeneity of variances were tested and since they were uniform the data was pooled across the two years.

Results

Temperature Trend in High Tunnel and Open Field in 2022

In May, the average HT daily maximum air temperature recorded was 32.2°C, the average daily air temperature was 18.2°C, and the average minimum temperature was 3.6°C. Open field average, minimum and maximum daily temperatures are not shown due to the data logger malfunction during this time. In June, the average OF daily maximum air temperature recorded was 38.5°C, the average daily air temperature was 21.2°C, and the average daily minimum temperature was 3.4°C. The average, maximum and minimum daily temperatures were 1.9°C, 1.1°C and 4°C higher inside the HT than in the OF, respectively. In July, the average OF daily maximum air temperature recorded was 36.6°C, the average daily air temperature was 22.8°C, and the average daily minimum temperature was 10.6°C. The average, maximum and minimum daily temperatures were 2.3°C, 1.9°C and 2.9°C higher inside the HT than in the OF, respectively. In August, the average OF daily maximum air temperature recorded was 35.9°C, the average daily air temperature was 20.8°C, and the average daily minimum temperature was 8.3°C. The average, maximum and minimum daily temperatures were 2.4°C, 2.7°C and 3.8°C higher inside the HT than in the OF, respectively (Table 19). The hottest month of this growing season was in June (39.6°C) in the HT while the lowest temperature was recorded in June (3.4°C) in the OF.

Table 19. Mean maximum (Max.), average (Avg.) and minimum (Min.) air temperature (°C) for the open field and high tunnel at the Horticulture Research Farm near Absaraka, ND during 2022.

	High tunnel[z]			Open field[y]		
Month	Avg	Max	Min	Avg	Max	Min
May	18.2	32.2	3.6	-	-	-
June	23.1	39.6	7.4	21.2	38.5	3.4
July	25.1	38.5	13.5	22.8	36.6	10.6
August	23.2	38.6	12.1	20.8	35.9	8.3

[z] High tunnel data is from 11 May to 26 August.

[y] Open field data represents data from 1 June to 25 August.

Temperature Trend in Open Field and High Tunnel in 2023

In June, the average OF daily maximum air temperature recorded was 35.9°C, the average daily air temperature was 21.8°C, and the average daily minimum temperature was 9.6°C. The average, maximum and minimum daily temperatures were 2.6°C, 2.3°C and 5.2°C higher inside the HT than in the OF, respectively. In July, the average OF daily maximum air temperature recorded was 36.4°F, the average daily air temperature was 20.6°C, and the average daily minimum temperature was 7.1°C. The average, maximum and minimum daily temperatures were 3.1°C, 4.3°C and 4.5°C higher inside the HT than in the OF, respectively. In August, the average OF daily maximum air temperature recorded was 34.6°C, the average daily air temperature was 20.9°C, and the average daily minimum temperature was 9.8°C. The average, maximum and minimum daily temperatures were 2.4°C, 3.5°C and 3.9°C higher inside the HT than in the OF, respectively. In September, the average OF daily maximum air temperature recorded was 35.6°C, the average daily air temperature was 17.5°C, and the average daily minimum temperature was 3.7°C. The average, maximum and minimum daily temperatures were 2.3°C, 1.8°C and 4.1°C higher in the HT than in the OF, respectively. In October, the average OF daily maximum air temperature recorded was 34.1°C, the average daily air temperature was 10.0°C, and the average daily minimum temperature was -3.8°C. The average daily temperatures were 2.4°C, 0.5°C and -0.8°C higher inside the HT than in the OF, respectively. In October, the average HT daily maximum air temperature recorded was 20.6°C, the average daily air temperature was 3.9°C, and the average daily minimum temperature was -2.1°C. Open field average, minimum and maximum daily temperatures are not shown due to the data logger malfunction. The lowest average daily temperature recorded for the 2023 growing season was in October (-4.6°C) in the HT while highest temperature was recorded in July (40.7°C) in the high tunnel as well (Table 20).

Table 20. Mean maximum (Max.), average (Avg.) and minimum (Min.) air temperature (°C) for the open field and high tunnel at the Horticulture Research Farm near Absaraka, ND during 2023.

	High tunnel[z]			Open field[y]		
Month	Avg	Max	Min	Avg	Max	Min
June	24.4	38.2	14.8	21.8	35.9	9.6
July	23.7	40.7	11.6	20.6	36.4	7.1
August	23.3	38.1	13.7	20.9	34.6	9.8
September	19.8	37.4	7.8	17.5	35.6	3.7
October	12.4	34.6	-4.6	10.0	34.1	-3.8
November	3.9	20.6	-2.1	-	-	-

[z] High tunnel data represents data from 15 June to 2 November
[y] Open field data represents data from 15 June to 27 October

In 2022 the HT accumulated 365 more growing degree days (°GDD) than in the OF before the T50 period was reached (Table 21). In contrast, in 2023 the °GDD in the OF was 118 more than those in the HT. In both seasons the HT accumulated more °GDD over the entire season when compared with the OF system. The HT accumulated 596 and 342 more °GDD than the OF in 2022 and 2023 respectively (Table 21).

Table 21. Growing degree-days (GDD) and the number of days between transplanting and 50% harvest (T50) for the high tunnel and field system, at the Horticulture Research Farm near Absaraka, ND during 2022 and 2023**.**

	Transplant date		T50(d)[z]		°GDD to T50[y]		°GDD for entire season[x]	
Year	High tunnel	Field	High tunnel	Field	High tunnel	Field	High tunnel	Field
2022	5 May	7 June	148	125	2004	1639	2382	1786
2023	1 May	12 June	116	80	1591	1709	2690	2348

[z] T50 represents the number of days between transplanting and when 50% of fruit was harvested.

[y] Growing degree-days (°GDD) until 50% of fruit was harvested.

[x] Growing degree-days (°GDD) from transplanting until end of growing season (high tunnel season was 10 and 20 days longer than the field system in 2022 and 2023 respectively).

High Tunnel 2022 and 2023

Marketable Yield

The main effects of irrigation and cultivar were significant for marketable yield produced per plant (Appendix table A.10). Irrigation by cultivar interactions also occurred for marketable yield per plant, thus analysis will focus on the interaction. ‘Intruder’ ‘Classic’, ‘Ninja’ and ‘Orange Blaze’ produced similar marketable yield per plant across the irrigation treatments (Table 22). Yields of ‘Early Sun’ and ‘King Arthur’ reduced across the irrigation treatments.

Table 22. Effect of interaction effect of irrigation and cultivar across the irrigation regimes on pepper marketable yield harvested per plant (kg) in the high tunnel at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

	Marketable yield		
Cultivar	10% MAD	30% MAD	Time based
	----------------------(kg plant^{-1}) ------------------------		
Classic	4.69 a^{z}	4.77 a	3.66 a
Early Sun	5.43 a	5.24 a	3.4 b
Intruder	4.3 a	4.45 a	3.94 a
King Arthur	6.19 a	5.37 a	3.73 b
Ninja	5.57 a	4.43 a	4.5 a
Olympus	4.97 a	2.94 b	4.8 a
Orange Blaze	3.09 a	3.21 a	2.52 a
X3R Red Knight	4.92 ab	5.38 a	3.91 b

^{z}Means followed by the same letter across different irrigation regimes are not significantly different on least significant difference (LSD) test at P< 0.05.

‘King Arthur’ produced the most fruits under 10% MAD, but this was similar with all the other cultivars except for ‘Orange Blaze’ and ‘Intruder’ (Table 23). ‘King Arthur’ was also the top producer under 30% MAD but similar to all cultivars except ‘Olympus’ and ‘Orange Blaze’.

Table 23. Effect of interaction effect of irrigation and cultivar within the irrigation regimes on pepper marketable yield harvested per plant (kg) in the high tunnel at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

	Marketable yield		
Cultivar	10% MAD	30% MAD	Time based
	---------------------------(kg plant^{-1}) ---------------------------		
Classic	4.69 bc^{z}	4.77 a	3.66 ab
Early Sun	5.43 abc	5.24 a	3.4 ab
Intruder	4.3 bc	4.45 ab	3.94 ab
King Arthur	6.19 a	5.37 a	3.73 ab
Ninja	5.57 abc	4.43 ab	4.5 a
Olympus	4.97 abc	2.94 c	4.8 a
Orange Blaze	3.09 d	3.21 bc	2.52 b
X3R Red Knight	4.92 abc	5.38 a	3.91 ab

^{z}Means followed by the same letter within a column are not significantly different on least significant difference (LSD) test at P< 0.05.

Marketable Number of Fruits

The main effects of irrigation and cultivar were significant for the marketable number of fruits produced per plant. Irrigation by cultivar interactions also occurred for marketable number of plants per plant, thus analysis will focus on the interaction (Appendix table A.10.) ‘Classic’, ‘Intruder’ ‘Ninja’ and ‘X3R Red Knight’ exhibited consistently similar number of marketable fruits per plant across all the irrigation treatments (Table 24a). For ‘Early Sun’ and ‘King Arthur’, the number of fruits reduced across the irrigation treatments.

Table 24a. Effect of interaction effect of irrigation and cultivar across the irrigation regimes on pepper marketable number of fruits harvested per plant in the high tunnel at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

	Marketable number of fruits per plant		
Cultivar	10% MAD	30% MAD	Time based
Classic	39.17 a ^{z}	39.17 a	29.67 a
Early Sun	41.17 a	41.00 a	25.33 b
Intruder	33.33 a	34.00 a	30.67 a
King Arthur	48.83 a	45.33 a	29.67 b
Ninja	44.67 a	39.83 a	38.67 a
Olympus	36.17 a	22.67 b	37.00 a
Orange Blaze	44.67 ab	52.33 a	41.67 b
X3R Red Knight	40.83 a	47.00 a	32.33 a

^{z}Means followed by the same letter across different irrigation regimes are not significantly different on least significant difference (LSD) test at P< 0.05.

‘King Arthur’ produced the most fruits under 10% MAD but didn’t differ from the rest of the cultivars except for ‘Intruder’ (Table 24b). ‘Orange Blaze’ produced the most fruits under 30% MAD and time-based while ‘Olympus’ and ‘Early Sun’ produced the least number of fruits under 30% MAD and time-based respectively.

Table 24b. Effect of interaction effect of irrigation and cultivar within the irrigation regimes on pepper marketable number of fruits harvested per plant in the high tunnel at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

	Marketable number of fruits per plant		
Cultivar	10% MAD	30% MAD	Time based
Classic	39.17 ab[z]	39.17 bc	29.67 ab
Early Sun	41.17 ab	41.00 abc	25.33 b
Intruder	33.33 b	34.00 cd	30.67 ab
King Arthur	48.83 a	45.33 abc	29.67 ab
Ninja	44.67 ab	39.83 abc	38.67 a
Olympus	36.17 ab	22.67 d	37.00 b
Orange Blaze	44.67 ab	52.33 a	41.67 a
X3R Red Knight	40.83 ab	47.00 ab	32.33 ab

[z] Means followed by the same letter within a column are not significantly different on least significant difference (LSD) test at $P < 0.05$.

Total Yield

The main effects of irrigation and cultivar were significant for total yield produced per plant. Irrigation by cultivar interaction also occurred for total yield produced per plant, thus analysis will focus on the interaction (Appendix table A.10.) ‘Classic’, Intruder, ‘Ninja’ ‘Orange Blaze’ and ‘X3R Red Knight’ exhibited consistently similar yields across all the irrigation treatments (Table 25a).

Table 25a. Effect of interaction effect of irrigation and cultivar across the irrigation regimes on pepper total yield harvested per plant (kg) in the high tunnel at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

Cultivar	Total yield 10% MAD	 30% MAD	 Time based
	------------------------	(kg plant^{-1})	--------------------------
Classic	4.81 a^{z}	4.89 a	3.72 a
Early Sun	5.45 a	5.40 a	3.62 b
Intruder	4.38 a	4.48 a	4.01 a
King Arthur	6.23 a	5.44 a	3.95 b
Ninja	5.74 a	4.56 a	4.67 a
Olympus	5.02 a	3.01 b	5.12 a
Orange Blaze	3.12 a	3.26 a	2.60 a
X3R Red Knight	5.02 a	5.48 a	4.18 a

^{z}Means followed by the same letter across different irrigation regimes are not significantly different on least significant difference (LSD) test at $P< 0.05$.

‘Early Sun’, ‘King Arthur’ and ‘Ninja’ yielded the best under irrigation treatment 10% MAD at 5.45, 6.23 and 5.74 kg/plant respectively but were not significantly different from each other (Table 25b). The best yielding cultivar under 30% MAD was ‘X3R Red Knight’ but it wasn’t different from the rest of the cultivars except for ‘Orange Blaze’ and ‘Olympus’. ‘Olympus’ yielded the highest under time-based irrigation while ‘King Arthur’ yielded the best under 30% MAD.

Table 25b. Effect of interaction effect of irrigation and cultivar within the irrigation regimes on pepper total yield harvested per plant (kg) in the high tunnel at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

	Total yield		
Cultivar	10% MAD	30% MAD	Time based
	------------------------(kg plant^{-1}) -------------------------		
Classic	4.81 ab[z]	4.89 a	3.72 ab
Early Sun	5.45 ab	5.40 a	3.62 ab
Intruder	4.38 bc	4.48 abc	4.01 ab
King Arthur	6.23 a	5.44 a	3.95 ab
Ninja	5.74 ab	4.56 ab	4.67 a
Olympus	5.02 ab	3.01 c	5.12 a
Orange Blaze	3.12 c	3.26 c	2.60 b
X3R Red Knight	5.02 ab	5.48 a	4.18 a

[z] Means followed by the same letter within a column are not significantly different on least significant difference (LSD) test at P< 0.05

Fruit Size

The average diameter of fruits produced per plant was highly significant while the average length of the fruits was significant as shown on (Appendix table A.11.) 'Intruder' was the longest at 7.91cm followed by 'Olympus' at 7.79 cm but not significantly longer than the rest of the cultivars except 'King Arthur' and 'X3R Red Knight' which measured 7.62 and 7.42 cm respectively (Table 26). 'X3R Red Knight' was the shortest in length and measured 7.42 cm while 'King Arthur' had the widest diameter (7.85 cm) but was not significantly wider than that of 'Intruder' (7.71 cm) (Table 26). 'Early Sun' and 'Ninja' measured 7.67 cm and 7.61 cm respectively but were not significantly different from each other (Table 26). 'Ninja' measured 7.61 cm but not statistically longer than 'Olympus' which measured 7.45 cm (Table 26). 'Classic' and 'Orange Blaze' measured 7.24 and 5.24 cm respectively and were significantly smaller in diameter when compared to the rest of the cultivars (Table 26).

‘Intruder’, ‘Ninja’, ’Early Sun’, ‘King Arthur’ and ‘X3R Red Knight’ had blocky shapes while ‘Classic’ and ‘Olympus’ had elongated shapes (Table 26). ‘Orange Blaze’ was much longer than any of the bell peppers tested since it’s generally a tapered type of pepper (Table 26).

Table 26. Average size of diameter and length of peppers produced per plant in the high tunnel.

Cultivar	Length	Diameter	Fruit shape ^{y}
	---------------------cm	---------------------	
X3R Red Knight	7.42 c^{z}	7.65 b	0.97
Classic	7.69 ab	7.24 d	1.06
Intruder	7.91 a	7.71 ab	1.03
Ninja	7.66 abc	7.61 bc	1.01
King Arthur	7.62 bc	7.85 a	0.97
Olympus	7.79 ab	7.45 c	1.05
Orange Blaze	7.75 ab	5.24 e	1.48
Early Sun	7.67 abc	7.67 b	1.00

^{z}Means followed by the same letter are not significantly different on least significant difference (LSD) test at P< 0.05.

^{y}Length to diameter ratio; ≤0.95: very blocky, flattened shape; 1.00: blocky, length equal to diameter; ≥1.05: elongated shape with length greater than diameter. Variable was not subjected to statistical analysis

Open Field 2022 and 2023

Marketable Yield

There were no significant differences for total yield, marketable yields and marketable number of fruits produced in the open field (Appendix table A.13). However, marketable fruit numbers ranged from 11 to 27 fruits per plant with ‘Orange Blaze’ being the top producer under time-based irrigation (data not available). For the total yields, ‘X3R Red Knight’ was the top producer under 10% MAD while ‘Classic’ and ‘X3R Red Knight’ produced the highest weights under 30% MAD (data not shown).

Unmarketable Fruit Number

There were no interactions among year, cultivar or irrigation on total yield, marketable yield but there was a significant cultivar effect on unmarketable weight and unmarketable number of fruits, across both years as shown on (Appendix table A.12). The number of unmarketable fruits and weight differed significantly between the cultivars (Table 27). Most fruit categorized as unmarketable exhibited sunscald or blossom end rot (BER), two disorders that are difficult to distinguish (data not shown). Cultivar ‘Ninja’ produced the highest number of unmarketable fruits (2.74) thus having the highest unmarketable weight of 0.29 kg per plant.

Table 27. Effect of variety on pepper unmarketable fruit number and unmarketable weight in the open field trial at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

Cultivar	Unmarketable fruit number	Unmarketable weight
		----------kg plant^{-1}----------
Classic	0.61 b[z]	0.06 b
Early Sun	0.86 b	0.06 b
Intruder	0.88 b	0.12 b
King Arthur	0.22 b	0.03 b
Ninja	2.74 a	0.29 a
Olympus	1.19 b	0.11 b
Orange Blaze	0.63 b	0.03 b
X3R Red Knight	1.06 b	0.11 b

[z] Means followed by the same letter are not significantly different on least significant difference (LSD) test at P< 0.05.

Fruit Size

The average diameter of fruits produced per plant was highly significant while the average length of the fruits was significant as shown on (Appendix table A.13.) ‘King Arthur’ measured the widest with a diameter of 7.64 cm but was not significantly wider when compared to ‘X3R Red Knight’, ‘Intruder’ and ‘Ninja’ at 7.51, 7.44 and 7.5 cm respectively (Table 28). ‘Classic’ measured 6.99 cm but wasn’t significantly wider than ‘Olympus’ at 6.87 cm (Table 28). ‘Orange Blaze’ had the least diameter of 5.21 cm and was significantly different from the rest of all the cultivars (Table 28). Cultivars ‘X3R Red Knight’, ‘Ninja’, ‘King Arthur’, ‘Early

Sun' and 'Olympus' had a blocky shape with their lengths being equal to their diameters while 'Classic' and 'Intruder' had elongated shapes, lengths were greater than the diameter (Table 28). 'Orange Blaze' was much longer than any of the bell peppers tested since it's generally a tapered type of pepper.

Table 28. Average size of diameter and length of peppers produced per plant in the open field at the Horticulture Research Farm near Absaraka, ND combined over 2022-2023.

Cultivar	Length	Diameter	Fruit shape [y]
	-----------------cm-----------------		
X3R Red Knight	7.83 ab[z]	7.51 ab	1.04
Classic	7.67 ab	6.99 c	1.10
Intruder	7.85 ab	7.44 ab	1.06
Ninja	7.76 ab	7.5 ab	1.03
King Arthur	7.94 a	7.64 a	1.04
Olympus	6.82 c	6.87 c	0.99
Orange Blaze	7.64 ab	5.21 d	1.47
Early Sun	7.4 b	7.35 b	1.01

[z] Means followed by the same letter are not significantly different on least significant difference (LSD) test at P< 0.05.

[y] Length to diameter ratio; ≤0.95: very blocky, flattened shape; 1.00: blocky, length equal to diameter; ≥1.05: elongated shape with length greater than diameter. Variable was not subjected to statistical analysis.

Discussion

From the HT results, we can conclude that cultivars respond differently to the three irrigation treatments. 'Intruder' and 'King Arthur' had rather high yields across all the irrigation treatments, but higher yields were achieved under 30% MAD and 10% MAD. This suggests that both cultivars may be less sensitive to changes in irrigation levels, and they might be suitable for growers experiencing periodic water shortages. 'King Arthur' produced the highest yield overall across all the treatments which was similar to that reported by (Hutton & Handley, 2007) where this cultivar was rated as a top producer in years 2003 and 2005 with no supplemental irrigation.

'Classic', 'Early Sun', 'Ninja' and 'Olympus' yielded the best under 10% MAD. This suggests that these cultivars are more sensitive to moisture stress and frequent irrigation is needed to achieve optimal yields. This was similar to reports by (de Freitas et al., 2011; Kashyap & Panda, 2003) who evaluated the effect of irrigation scheduling on potato and concluded the highest tuber yields were produced under 10% MAD. ‘Olympus’ and ‘Ninja’ produced more marketable yields under time based irrigation (control) when compared to 30% MAD. Similar results were achieved by Shah et al. (2023) where a cultivar of watermelon (*Citrullus lanatus*) did the best under the time based irrigation which was the control. This result suggests that these cultivars do well under fluctuating water conditions and therefore it’s crucial for growers to understand specific water requirements for each cultivar.

For the marketable number of fruits there was a variability of number of fruits among the cultivars. The difference in performance of these cultivars under the three irrigation treatments was attributed to genetic differences among cultivars, with some cultivars having traits that enabled them to still perform better under a more limited water supply.

‘Olympus’ showed an exceptional performance on the marketable yield, fruit number and total yield under time-based irrigation (control). This makes it desirable for growers who are seeking both quality and quantity in their pepper production but do not have the capabilities for remote sensing. Furthermore, ‘Olympus’ can be considered as the best cultivar with high productivity under conditions where irrigation is done on a predetermined schedule rather than based on soil moisture status.

The significant differences in average fruit diameter and lengths of peppers indicates that sizes of pepper fruits is genetically controlled and was consistent with the results reported by (Langenhoven, 2019; Sideman, 2020). Although, the lengths were not statistically significant with each other for some comparisons, they are important as they contribute to overall appearance and marketability of the fruit. The differences in shape exhibited by the different cultivars i.e. ‘Ninja’ and ‘Early Sun’ having blocky shapes and ‘Classic and ‘Olympus’ having elongated shapes are important to note as this can influence consumers preferences. In conclusion, The HT production system did increase the yield of peppers.

In the OF trial, ‘Orange Blaze’ produced the least weight of unmarketable fruits because it was among the fruits with the least overall total yield and marketable yield. The lack of differences in total yield, marketable yield, and number of fruits indicated that supplemental water from rainfall nullified any differences that the irrigation regimes may have caused.

Previous research has demonstrated that irrigation frequency, cultivar susceptibility and fertilization program can impact blossom end rot .However, our results do contrast those of (Martin, 2013) who reported the potential of high tunnels to increase blossom end rot occurrence when compared to the open field system.

‘Orange Blaze’ standing out as having the smallest diameter but the longest length among all cultivars is an important characteristic that might influence a grower’s choice for their desired pepper shapes based on consumer demand. On the other hand, growers who are looking to produce large, blocky and robust peppers cultivars, should select ‘X3R Red Knight’, ‘Intruder’ or ‘Ninja’.

Conclusion and Future Research

The principal benefits of HT production systems that have been extensively documented across different climatic conditions and in different crops include season extension, increased yields and decreased disease incidence (Demchak, 2009; Galinato & Miles, 2013; Lamont, 2009; O’Connell et al., 2012; Powell et al., 2014). From our study transplanting in the HT was possible ≈ 4 to 6 weeks earlier compared with that in the OF for the 2022 and 2023 growing seasons, respectively (Table 3). The earlier start of the growing season in that when compared with the

OF resulted in earlier harvesting of the crops. (O’Connell et al., 2012) found similar results (1-3 weeks earlier planting and harvesting) for an open pollinated tomato cultivar in North Carolina. Similarly, transplanting in the HT was possible ≈3 to 6 weeks earlier compared with that in the OF for the 2018 and 2019 seasons, respectively in production of jalapeno pepper and tomatoes in the Texas Plains (Rho et al., 2020). Earlier harvesting of HT crops compared with the OF has the potential to increase premium prices for producers (Bruce et al., 2019; Galinato & Miles, 2013). The total number of fruits, marketable yield and total yield per plant produced in the HT was almost double the amount produced in the OF.

The increased daily minimum temperatures in the HT as compared to the OF during the growing seasons observed in our study was similar to those observed by (Heckler, 2017). Additionally, the HT was able to accrue more daytime heat which resulted from faster accumulation of the GDD at a faster rate than in the OF in the early growing season (Table 3). By the end of the growing season the HT had accumulated 596 and 342 more GDD than the OF in 2022 and 2023 respectively. This is beneficial to growers as they are able to get early peppers and this helps them with obtaining greater profits and developing customer loyalty (O’Connell et al., 2012).

Due to lack of production system replication and thus no comparison between the two systems, the results of this research suggest that HT can be used to achieve consistent greater marketable yield when compared to the OF. In addition, high tunnels use may be particularly advantageous to the growers in the Northern regions as a season extension tool for bell pepper production.

REFERENCES

Alvarenga, M. A. A. R. (2004). *Tomate: produção em campo, em casa-de-vegetação e em hidroponia*. Ufla.

Anthon, G. E., LeStrange, M., & Barrett, D. M. (2011). Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. *Journal of the Science of Food and Agriculture, 91*(7), 1175-1181. https://doi.org/10.1002/jsfa.4312

Antignus, Y. (2000). Manipulation of wavelength-dependent behaviour of insects: an IPM tool to impede insects and restrict epidemics of insect-borne viruses. *Virus Research*, *71*(1-2), 213-220. https://doi.org/10.1016/S0168-1702(00)00199-4

Antignus, Y., Mor, N., Ben Joseph, R., Lapidot, M., & Cohen, S. (1996). Ultraviolet-absorbing plastic sheets protect crops from insect pests and from virus diseases vectored by insects. *Environmental Entomology*, *25*(5), 919-924. https://doi.org/10.1093/ee/25.5.919

Aujla, M. S., Thind, H. S., & Buttar, G. S. (2007). Fruit yield and water use efficiency of eggplant (Solanum melongema L.) as influenced by different quantities of nitrogen and water applied through drip and furrow irrigation. *Scientia Horticulturae*, *112*(2), 142-148. https://doi.org/10.1016/j.scienta.2006.12.020

Awondo, S. N., Fonsah, E. G., Riley, D., & Abney, M. (2012). Effectiveness of tomato-spotted wilt virus management tactics. *J Econ Entomol*, *105*(3), 943-948. https://doi.org/10.1603/ec11272

Balibrea, M. E., Martínez-Andújar, C., Cuartero, J., Bolarín, M. C., & Pérez-Alfocea, F. (2006). The high fruit soluble sugar content in wild Lycopersicon species and their hybrids with cultivars depends on sucrose import during ripening rather than on sucrose metabolism. *Functional Plant Biology*, *33*(3), 279-288. https://doi.org/10.1071/FP05134

Barber, H. N., & Sharpe, P. J. H. (1971). Genetics and physiology of sunscald of fruits. *Agricultural Meteorology, 8*, 175-191. https://doi.org/10.1016/0002-1571(71)90107-5

Barbero, G. F., Ruiz, A. G., Liazid, A., Palma, M., Vera, J. C., & Barroso, C. G. (2014). Evolution of total and individual capsaicinoids in peppers during ripening of the Cayenne pepper plant (Capsicum annuum L.). *Food chemistry, 153,* 200-206. https://doi.org/10.1016/j.foodchem.2013.12.068

Biernbaum, J. A. (2006). Hoophouses and High Tunnels for Local Food and Farming. *Michigan State University Department of Horticulture*, 1-21. https://www.canr.msu.edu/hrt/uploads/535/78622/HightunnelHoophouseSolarGreenhouse2013-21pgs.pdf

Borguini, R. G., & Ferraz da Silva Torres, E. A. (2009). Tomatoes and tomato products as dietary sources of antioxidants. *Food Reviews International*, *25*(4), 313-325. https://doi.org/10.1080/87559120903155859

Bosland, P. W. (1992). Chiles: a diverse crop. *HortTechnology*, *2*(1), 6-10. https://doi.org/10.21273/HORTTECH.2.1.6

Both, A. J., Reiss, E., Sudal, J. F., Holmstrom, K. E., Wyenandt, C. A., Kline, W. L., & Garrison, S. A. (2007). Evaluation of a manual energy curtain for tomato production in high tunnels. *HortTechnology*, *17*(4), 467-472. https://doi.org/10.21273/HORTTECH.17.4.467

Brown, C. (2003). Consumers' preferences for locally produced food: A study in southeast Missouri. *American Journal of Alternative Agriculture*, *18*(4), 213-224. https://doi.org/10.1079/AJAA200353

Brown, S. L., & Brown, J. E. (1992). Effect of plastic mulch color and insecticides on thrips populations and damage to tomato. *HortTechnology*, *2*(2), 208-211. https://doi.org/10.21273/HORTTECH.2.2.208

Bruce, A., Maynard, E., Farmer, J., & Carpenter, J. (2018). Indiana high tunnel handbook. In: Purdue Extension. https://www. extension. purdue. edu/extmedia/HO/HO-296. pdf.

Bruce, A. B., Farmer, J. R., Maynard, E. T., & Valliant, J. C. D. (2017). Assessing the impact of the EQIP High Tunnel Initiative. *Journal of Agriculture, Food Systems, and Community Development*, *7*(3), 159-180. https://doi.org/10.5304/jafscd.2017.073.012

Bruce, A. B., Maynard, E. T., & Farmer, J. R. (2019). Farmers' perspectives on challenges and opportunities associated with using high tunnels for specialty crops. *HortTechnology*, *29*(3), 290-299. https://doi.org/10.21273/HORTTECH04258-18

Bruce, R. R. (1980). *Irrigation of crops in the Southeastern United States: Principles and practice* (Vol. 9). Agricultural Research, Southern Region, Science and Education Administration. https://doi.org/10.1016/b978-0-12-024303-7.50007-8

Burlakoti, R. R., Zandstra, J., & Jackson, K. (2013). Comparison of epidemiology of gray mold, anthracnose fruit rot, and powdery mildew in day-neutral strawberries in field and high-tunnel conditions in Ontario. *International Journal of Fruit Science*, *13*(1-2), 19-27. https://doi.org/10.1080/15538362.2012.696956

Byrne, P. F., Volk, G. M., Gardner, C., Gore, M. A., Simon, P. W., & Smith, S. (2018). Sustaining the future of plant breeding: The critical role of the USDA-ARS National Plant Germplasm System. *Crop Science*, *58*(2), 451-468. https://doi.org/10.2135/cropsci2017.05.0303

Carey, E. E., Jett, L., Lamont, W. J., Nennich, T. T., Orzolek, M. D., & Williams, K. A. (2009). Horticultural crop production in high tunnels in the United States: A snapshot. *HortTechnology*, *19*(1), 37-43. https://doi.org/10.21273/HORTTECH.19.1.37

Conner, D. S., Montri, A. D., Montri, D. N., & Hamm, M. W. (2009). Consumer demand for local produce at extended season farmers' markets: guiding farmer marketing strategies. *Renewable Agriculture and Food Systems*, *24*(4), 251-259. https://doi.org/10.1017/S1742170509990044

Conner, D. S., Waldman, K. B., Montri, A. D., Hamm, M. W., & Biernbaum, J. A. (2010). Hoophouse contributions to economic viability: Nine Michigan case studies. *HortTechnology*, *20*(5), 877-884. https://doi.org/10.21273/HORTTECH.20.5.877

Costa, H. S., Robb, K. L., & Wilen, C. A. (2002). Field trials measuring the effects of ultraviolet-absorbing greenhouse plastic films on insect populations. *Journal of Economic Entomology*, *95*(1), 113-120. https://doi.org/10.1603/0022-0493-95.1.113

Cowan, J. S., Miles, C. A., Andrews, P. K., & Inglis, D. A. (2014). Biodegradable mulch performed comparably to polyethylene in high tunnel tomato (Solanum lycopersicum L.) production. *Journal of the Science of Food and Agriculture*, *94*(9), 1854-1864. https://doi.org/10.1002/jsfa.6504

Dalrymple, D. G. (1973). Controlled environment agriculture: A global review of greenhouse food production. https://doi.org/10.1177/003072707400800212

De Freitas, S. T., Shackel, K. A., & Mitcham, E. J. (2011). Abscisic acid triggers whole-plant and fruit-specific mechanisms to increase fruit calcium uptake and prevent blossom end rot development in tomato fruit. *Journal of Experimental Botany, 62*(8), 2645-2656. https://doi.org/10.1093/jxb/erq430

De Kreij, C. (1996). Interactive effects of air humidity, calcium and phosphate on blossom-end rot, leaf deformation, production and nutrient contents of tomato. *Journal of Plant Nutrition*, *19*(2), 361-377. https://doi.org/10.1080/01904169609365127

Deepa, N., Kaur, C., George, B., Singh, B., & Kapoor, H. C. (2007). Antioxidant constituents in some sweet pepper (Capsicum annuum L.) genotypes during maturity. *LWT-Food Science and Technology*, *40*(1), 121-129. https://doi.org/10.1016/j.lwt.2005.09.016

Demchak, K. (2009). Small fruit production in high tunnels. *HortTechnology*, *19*(1), 44-49. https://doi.org/10.21273/HORTTECH.19.1.44

Devi, J., Sagar, V., Kaswan, V., Ranjan, J. K., Kumar, R., Mishra, G. P., . . . Verma, R. K. (2021). Advances in breeding strategies of bell pepper (Capsicum annuum L. var. grossum Sendt.). *Advances in Plant Breeding Strategies: Vegetable Crops: Volume 9: Fruits and Young Shoots*, 3-58.

Dorais, M., Papadopoulos, A. P., & Gosselin, A. (2002). *Greenhouse tomato fruit quality* (Vol. 26). John Wiley and Sons: New York, NY, USA.

Drees, B. M. (1993). Aphid management. *College Station Texas: A & M University*.

Dukes, M. D. (2020). Two decades of smart irrigation controllers in US landscape irrigation. *Transactions of the ASABE*, *63*(5), 1593-1601. doi: 10.13031/trans.13930

Dumas, Y., Dadomo, M., Di Lucca, G., & Grolier, P. (2003). Effects of environmental factors and agricultural techniques on antioxidantcontent of tomatoes. *Journal of the Science of Food and Agriculture*, *83*(5), 369-382. https://doi.org/10.1002/jsfa.1370

Díaz-Pérez, J. C. (2014). Bell pepper (Capsicum annum L.) crop as affected by shade level: fruit yield, quality, and postharvest attributes, and incidence of phytophthora blight (caused by Phytophthora capsici Leon.). *HortScience*, *49*(7), 891-900. https://doi.org/10.21273/HORTSCI.49.7.891

Díaz-Pérez, J. C., & Smith, E. (2017). Training of growers and extension agents in the Dominican Republic on managing heat stress of bell pepper (Capsicum annum L.) grown in high tunnels. *HortScience*, *52*(9), 1148-1150. https://doi.org/10.21273/HORTSCI12102-17

Elkner, K., & Kaniszewski, S. (1993). Effect of drip irrigation and mulching on quality of tomato fruits. https://doi.org/10.17660/actahortic.1995.379.20

Emmert, E. M. (1955). *Low-cost plastic greenhouses*. Agricultural Experiment Station, University of Kentucky.

Erickson, A. N., & Markhart, A. H. (2001). Flower production, fruit set, and physiology of bell pepper during elevated temperature and vapor pressure deficit. *Journal of the American Society for Horticultural Science*, *126*(6), 697-702. https://doi.org/10.21273/JASHS.126.6.697

Evans, R. G., & Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water resources research*, *44*(7). https://doi.org/10.1029/2007WR006200

Feldmann, C., & Hamm, U. (2015). Consumers' perceptions and preferences for local food: A review. *Food quality and preference*, *40*, 152-164. https://doi.org/10.1016/j.foodqual.2014.09.014

Fitzgerald, C. B., & Hutton, M. (2012). Production practices and challenges with high tunnel systems in Maine. *Journal of the NACAA*, *5*(2). https://www.nacaa.com/journal/index.php?jid=170

Foust-Meyer, N., & O'Rourke, M. E. (2014). High tunnels for local food systems: Subsidies, equity, and profitability. https://doi.org/10.5304/jafscd.2015.052.015

Frey, C. J., Zhao, X., Brecht, J. K., Huff, D. M., & Black, Z. E. (2020). High tunnel and grafting effects on organic tomato plant disease severity and root-knot nematode infestation in a subtropical climate with sandy soils. *HortScience*, *55*(1), 46-54. https://doi.org/10.21273/HORTSCI14166-19

Galinato, S. P., & Miles, C. A. (2013). Economic profitability of growing lettuce and tomato in western Washington under high tunnel and open-field production systems. *HortTechnology*, *23*(4), 453-461. https://doi.org/10.21273/HORTTECH.23.4.453

Garbos, G. R. (2013). Integrated moving and anchoring system for movable agriculture structures. In: Google Patents. https://doi.org/10.36001/phmconf.2013.v5i1.2217

Gent, M. P. N. (1992). Effect of planting date, ventilation and soil temperature on growth and nutrition of tomato in high tunnels. *Plant and soil*, *145*, 81-91. https://doi.org/10.1007/BF00009544

Gerber, J. M., Mohd-Khir, I., & Splittstoesser, W. E. (1988). Row tunnel effects on growth, yield and fruit quality of bell pepper. *Scientia horticulturae*, *36*(3-4), 191-197. https://doi.org/10.1016/0304-4238(88)90053-2

Giovanelli, G., & Paradiso, A. (2002). Stability of dried and intermediate moisture tomato pulp during storage. *Journal of Agricultural and Food Chemistry*, *50*(25), 7277-7281. https://doi.org/10.1021/jf025595r

González-Zamora, A., Sierra-Campos, E., Luna-Ortega, J. G., Pérez-Morales, R., Ortiz, J. C. R., & García-Hernández, J. L. (2013). Characterization of different capsicum varieties by evaluation of their capsaicinoids content by high performance liquid chromatography, determination of pungency and effect of high temperature. *Molecules*, *18*(11), 13471-13486. https://doi.org/10.3390/molecules181113471

Gärtner, C., Stahl, W., & Sies, H. (1997). Lycopene is more bioavailable from tomato paste than from fresh tomatoes. *The American journal of clinical nutrition*, *66*(1), 116-122. https://doi.org/10.1093/ajcn/66.1.116

Hanson, E., Von Weihe, M., Schilder, A. C., Chanon, A. M., & Scheerens, J. C. (2011). High tunnel and open field production of floricane-and primocane-fruiting raspberry cultivars. *HortTechnology*, *21*(4), 412-418. https://doi.org/10.21273/HORTTECH.21.4.412

Hartz, T., Cantwell, M., Lestrange, M., Smith, R., Aguiar, J., & Daugovish, O. (2008). Bell pepper production in California.https://doi.org/10.3733/ucanr.7217

Heckler, S. (2017). *Quantifying How High Tunnels Create A Microclimate For Improved Crop Growth* (Doctoral dissertation, University of Nevada, Reno). https://www.proquest.com/docview/2013309116?pq-origsite=gscholar&fromopenview=true&sourcetype=Dissertations%20&%20Theses

Heidenreich, C., Pritts, M., Kelly, M. J., & Demchak, K. (2012). High tunnel raspberries and blackberries. *Cornell Univ. Dept. Hort. Publ*, *47*. https://doi.org/10.17660/actahortic.2010.873.29

Helyes, L., Dimény, J., Bőcs, A., Schober, G., & Pék, Z. (2008). The effect of water and potassium supplement on yield and lycopene content of processing tomato. https://doi.org/10.17660/ActaHortic.2009.823.11

Heuvelink, E. (2018). *Tomatoes* (Vol. 27). CABI.

Ho, L. C., & White, P. J. (2005). A cellular hypothesis for the induction of blossom-end rot in tomato fruit. *Annals of Botany*, *95*(4), 571-581. https://doi.org/10.1093/aob/mci065

Hobson, G., & Grierson, D. (1993). *Tomato*. Springer.

Hutton, M. G., & Handley, D. T. (2006). *Vegetable varieties for Maine gardens*. University of Maine Cooperative Extension. https://extension.umaine.edu/publications/2190e/

Hutton, M. G., & Handley, D. T. (2007). Bell pepper cultivar performance under short, variable growing seasons. *HortTechnology, 17*(1), 136-141. https://doi.org/10.21273/HORTTECH.17.1.136

Ingwell, L. L., Thompson, S. L., Kaplan, I., & Foster, R. E. (2017). High tunnels: protection for rather than from insect pests? *Pest management science*, *73*(12), 2439-2446. https://doi.org/10.1002/ps.4634

Janke, R. R., Altamimi, M. E., & Khan, M. (2017). The use of high tunnels to produce fruit and vegetable crops in North America. *Agricultural Sciences*, *8*(7), 692-715. https://www.product24swiss.net/?_=%2F10.4236%2Fas.2017.87052%23KJWqMdlUlBnvJORbXw%2Fn

Jarquín-Enríquez, L., Mercado-Silva, E. M., Maldonado, J. L., & Lopez-Baltazar, J. (2013). Lycopene content and color index of tomatoes are affected by the greenhouse cover. *Scientia Horticulturae*, *155*, 43-48. https://doi.org/10.1016/j.scienta.2013.03.004

Jensen, M. H. (1997). *Food production in greenhouses*.https://doi.org/10.1007/978-94-015-8889-8_1

Jett, L. W. (2017). High tunnels. In *A guide to the manufacture, performance, and potential of plastics in agriculture* (pp. 107-116). Elsevier.

Jiang, W., Qu, D., Mu, D., & Wang, L. (2004). Protected cultivation of horticultural crops in China. *HORTICULTURAL REVIEWS-WESTPORT THEN NEW YORK-*, *30*, 115-162. https://doi.org/10.1002/9780470650837.ch4

Kadir, S., Carey, E., & Ennahli, S. (2006). Influence of high tunnel and field conditions on strawberry growth and development. *HortScience*, *41*(2), 329-335. https://doi.org/10.21273/hortsci.41.2.329

Kaiser, C., & Ernst, M. (2012). High Tunnel Overview. *Agriculture & Natural Resources*, 1-7. Hight Tunnel Overview.pdf (uky.edu) https://edis.ifas.ufl.edu/publication/HS1466

Kashyap, P. S., & Panda, R. K. (2003). Effect of irrigation scheduling on potato crop parameters under water stressed conditions. *Agricultural water management*, *59*(1), 49-66. https://doi.org/10.1016/s0378-3774(02)00110-5

Kelley, W. T., Boyhan, G. E., Harrison, K. A., Granberry, D. M., Langston, D. B., Sparks, A. N., . . . Fonsah, E. G. (2009). *Commercial pepper production handbook*. https://doi.org/10.21273/hortsci.30.3.438d

Kennedy, J. S., Day, M. F., & Eastop, V. F. (1962). *A conspectus of aphids as vectors of plant viruses.* CABI

Kim, S., Park, M., Yeom, S.-I., Kim, Y.-M., Lee, J. M., Lee, H.-A., . . . Kim, K.-T. (2014). Genome sequence of the hot pepper provides insights into the evolution of pungency in Capsicum species. *Nature genetics*, *46*(3), 270-278. https://doi.org/10.1038/ng.2877

Knewtson, S. J. B., Carey, E. E., & Kirkham, M. B. (2010). Management practices of growers using high tunnels in the central great plains of the United States. *HortTechnology*, *20*(3), 639-645. https://doi.org/10.21273/HORTTECH.20.3.639

Knewtson, S. J. B., Janke, R., Kirkham, M. B., Williams, K. A., & Carey, E. E. (2010). Trends in soil quality under high tunnels. *HortScience*, *45*(10), 1534-1538. https://doi.org/10.21273/HORTSCI.45.10.1534

Krishna Kumar, N. K., Ullman, D. E., & Cho, J. J. (1995). Resistance among Lycopersicon species to Frankliniella occidentalis (Thysanoptera: Thripidae). *Journal of Economic Entomology*, *88*(4), 1057-1065. https://doi.org/10.1093/jee/88.4.1057

Krishna-Kumar, N. K., Ullman, D. E., & Cho, J. J. (1993). Evaluation of Lycopersicon germ plasm for tomato spotted wilt tospovirus resistance by mechanical and thrips transmission. *Plant disease*. https://doi.org/10.1094/PD-77-0938

Kubota, C., McClure, M. A., Kokalis-Burelle, N., Bausher, M. G., & Rosskopf, E. N. (2008). Vegetable grafting: History, use, and current technology status in North America. *HortScience*, *43*(6), 1664-1669. https://doi.org/10.21273/HORTSCI.43.6.1664

Kuchenbuch, R., Claassen, N., & Jungk, A. (1986). Potassium availability in relation to soil moisture: II. Calculations by means of a mathematical simulation model/Kaliumverfügbarkeit in Beziehung zur Bodenfeuchte: II. Rechnungen mit einem Simulationsmodell. *Plant and Soil*, 233-243. https://www.jstor.org/stable/42935789

Kumar, K. P. S., Paswan, S., & Srivastava, S. (2012). Tomato-a natural medicine and its health benefits. *Journal of Pharmacognosy and Phytochemistry*, *1*(1), 33-43. https://www.researchgate.net/publication/285176270

Lamont, W. J. (2009). Overview of the use of high tunnels worldwide. *HortTechnology*, *19*(1), 25-29. https://doi.org/10.21273/HORTTECH.19.1.25

Lamont, W. J., McGann, M. R., Orzolek, M. D., Mbugua, N., Dye, B., & Reese, D. (2002). Design and construction of the Penn State high tunnel. *HortTechnology*, *12*(3), 447-453. https://journals.ashs.org/horttech/view/journals/horttech/12/3/article-p447.xml

Langenhoven, P. (2023, May 1). *Colored sweet bell and tapered pepper cultivar evaluation for high tunnel production in west-central Indiana, 2022*. Purdue Student Farm. https://www.purdue.edu/hla/sites/studentfarm/colored-sweet-bell-and-tapered-pepper-cultivar-evaluation-for-high-tunnel-production-in-west-central-indiana-2022/

Lu, Q.-Y., Hung, J.-C., Heber, D., Go, V. L. W., Reuter, V. E., Cordon-Cardo, C., . . . Zhang, Z.-F. (2001). Inverse associations between plasma lycopene and other carotenoids and prostate cancer. *Cancer Epidemiology Biomarkers & Prevention*, *10*(7), 749-756. https://aacrjournals.org/cebp/article/10/7/749/164348

Maboko, M. M. (2006). Pruning and trellising of tomato. *Undercover farming*, *3*, 24-25. https://issuu.com/undercoverfarmingmagazine/docs/ucfjuly.aug20/s/10976617

Madakadze, R. M., & Kwaramba, J. (2004). Effect of preharvest factors on the quality of vegetables produced in the tropics. *Production Practices and Quality Assessment of Food Crops Volume 1*, 1-36. https://www.researchgate.net/publication/226297514

Madramootoo, C. A., & Rigby, M. (1991). Effects of trickle irrigation on the growth and sunscald of bell peppers (Capsicum annuum L.) in southern Quebec. *Agricultural water management*, *19*(2), 181-189. https://doi.org/10.1016/0378-3774(91)90007-6

Malundo, T. M. M., Shewfelt, R. L., & Scott, J. W. (1995). Flavor quality of fresh tomato (Lycopersicon esculentum Mill.) as affected by sugar and acid levels. *Postharvest Biology and Technology*, *6*(1-2), 103-110. https://doi.org/10.1016/0925-5214(94)00052-T

Marcelis, L. F. M., & Ho, L. C. (1999). Blossom-end rot in relation to growth rate and calcium content in fruits of sweet pepper (Capsicum annuum L.). *Journal of experimental botany*, *50*(332), 357-363. https://doi.org/10.1093/jxb/50.332.357

Martin, J. T. (2013). The Influence of organically managed high tunnel and open field production systems on strawberry (Fragaria x ananassa) quality and yield, tomato (Solanum lycopersicum) Yield, and evaluation of plastic mulch alternatives. Master's Thesis, University of Tennessee, 2013.

Martinez, S. (2010). *Local food systems; concepts, impacts, and issues*. Diane Publishing.

Maul, F., Sargent, S. A., Sims, C. A., Baldwin, E. A., Balaban, M. O., & Huber, D. J. (2000). Tomato flavor and aroma quality as affected by storage temperature. *Journal of Food Science*, *65*(7), 1228-1237. https://doi.org/10.1111/j.1365-2621.2000.tb10270.x

Maynard, E., Calsoya, I. S., & Malecki, J. (2017). *Potassium applications and yellow shoulder disorder of tomatoes in high tunnels.* Purdue University.

Mills, D. J., Coffman, C. B., Teasdale, J. R., Everts, K. L., & Anderson, J. D. (2002). Factors associated with foliar disease of staked fresh market tomatoes grown under differing bed strategies. *Plant Disease*, *86*(4), 356-361. https://doi.org/10.1094/PDIS.2002.86.4.356

Mngoma, M. F., Magwaza, L. S., Sithole, N. J., Magwaza, S. T., Mditshwa, A., Tesfay, S. Z., & Ncama, K. (2022). Effects of stem training on the physiology, growth, and yield responses of indeterminate tomato (Solanum lycopersicum) plants grown in protected cultivation. *Heliyon*, *8*(5). https://doi.org/10.1016/j.heliyon.2022.e09343

Momol, M. T., Olson, S. M., Funderburk, J. E., Stavisky, J., & Marois, J. J. (2004). Integrated management of tomato spotted wilt on field-grown tomatoes. *Plant Disease*, *88*(8), 882-890. https://doi.org/10.1094/PDIS.2004.88.8.882

Nie, C., & Zepeda, L. (2011). Lifestyle segmentation of US food shoppers to examine organic and local food consumption. *Appetite*, *57*(1), 28-37. https://doi.org/10.1016/j.appet.2011.03.012

Nischwitz, C., Noorlander, M., & Hubbell, M. A. (2019). Tomato spotted wilt virus of tomato & pepper. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3064&context=extension_curall

Olson, S. M. (2004). Physiological, Nutritional, and Other Disorders of Tomato Fruit: HS-954/HS200, 2/2004. *EDIS*, *2004*(3).

Orzolek, M. D., Lamont, W. J., & White, L. (2002). Promising horticultural crops for production in high tunnels in the mid-Atlantic area of the United States. *Journal of International Society for Horticulural Science.* https://doi.org/10.17660/ActaHortic.2004.633.56

Osborne, R. S., Leppla, N. C., & Osborne, L. S. (2002). Predatory gall midge (unofficial common name), Feltiella acarisuga (Vallot)(Insecta: Diptera: Cecidomyiidae). *Univ Florida IFAS Ext EENY*, *269*, 1-4. https://edis.ifas.ufl.edu/publication/IN549

O'Connell, S., Rivard, C., Peet, M. M., Harlow, C., & Louws, F. (2012). High tunnel and field production of organic heirloom tomatoes: Yield, fruit quality, disease, and microclimate. *HortScience*, *47*(9), 1283-1290. https://doi.org/10.21273/HORTSCI.47.9.1283

Paiva, E. A. S., Martinez, H. E. P., Casali, V. W. D., & Padilha, L. (1998). Occurrence of blossom-end rot in tomato as a function of calcium dose in the nutrient solution and air relative humidity. *Journal of Plant Nutrition*, *21*(12), 2663-2670. https://doi.org/10.1080/01904169809365596

Pathak, T. B., & Stoddard, C. S. (2018). Climate change effects on the processing tomato growing season in California using growing degree day model. *Modeling Earth Systems and Environment*, *4*, 765-775. https://doi.org/10.1007/s40808-018-0460-y

Peet, M. M. (1992). Fruit cracking in tomato. *HortScience*, 30(1), 65–68. https://journals.ashs.org/hortsci/view/journals/hortsci/30/1/article-p65.xml

Peixoto, J. V. M., Garcia, L. G. C., Nascimento, A. d. R., Moraes, E. R. d., Ferreira, T. A. P. d. C., Fernandes, M. R., & Pereira, V. d. A. (2018). Post-harvest evaluation of tomato genotypes with dual purpose. *Food Science and Technology*, *38*, 255-262. https://doi.org/10.1590/1678-457X.00217

Peralta, I. E., & Spooner, D. M. (2006). History, origin and early cultivation of tomato (Solanaceae). *Genetic improvement of solanaceous crops*, *2*, 1-27.

Phene, C. J., & Howell, T. A. (1984). Soil sensor control of high-frequency irrigation systems. *Transactions of the ASAE*, *27*(2), 392-0396.

Powell, M., Gundersen, B., Cowan, J., Miles, C. A., & Inglis, D. A. (2014). The effect of open-ended high tunnels in western Washington on late blight and physiological leaf roll among five tomato cultivars. *Plant Disease*, *98*(12), 1639-1647. https://doi.org/10.1094/PDIS-12-13-1261-RE

Pérez-Conesa, D., García-Alonso, J., García-Valverde, V., Iniesta, M.-D., Jacob, K., Sánchez-Siles, L. M., . . . Periago, M. J. (2009). Changes in bioactive compounds and antioxidant activity during homogenization and thermal processing of tomato puree. *Innovative Food Science & Emerging Technologies*, *10*(2), 179-188. https://doi.org/10.1016/j.ifset.2008.12.001

Racsko, J., & Schrader, L. E. (2012). Sunburn of apple fruit: Historical background, recent advances and future perspectives. *Critical reviews in plant sciences, 31*(6), 455-504. https://doi.org/10.1080/07352689.2012.696453

Rai, V. P., Kumar, R., Kumar, S., Rai, A., Kumar, S., Singh, M., . . . Paliwal, R. (2013). Genetic diversity in Capsicum germplasm based on microsatellite and random amplified microsatellite polymorphism markers. *Physiology and Molecular Biology of Plants*, *19*, 575-586. https://pubmed.ncbi.nlm.nih.gov/24431527/

Reeve, J., & Drost, D. (2012). Yields and soil quality under transitional organic high tunnel tomatoes. *HortScience, 47*(1), 38-44. https://doi.org/10.21273/HORTSCI.47.1.38

Rho, H., Colaizzi, P., Gray, J., Paetzold, L., Xue, Q., Patil, B., & Rush, C. (2020). Yields, fruit quality, and water use in a jalapeno pepper and tomatoes under open field and high-tunnel production systems in the Texas high plains. *HortScience, 55*(10), 1632-1641. https://doi.org/10.21273/HORTSCI15143-20

Riley, D. G., & Pappu, H. R. (2000). Evaluation of tactics for management of thrips-vectored tomato spotted wilt virus in tomato. *Plant disease*, *84*(8), 847-852. https://doi.org/10.1094/PDIS.2000.84.8.847

Rogers, M. A., & Wszelaki, A. L. (2012). Influence of high tunnel production and planting date on yield, growth, and early blight development on organically grown heirloom and hybrid tomato. *HortTechnology*, *22*(4), 452-462. https://doi.org/10.21273/HORTTECH.22.4.452

Rosales, M. A., Ruiz, J. M., Hernández, J., Soriano, T., Castilla, N., & Romero, L. (2006). Antioxidant content and ascorbate metabolism in cherry tomato exocarp in relation to temperature and solar radiation. *Journal of the Science of Food and Agriculture*, *86*(10), 1545-1551. https://doi.org/10.1002/jsfa.2546

Rylski, I., & Spigelman, M. (1986). Effect of shading on plant development, yield and fruit quality of sweet pepper grown under conditions of high temperature and radlation. *Scientia Horticulturae, 29*(1-2), 31-35. https://doi.org/10.1016/0304-4238(86)90028-2

Sacks, E. J., & Francis, D. M. (2001). Genetic and environmental variation for tomato flesh color in a population of modern breeding lines. *Journal of the American Society for*

Horticultural Science, *126*(2), 221-226. https://journals.ashs.org/jashs/view/journals/jashs/126/2/article-p221.xml

Saha, S. R., Hossain, M. M., Rahman, M. M., Kuo, C. G., & Abdullah, S. (2010). Effect of high temperature stress on the performance of twelve sweet pepper genotypes. *Bangladesh Journal of Agricultural Research*, *35*(3), 525-534. https://www.banglajol.info/index.php/BJAR/article/view/6459

Santos, B. M. (2012). Pepper fertilization and irrigation management. In *Peppers: botany, production and uses* (pp. 125-136). CAB International Wallingford UK.

Saure, M. C. (2001). Blossom-end rot of tomato (Lycopersicon esculentum Mill.)—a calcium-or a stress-related disorder? *Scientia horticulturae*, *90*(3-4), 193-208. https://doi.org/10.1016/S0304-4238(01)00227-8

Savić, S., Belić, L., Marjanović, M., Radović, I., Girek, Z., Zečević, V., & Jovanović, Z. (2024). Determination of bioactive components in different tomato lines: Physicochemical properties and antioxidant activity. *International Food Research Journal*, *31*, 87-97. http://dx.doi.org/10.47836/ifrj.31.1.08

Schaible, G., & Aillery, M. (2012). Water conservation in irrigated agriculture: Trends and challenges in the face of emerging demands. *USDA-ERS Economic Information Bulletin*(99).

Sethi, V. P. (2009). On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. *Solar Energy*, *83*(1), 21-38. https://doi.org/10.1016/j.solener.2008.05.018

Sezen, S. M., Yazar, A., & Eker, S. (2006). Effect of drip irrigation regimes on yield and quality of field grown bell pepper. *Agricultural Water Management*, *81*(1-2), 115-131. https://doi.org/10.1016/j.agwat.2005.04.002

Shah, B. P., Vaddevolu, U. B. P., Jia, X., Hatterman-Valenti, H., & Scherer, T. F. (2023). Yield Responses of Watermelon, Muskmelon, and Squash to Different Irrigation Treatments in a Mulched Sandy Soil. *ASABE.*

Shaheen, M. R., Ayyub, C. M., Amjad, M., & Waraich, E. A. (2016). Morpho-physiological evaluation of tomato genotypes under high temperature stress conditions. *Journal of the Science of Food and Agriculture*, *96*(8), 2698-2704. https://doi.org/10.1002/jsfa.7388

Shaykewich, C. F., Yamaguchi, M., & Campbell, J. D. (1971). Nutrition and blossom-end rot of tomatoes as influenced by soil water regime. *Canadian Journal of Plant Science*, *51*(6), 505-511. https://doi.org/10.4141/cjps71-098

Sideman, R. G. (2020). Colored Bell Pepper Yields from Cultivars Grown in High Tunnels in Northern New England. *HortTechnology*, *30*(3), 456-462. https://doi.org/10.21273/HORTTECH04577-20

Škaloudová, B., Křivan, V., & Zemek, R. (2006). Computer-assisted estimation of leaf damage caused by spider mites. Computers and electronics in agriculture, 53(2), 81-91. https://doi.org/10.1016/j.compag.2006.04.002

Soler, S., Debreczeni, D. E., Vidal, E., Aramburu, J., López, C., Galipienso, L., & Rubio, L. (2015). A new Capsicum baccatum accession shows tolerance to wild-type and resistance-breaking isolates of Tomato spotted wilt virus. *Annals of Applied biology*, *167*(3), 343-353. https://doi.org/10.1111/aab.12229

Suzuki, K., Sasaki, H., & Nagata, M. (2013). Causes and control of blotchy ripening disorder in tomato fruit. *Bulletin of the National Institute of Vegetable and Tea Science*, 81-88. http://vegetea.naro.affrc.go.jp/print/bulletin/bullindex_en.html

Sánchez, E. S., Butzler, T. M., Bogash, S. M., Elkner, T. E., Oesterling, R. E., Orzolek, M. D., & Stivers, L. J. (2011). Pennsylvania statewide bell pepper cultivar evaluation. *HortTechnology*, *21*(3), 384-390. https://doi.org/10.21273/HORTTECH.21.3.384

Tang, S. (2021). Tracing Tomato Timelines: The Domestication of Solanum lycopersicum. *Prized Writing*. https://prizedwriting.ucdavis.edu

Taylor, M. D., & Locascio, S. J. (2004). Blossom-end rot: a calcium deficiency. *Journal of Plant nutrition*, *27*(1), 123-139. https://doi.org/10.1081/PLN-120027551

Tigist, M., Workneh, T. S., & Woldetsadik, K. (2013). Effects of variety on the quality of tomato stored under ambient conditions. *Journal of food science and technology*, *50*, 477-486. https://pubmed.ncbi.nlm.nih.gov/24425942/

Tollerud, H., Brown, J., Loveland, T., Mahmood, R., & Bliss, N. (2018). Drought and land-cover conditions in the great plains. *Earth Interactions*, *22*(17), 1-25. https://doi.org/10.1175/EI-D-17-0025.1

Tomczyk, A. (1985). Effects on the host plant. *Spider mites: their biology, natural enemies, and control*, *1*, 317-329. https://cir.nii.ac.jp/crid/1130282271534626304

Toor, R. K., Lister, C. E., & Savage, G. P. (2005). Antioxidant activities of New Zealand-grown tomatoes. *International Journal of Food Sciences and Nutrition*, *56*(8), 597-605. https://doi.org/10.1080/09637480500490400

Topcu, Y., Nambeesan, S. U., & van der Knaap, E. (2022). Blossom-end rot: a century-old problem in tomato (Solanum lycopersicum L.) and other vegetables. *Molecular Horticulture*, *2*(1), 1. https://molhort.biomedcentral.com/articles/10.1186/s43897-021-00022-9

Torres-Quezada, E. A., Zotarelli, L., Treadwell, D. D., & Santos, B. M. (2021). Growth habit and in-row distance for bell pepper under protected culture. *International Journal of Vegetable Science*, *27*(6), 561-573. https://doi.org/10.1080/19315260.2021.1888840

Ullman, D. E., Sherwood, J. L., & German, T. L. (1997). Thrips as vectors of plant pathogens. CABI.

Ünlü, M., Kanber, R., Şenyigit, U., Onaran, H., & Diker, K. (2006). Trickle and sprinkler irrigation of potato (Solanum tuberosum L.) in the Middle Anatolian Region in Turkey. Agricultural water management, 79(1), 43-71. https://doi.org/10.1016/j.agwat.2005.02.004

Volesky, N., & Schrumm, Z. R. (2021). High Tunnel Pest Management-Aphids. https://digitalcommons.usu.edu/extension_curall/2177/

Warren, N. D., Sideman, R. G., & Smith, R. G. (2015). Performance of high tunnel tomato cultivars in northern New England. *HortTechnology*, *25*(1), 139-146. https://doi.org/10.21273/HORTTECH.25.1.139

Waterer, D., & Bantle, J. (2018). High tunnel temperature observations. https://www.nacaa.com/journal/index.php?jid=170

Watts, D. C. H., Ilbery, B., & Maye, D. (2017). Making reconnections in agro-food geography: alternative systems of food provision. *The Rural*, 165-184.

Weeden, C. R. (2002). *Biological control: a guide to natural enemies in North America*. Cornell University.

Welbaum, G. E. (2015). *Vegetable production and practices*. CABI.

Wells, O. S. (1998). *Rowcovers and high tunnels-growth-enhancing technology*. CABI

Wells, O. S. (1991). Guidelines for using high tunnels for tomato production. *Univ. of New Hampshire Coop. Ext. Publ*, *3*, 92-95.

Wells, O. S. (1996). Rowcover and high tunnel growing systems in the United States. *HortTechnology*, *6*(3), 172-176. https://journals.ashs.org/horttech/view/journals/horttech/6/3/article-p172.xml

Wells, O. S., & Loy, J. B. (1993). Rowcovers and high tunnels enhance crop production in the northeastern United States. *HortTechnology*, *3*(1), 92-95. https://journals.ashs.org/horttech/view/journals/horttech/3/1/article-p92.xml

White, L., Burkhart, E., Lamont, W. J., & Orzolek, M. D. (2003). High Tunnel Production Manual. *The Pennsylvania State University College of Agriculture Department of Horticulture Center for Plasticulture*.

Wien, H. C. (1990). Screening pepper cultivars for resistance to flower abscission: a comparison of techniques. *HortScience*, *25*(12), 1634-1636. https://link.springer.com/chapter/10.1007/978-94-011-2458-4_52

Wien, H. C. (2009). Microenvironmental variations within the high tunnel. *HortScience*, *44*(2), 235-238. https://doi.org/10.21273/HORTSCI.44.2.235

Williams, T. V., & Roberts, W. (2002). Is vegetable variety evaluation and reporting becoming a lost art? An industry perspective. *HortTechnology*, *12*(4), 553-559. https://journals.ashs.org/horttech/view/journals/horttech/12/4/article-p553.xml

Wittwer, S. H., & Castilla, N. (1995). Protected cultivation of horticultural crops worldwide. *HortTechnology*, *5*(1), 6-24. https://journals.ashs.org/horttech/view/journals/horttech/5/1/article-p6.xml

Xiao, C. L., Chandler, C. K., Price, J. F., Duval, J. R., Mertely, J. C., & Legard, D. E. (2001). Comparison of epidemics of Botrytis fruit rot and powdery mildew of strawberry in large plastic tunnel and field production systems. *Plant Disease*, *85*(8), 901-909. https://doi.org/10.1094/PDIS.2001.85.8.901

Yao, S., & Rosen, C. J. (2011). Primocane-fruiting raspberry production in high tunnels in a cold region of the upper Midwestern United States. *HortTechnology*, *21*(4), 429-434. https://doi.org/10.21273/HORTTECH.21.4.429

Yuan, B.Z., Sun, J., Kang, Y., & Nishiyama, S. (2006). Response of cucumber to drip irrigation water under a rainshelter. *Agricultural water management*, *81*(1-2), 145-158. https://doi.org/10.1016/j.agwat.2005.03.002

Yudin, L. S., Cho, J. J., & Mitchell, W. C. (1986). Host range of western flower thrips, Frankliniella occidentalis (Thysanoptera: Thripidae), with special reference to Leucaena glauca. *Environmental Entomology*, *15*(6), 1292-1295. https://doi.org/10.1093/ee/15.6.1292

Zahid, B., Ansari, R., Cheema, M. J. M., & Anjum, L. (2020). Evaluation of deficit irrigation regime, row spacing and dual plantation of drip irrigated tomato under high tunnel. *Journal of Central European Agriculture*, *21*(4), 851-860. https://doi.org/10.5513/JCEA01/21.4.2990

Zhao, X., & Carey, E. E. (2009). Summer production of lettuce, and microclimate in high tunnel and open field plots in Kansas. *HortTechnology*, *19*(1), 113-119. https://doi.org/10.21273/HORTTECH.19.1.113

Zheng, M. Z., Leib, B., Butler, D. M., Wright, W., Ayers, P., Hayes, D., . . . Vanchiasong, P. (2019). Assessing heat management practices in high tunnels to improve organic production of bell peppers. *Scientia horticulturae*, *246*, 928-941. https://doi.org/10.1016/j.scienta.2018.10.046

Zumkehr, A., & Campbell, J. E. (2015). The potential for local croplands to meet US food demand. *Frontiers in Ecology and the Environment*, *13*(5), 244-248. https://doi.org/10.1890/140246

APPENDIX TABLES

Table. A.1. Analysis of variance for response variable marketable yield, average fruit weight and marketable number of fruits in the high tunnel 2022.

			P Value	
Effects	Df	Average fruit weight	Marketable yield	Marketable no. fruits
Irrigation (I)	2	0.5526 ns	0.2972 ns	0.2504 ns
Cultivar (C)	7	<.0001 ***	0.0078 **	<.0001 ***
I × C	14	0.7560 ns	0.6232 ns	0.4246 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.2. Analysis of variance for response variable unmarketable yield, total yield and percentage of cracks in the high tunnel 2022.

			P value	
Effects	Df	Total yield	Unmarketable yield	% Cracks
Irrigation (I)	2	0.3668 ns	0.9648 ns	0.2035 ns
Cultivar (C)	7	0.0356 *	0.0016 **	<.0001 ***
I × C	14	0.8454 ns	0.9544 ns	0.1002 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.3. Analysis of variance for response variable marketable yield, marketable fruit number and average fruit size in the high tunnel 2023.

		P value		
Effects	Df	Marketable yield	Marketable fruit number	Avg. fruit size
Irrigation (I)	2	0.0033 **	0.1301 ns	0.1230 ns
Cultivar (C)	7	0.0004 **	0.0001 **	<.0001 ***
I × C	14	0.4556 ns	0.4303 ns	0.7421 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.4. Analysis of variance for response variable total yield, unmarketable yield cracks and yellow shoulder in the high tunnel 2023.

	P value				
Effects	Df	Total yield	Unmarketable yield	% Cracks	% Yellow Shoulder
Irrigation (I)	2	0.0118 *	0.8369 ns	0.2156 ns	0.6011 ns
Cultivar (C)	7	0.0006***	<.0001 ***	<.0001 ***	<.0001 ***
I × C	14	0.8791 ns	0.9261 ns	0.2294 ns	0.5902 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table A.5. Analysis of variance for response variable total weight of blossom end rot in the high tunnel trial conducted in 2023 in Absaraka.

	P Value	
Effects	Df	Blossom end rot
Irrigation	2	0.7526 ns
Cultivar	7	0.0025 *
I × C	14	0.2226 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.6. Analysis of variance for response SSC(°Brix), pH and Titratable Acidity (TA) in the high tunnel 2023.

			P value	
Effects	Df	SSC (°Brix)	pH	Titratable Acidity (TA)
Irrigation (I)	2	0.9491 ns	0.2922 ns	0.3584 ns
Cultivar (C)	7	<.0001 ***	0.1212 ns	0.0469 *
I × C	14	0.3599 ns	0.7909 ns	0.8104 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.7. Analysis of variance for response variable marketable yield, marketable fruit number and average fruit size in the open field 2023.

		P value		
Effects	Df	Marketable yield	Marketable fruit number	Avg. fruit size
Irrigation (I)	2	0.5538 ns	0.8075 ns	0.0328 *
Cultivar (C)	7	0.0423 *	0.0015 **	<.0001 ***
I × C	14	0.3300 ns	0.5120 ns	0.5393 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.8. Analysis of variance for response variable total yield, unmarketable yield, percentage cracks and yellow disorder in the open field 2023.

			P value		
Effects	Df	Total yield	Unmarketable yield	% Cracks	% Yellow Shoulder
Irrigation (I)	2	0.1475 ns	0.1362 ns	0.6216 ns	0.1650 ns
Cultivar(C)	7	0.0200 *	<.0001 ***	<.0001 ***	<.0001 ***
I × C	14	0.0478 *	0.0036 *	0.1043 ns	0.1819 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table. A.9.Analysis of variance for response SSC (°Brix), pH and Titratable Acidity (TA) in the open field 2023.

		P value		
Effects	Df	SSC (°Brix)	pH	Titratable Acidity (TA)
Irrigation (I)	2	0.1358 ns	0.3791 ns	0.0777 ns
Cultivar (C)	7	0.2320 ns	0.0365 *	0.6059 ns
I × C	14	0.4413 ns	0.6511 ns	0.8138 ns

* Significant at $P < 0.05$, ** significant at $P < 0.001$ and ns not significant at $P < 0.05$.

Table A.10. Analysis of variance for response variable total yield, marketable yield and marketable number of fruits in the high tunnel pepper trial conducted in 2022 and 2023.

		P value		
Effects	Df	Total yield	Marketable yield	Marketable no. fruits
Irrigation (I)	2	0.1131 ns	0.0270*	0.0958 ns
Cultivar (C)	7	0.0525 ns	0.0411*	0.1722 ns
I × C	14	0.0386 *	0.0239*	0.0218 *

* Significant at $P < 0.05$, ** significant at $P < 0.001$ and ns not significant at $P < 0.05$.

Table A.11. Analysis of variance for response variable diameter and length in the high tunnel pepper trial conducted in 2022 and 2023.

		P Value	
	Df	Diameter	Length
Irrigation (I)	2	0.0591 ns	0.5435 ns
Cultivar (C)	7	<.0001 ***	0.0390*
I × C	14	0.0949 ns	0.2933 ns

* Significant at P < 0.05, ** significant at P < 0.001 and ns not significant at P < 0.05.

Table A.12. Analysis of variance for response variable marketable yield, unmarketable number of fruits and unmarketable weight in the open field pepper trial conducted in 2022 and 2023.

		P value			
	Df	Total yield	Marketable yield	Unmarketable no. fruits	Unmarketable weight
Irrigation (I)	2	0.9851 ns	0.9664 ns	0.5132 ns	0.4764 ns
Cultivar (C)	7	0.6871 ns	0.6763 ns	0.0217 *	0.0029 *
I × C	14	0.8218 ns	0.8294 ns	0.3587 ns	0.6615 ns

Table A.13. Analysis of variance for response variable diameter and length in the open field pepper trial conducted in 2022 and 2023 in Absaraka.

		P Value	
Effects	Df	Diameter	Length
		-----------------cm------------------	
Irrigation (I)	2	0.7381ns	0.5750 ns
Cultivar (C)	7	<0.0027*	0.5710 ns
I × C	14	0.1353 ns	0.2959 ns

* Significant at $P < 0.05$, ** significant at $P < 0.001$ and ns not significant at $P < 0.05$.