Effect of Fertilizer Rate and Panel Orientation on Growth and Fruit Yield of Sweet 'n' Neat Cherry Tomato in Greenhouse Vertical Production

by

Zhuo Yang

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Approved by

Donald J. Eakes, Chair, Jimmy and Chris Pursell Endowed Professor of Horticulture
J. Raymond Kessler, Jr., Professor of Horticulture
Carolyn Robinson, Associate Professor of Horticulture
Floyd Woods, Associate Professor of Horticulture

Abstract

This study evaluated container production of Sweet 'n' Neat cherry tomato (*Solanum lycopersium* L.) using a novel, inexpensive A-frame vertical structure compared to a traditional horizontal bench production system in a greenhouse setting. The objective of this research was to compare how three plant orientations (south facing A-frame panel, north facing A-frame panel and horizontal bench) and three controlled release fertilizer (CRF) rates [2.8, 4.1, and 5.4 kg/m^3 (4.7, 7.0, and 9.3 lb/yd^3)] affect cherry tomato fruit yield. There were two experiments conducted. The experimental design for each was a randomized complete block design. All plants received pre-plant incorporated CRF and drip irrigation. Data collection included growth indices, total fruit yield, marketable fruit yield, days to first flower and fruit, foliage nitrogen (N) content, shoot dry weight, and substrate solution EC and pH. The two vertical panels produced more marketable fruit when compared to the horizontal bench regardless of CRF rate, while each vertical panel only occupied half the greenhouse growing space compared to the horizontal bench. The peak harvest time for cherry tomato on the A-frame structure was 90 to 100 days after transplanting (DAT) compared to 90 DAT on the horizontal. The south panel produced more total fruit while the north panel had greater foliar N content and shoot dry weight. Fewer days to first fruit occurred on the south facing panel than the north panel. CRF rate had little affect of marketable fruit yield but did affect fruit ripening. The only interaction between CRF rate and plant orientation was in experiment 1 for cherry tomato at the four different maturity stages. Earliest red fruit was harvested on the south panel receiving low CRF rate. Both production orientation and CRF rate had little impact on container substrate EC or pH.

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List of Abbreviations

CRF Controlled release fertilizer

DAT Days after transplanting

DFL Days to first flower

DFR Days to first fruit

EC Electrical conductivity

FMS Fruit maturity stage

CHAPTER 1

Literature Review

World Hunger and Malnutrition

Hunger is defined by the World Food Program as "not having enough to eat to meet energy requirements" (World Food Program, 2016). Malnutrition is lacking adequate nutrients in a person's diet to grow and maintain body function and can occur with under-nutrition or over-nutrition. Hunger can lead to malnutrition, and people could be under-nourished when they are not hungry.

As leading health risks in the world, both hunger and malnutrition contribute to higher mortality rates each year than Acquired Immune Deficiency Syndrome (AIDS), malaria, and tuberculosis combined (World Food Program, 2009). The Food and Agriculture Organization of the United Nations (2015) estimates that 793 million of the 7.3 billion people in the world suffer from chronic hunger. Due to decreasing economies and imperfect politics, the majority of people (780 million) suffering from chronic hunger are from developing countries (World Hunger Organization, 2016). As one major type of malnutrition, obesity causes the death of 3.4 million people annually, and the cost of malnutrition is estimated at 3.5 trillion U.S. dollars per year (Food and Agriculture Organization of the United Nations, 2015).

Increasing Food Demand with Decreasing Arable Land and Climate Change

The Food and Agriculture Organization of the United Nations (2009a) estimates that the world's population will grow to approximately 9 billion by 2050. The competitive challenge of divergent food production and agriculture bioenergy needs creates an attractive research paradigm requiring resourceful and efficient technologies to meet consumer demand for fresh, safe agricultural commodities. With this acknowledgement, the increased urbanization and opposing agricultural resources pertaining to arable land are incumbent on food scientists, agriculturalists, and economists to innovatively provide new technologies to meet global food demand.

Arable land is a non-renewable resource because land modifications are always expensive, energy intensive, or politically untenable (Campbell, 2011). Unfortunately, existing arable land is declining due to a number of human and climatic related issues. It is estimated that there are 2.7 billion hectares of potential crop production land, which is nearly twice the land currently in crop production worldwide. However, arable land is unevenly distributed among regions and countries. Two-thirds of this estimated potential arable land is located in developing countries, where food demand is rapidly increasing due to increasing populations. Among developing countries, 90% of potential arable land is in Latin America and Sub-Saharan Africa, but there is virtually no potential arable land in South Asia, the Near East, or North Africa (Campbell, 2011).

Crop production practices need to adapt to climate change and strive to protect habitats for biodiversity with increasing urbanization. All the while, crop production has to compete for land and available water resources. What's more, there will be fewer people living in rural areas and participating in food crop production. Therefore, more efficient and stable crop production methods are needed to grow more food from less land and with less labor (Food and Agiculture Organization of the United Nations, 2009b).

Limited Food Access

A "food desert" is defined as an area with limited access to fresh, healthy food, often due to poverty and food insecurity (Schafft et al., 2009). Though the majority of food consumed comes from locally grown produce, Furey el al. (2001) found that high product prices and transportation costs are two factors limiting consumer's access to fresh, high quality, and nutritional food in Northern Ireland. Global arable land for agricultural food production is also unevenly distributed worldwide (Food and Agiculture Organization of the United Nations, 2014). Thus, many developing countries will need to import high priced food in the future when local food production is inadequate to feed residents.

Dietary patterns are variable among individuals and within cultures. Even with sufficient dietary energy intake, people could still face malnutrition or "hidden hunger" due to limited dietary diversity or poor food quality (Food and Agiculture Organization of the United Nations, 2012). Janssen el al. (2005) found large variations among countries in food consumption. In Estonia, 20.1% of the population surveyed consumed one or more fruit per day, while 51.5% of the population surveyed in Israel consumed a similar amount of fruit daily. In the same study, 11.1% of the participants surveyed in Spain ate one or more vegetables per day, while 52.5% of Belgians consumed a similar amount of vegetables daily. Currently, a typical dietary pattern for U.S. urban life is a narrow base of staple grains (wheat and rice), increased consumption of meat, dairy, edible oils, salt and sugar, and a lower intake of fiber – much of the food is in the form of highly processed foodstuffs (Food and Agiculture Organization of the United Nations, 2012).

History of Vertical Gardening

Ancient gardens were designed to demonstrate political power and wealth, as well as for religious ceremony (Rakow and Lee, 2011). The earliest of these recorded gardens date back to about 2065 BC (Robinson and Zajicek, 2005). As one garden type with a long history, vertical gardening was for aesthetic, economic, educational, and medicinal purposes as well as food production in the past. The earliest known vertical garden was created approximately 2100 years ago in the Mediterranean region of Europe and Asia, including vines covering structures in courtyards of palaces (Köhler, 2008). The Hanging Gardens of Babylon in Nineveh were created in 700 BC. It is still recognized as one of humanity's greatest accomplishments because of its sophisticated engineering, and the extensive labor requirements with regard to design and maintenance of the garden (Rakow and Lee, 2011). The construction standards for these gardens would be difficult to achieve with the modern technologies of today.

Five hundred years ago, an early form of what is now called a green façade, consisting of woody vines, along with fruit espaliers and climbing roses, on walls was popular for castles and villages in Central Europe (Köhler, 2008). In more recent times (early 1920s), Europe and America encouraged the use of green façades to enhance the visual appeal of urban settings along with benefiting the environment. These green façades included pergolas and trellis structures with climbing type plants. Structurally, green façades support shoot growth of climbing plants, while plant roots remain in the ground (Growing Green Guide, 2016). Since the 1980s, Central Europe has exhibited a growing interest in vertical greenery systems for improving urban environmental issues, such as mitigating dust particles, providing evaporative cooling, insulating structures, and creating an improved habitat for urban dwellers (Köhler, 2008). During this time, living wall systems, a type of vertical greenery system, became popular. In this system, plants are grown vertically on a structure along an indoor or outdoor wall surface. These vertical systems contain layers of vegetation, including root systems, with the wall surface protected by a waterproof membrane. Plants are planted in fabric pockets or pots containing soilless substrate placed in a vertical structure (Dunnett and Kingsbury, 2004).

Currently, there are many countries that have great interest in vertical greenery systems, and Japan is a global leader in developing vertical greenery systems (Wong et al., 2010). One of the newest vertical systems is vertical farming, where a stacked greenhouse production facility is built on top of an existing building, or is built at ground level or stand-alone. Many of these vertical farms are supported by non-profit organizations hoping to support the local environment and create local jobs. The others are for-profit businesses aiming to meet the demand for local produce (Fletcher, 2012). One such farm is Local Garden located in Vancouver, Canada (Denis and Greer, 2015). The 557 m^2 farm is set on the roof of a parking garage with production and packaging facilities, and produces leafy green vegetables hydroponically. The eco-friendly produce from the garden is pesticide-free and delivered by bicycle. Currently, Local Garden is facing some financial difficulties after 4 years of operation due to unprofitability as well as the safety risk of excess roof weight from heavy snowfall.

Modern vertical gardening systems have a number of agricultural advancements that may provide fresh, local, and safe food produced in urban areas, which in turn could shorten transportation distance and reduce costs. Many of the systems utilize fewer chemicals and produce less waste water. Additionally, vertical gardening systems produce vegetables that a restaurant could use to promote a heathier diet for consumers (Semilla, 2017). Vertical gardening is no longer a thing of the past, but an integral part of the future.

Benefits of Vertical Gardening

As a resourceful, versatile, and sustainable design, vertical garden systems have many benefits for the environment, human health, and the economy (Design for London, 2008; Dunnett and Kingsbury, 2004; Lewis, 1996; Specht et al., 2013; Sternberg et al., 2010; Wong et al., 2010). Since more researchers, companies, manufacturers, and consumers have realized these benefits, vertical gardening systems are becoming more popular worldwide.

Vertical gardening has been known to improve the urban environment with living walls and green roofs providing a wide variety of both private and public benefits. One benefit is reducing the negative effects of urbanization by providing energy conservation for large cities around the world (Design for London, 2008). Increasing temperatures due to the "urban heat island effect" have been known to cause health problems including respiratory issues. Other issues like restricted airflow, polluted air, and air particulate problems have all been known to be results of the "urban heat islands." Dunnett and Kingsbury (2004) state that living wall systems can create an evaporative cooling surface to protect the urban environment by reducing temperatures caused by "urban heat island effect." Living wall systems have also been shown to improve air quality by absorbing and isolating air pollutants through living plant tissue (Dunnett and Kingsbury, 2004). Research has shown English ivy acts as a 'particle sink', absorbing particulate matter, particularly in high-traffic areas, which can retard bio-deteriorative processes on historic walls, as well as reducing human exposure to respiratory allergens from vehicle pollutants (Sternberg et al., 2010). Buildings can also benefit from the insulating effect of these green surfaces, preventing heat produced by vehicles, air conditioners, and factories from heating the interior space of structures (Wong et al., 2010). Living wall systems also provide sound insulation by absorbing or reflecting sound, reducing noise pollution in large urban areas (Design for London, 2008).

Another benefit of vertical gardening systems is efficient use of natural resources. Zero-acreage farming, which includes roof farms and green wall farms, can reduce land costs and save water by harvesting and using rainwater (Specht et al., 2013). By shortening the transportation distance, vertical gardening systems can reduce transportation costs, as well as pollutants produced by vehicles used to transport produce from point to point. The Sky Green vertical farm in Singapore uses low energy techniques by using the momentum of flowing water and gravity to rotate plants on the top of a 13 m A-frame vertical structure to get equivalent light, using only 40W of electricity (equivalent to one light bulb). The system uses only 0.5 L of water to rotate the 1,700 kg vertical structure via a flooding method producing 10 times more yield per unit area than traditional horizontal production (Sky Green, 2016).

Lewis (1996) found that gardening produces unintentional beneficial effects on people's feelings, thoughts, and emotions. These benefits of urban landscaping are experienced by people who live in highly industrialized cities where landscapes can enhance the visual appeal of these urban areas and improve how they feel about their living environment. Furthermore, street trees, turf areas, and living wall systems create green spaces in urban environments encouraging people to connect with nature. Plants were shown to have therapeutic benefits for people. For example, hospital patients recuperated more quickly when able to view a tree though their window versus patients who did not have that accessibility (Ulrich, 1984). The Green Wall at Longwood Gardens, Kennett Square, PA, was built in front of the hallway of the new restroom facility in the conservatory to create a calming environmental surrounding for the public. The Green Wall consists of a high density of shade loving plants, such as ferns, which suit the lowlight environment and moisture conditions in the facility (Longwood Gardens, 2016).

Vertical gardening can positively impact economies. Fresh vegetables for urban areas are usually produced in nearby rural areas, however, in some Southeast Asian countries such as Singapore, fresh vegetables have to be imported from neighboring countries due to limited arable land causing high land prices (Tey et al., 2009). There are also countries in Africa that do not have enough arable land at any price to produce adequate quantities of fresh vegetables for their population. The advantage of vertical garden systems is that the systems can fit in urban areas by using soilless substrates reducing food transportation costs. Vertical gardening systems are scalable and space efficient helping utilize small vacant areas in urban settings.

Vertical gardens require lower maintenance costs. Many vertical systems are designed as hydroponic systems, limiting the need or expense of soilless substrates (Fletcher, 2012). Although setup of hydroponic systems can be expensive due to the need for specialized equipment, hydroponic systems use fertilizer and water efficiently while reducing incidence of plant diseases. However, not all vertical systems are expensive to set up making them suitable for non-commercial households. Such a system is the A-frame vertical structure designed by Auburn University's Agricultural Land and Resource Management Division of the Alabama Agricultural Experiment Station (Heath, 2016). Each structure provides almost 5.2 m^2 of growing space placed in a 1.5 m^2 horizontal footprint at the cost of about $60.00, excluding the cost of an irrigation system.

Benefits of vertical gardening systems were dependent on crop type and the substrate depth being utilized and its effect on root system size and nutrient uptake from the substrate (Design for London, 2008). Season also impacted crop growth due to changing temperatures and sun exposure though the year (Dunnett and Kingsbury, 2004). Therefore, there is a need to build a sustainable, vertical gardening system that minimizes the influence of these factors and to determine the potential of various food crops through the year.

Limitations of Vertical Gardening

Vertical gardening can have limitations due to the type of vertical structure chosen, plant material grown, and system cost. Structure weight, including the substrate, plant material and water, is a major limitation for vertical gardening depending on the load-bearing capacity of an existing structure (Carpenter, 2008; Dunnett and Kingsbury, 2004).

Fletcher (2012) noted that building a vertical greenhouse was more expensive than a typical greenhouse because all construction material chosen needs to be lightweight but strong, including the irrigation system. There were also high maintenance costs associated with this type of system. Wong et al. (2010) surveyed five groups of participants, including architects, landscape architects, developers, government agencies, and building companies. Findings from this survey showed that the costs associated with vertical gardening system construction was mainly in installation rather than in the space and energy needed to maintain the system. Once the system is constructed, the long-term costs were reasonable.

Mårtensson et al. (2014) point out that current research looking at plant selection suitability for vertical growing systems was extremely limited. Most research focused on plant material to be used for green façades or those looking at botanical aspects for enhancing the environment rather than for crop production (Köhler, 2008). Additionally, there is limited work evaluating different plant species on different vertical structure types. For example, plants chosen for vertical farms are usually leafy greens, herbs, or vegetables, which are generally lightweight with shallow root systems that limit fertilizer and water needs. Different climates and environmental conditions also affected plant performance in vertical gardening systems (Kontoleon and Eumorfopoulou, 2010). Vertical gardening systems outside a greenhouse setting can be exposed to unexpected and adverse weather conditions, such as extreme hot or cold, and too much or too little rainfall. Pollution is another adverse environmental condition that can be encountered when vertical gardening systems are used in urban settings with no protection. Therefore, more work is needed to determine the suitability of a variety of plants to be grown using different vertical systems under different environment conditions.

Research evaluating vertical gardening systems is still in its initial stages, especially for living wall systems (Specht et al., 2013). Vertical gardening systems need more research to build on previous knowledge and experience, and to evaluate plant species suitability, systems, and environmental conditions the systems may be placed under. Key points of technical and research literature have been focused on the problematic limitations stated above arising from improper planning or implementation of these vertical gardening systems (Köhler, 2008).

Vertical Crop Production

The purpose of vertical crop production is to create sustainable approaches to provide locally fresh, nutritional, easily accessible, and inexpensive food in an efficient manner (Brock, 2008). The idea of growing crops vertically has blossomed over the past 20 years (Fletcher, 2012) .

According to Heath (2016), A-frame vertical structures provided an efficient means of greenhouse containerized production for three herbaceous species (*Amaranthus tricolor* L., *Ocimum basilicum* L. 'Cardinal Basil', and *Beta vulgaris* L. 'Detroit Dark Red') in a limited space with low construction costs. Compared to traditional horizontal container crop production on a greenhouse bench, crop yield was higher on the vertical structure. For *Ocimum basilicum* 'Cardinal Basil', the leaf fresh weight from plants grown on the vertical structures was twice that of the weight from plants grown on a horizontal bench. Heath (2016) also reported substrates in containers on vertical structures maintained higher electrical conductivities (EC) than those under traditional greenhouse bench production when fertilized with a controlled release fertilizer. Higher EC levels in substrate leachates collected during production indicate that there were more nutrients remaining in the substrate for plant uptake. Therefore, it may be possible to reduce fertilizer input when using these A-frame vertical structures while producing similar or greater yields than in traditional horizontal production systems.

Another type of urban food production, Zero-acreage Farming, funded by the German Federal Ministry of Education and Research, was used in innovative research on vertical crop production in and on urban buildings (Thomaier et al., 2015). Zero-acreage Farming utilizes several types of roof gardens, indoor farms, edible green walls and vertical farm systems and serves a number of consumer markets (Specht et al., 2013). Zero-acreage Farming is typically placed in or on existing urban structures, utilizing rooftops or abandoned buildings. This type of vertical crop production utilized land unsuitable for farming activities. Zero-acreage Farming is a new way of looking at vertical crop production and holds great potential for having positive impacts on environmental, social, and economic issues.

Highly urbanized areas that have limited space often decrease or restrict the size of food production units, resulting in smaller production yields (Dubbeling, 2011). Consequently, the use of low-space or no-space technologies holds great promise for increasing food production in confined areas of the urban environment. Using low-space techniques, such as vertical structures, Dubbeling (2011) could produce fresh vegetables, up to 45 $kg/yr/m^2$, providing a substantial part of the vegetable consumption for a family in Bogota, Columbia. Vertical gardening systems, particularly living wall systems, can be designed to suit the needs of both urban and rural environments helping conserve valuable resources and producing more yields than those from traditional horizontal greenhouse production (Heath, 2016). Consumers often ask for fresh, local produce, and they want to know where and how this produce was grown. One consumer concern was the increased distance between farms and consumer markets as industrialization increases (Specht et al., 2013). Potential production space is limited in spite of increasing demand for quality produce and the cost of potential arable land is increasing with developing urbanization, so growers are forced to move further from urban areas because of increasing costs including transportation, time, and labor to bring produce to urban environments. Therefore, urban vertical crop production may be a potential solution to reduce production costs while utilizing small, limited urban spaces.

In conclusion, vertical gardening can be a means for people to grow their own fresh, secure, and nutritional food, potentially enhancing their health. However, the benefits of vertical gardening to human health and welfare vary based on the time of year, plant material produced, and orientation of the vertical garden (Valesan and Sattler, 2008). Heath (2016) found that an A-frame vertical structure with a north to south orientation produced greater plant height and growth indices for *Amaranthus tricolor* and *Ocimum basilicum* 'Cardinal Basil' on the south panel compared to the north panel. Derrow (2017) using the same A-frame structures with 'Cardinal Basil' found the south facing vertical panel produced just as well as the horizontal bench throughout most of the years except for leaf fresh weight during the summer season. In the same study, east and west facing panels produced similar 'Cardinal Basil' leaf fresh weights, leaf dry weights and leaf numbers as south facing panel. Therefore, different panel orientation for vertical gardening systems may be required to meet different crop production needs.

Greenhouse Vertical Cherry Tomato Production

In the past, plant material produced using vertical production methods was limited to herbs, true vegetables (leafy), and succulents. Though there was some tomato and chili pepper production in vertical hydroponic systems, the only published research on vertical crop production was for *Amaranthus tricolor, Ocimum basilicum* ‘Cardinal Basil’, and *Beta vulgaris* ‘Detroit Dark Red’ by Heath (2016). All of these plants are herbs or leafy vegetables.

Cherry tomatoes (*Solanum lycopersicum* L.) are high in antioxidant compounds and phytonutrients, which provide many benefits to people such as antiaging qualities and cancer prevention (Rosales et al., 2006). As one of the most important types of fresh produce for consumption (Raffo et al., 2002), cherry tomatoes make up more than 25% of the produce market in Mediterranean regions of the world (Leonardi et al., 2000). As for their ornamental aspect, the cherry tomato plant has small red fruit adding more color to traditional green living wall systems. Therefore, growing cherry tomato on vertical structures could serve both a food and ornamental function.

Tomato field production yield in sandy soils was affected by nitrogen rate and irrigation schedule. Limited nitrogen was shown to reduce fruit yield, and excessive irrigation can cause nutrient leaching while wasting water (Zotarelli et al., 2009). Lowering nitrogen supply for tomato was shown to reduce greenhouse commercial fruit yield by 7.5% as well as reducing plant vegetative growth. Consequently, there was an increase in fruit dry matter yield, and an improvement in fruit quality with a lower nitrogen rate (Bénard et al., 2009). Reducing nitrogen fertilization can limit environmental pollution and potentially improve fruit quality for consumers by increasing tomato sugar content. Bénard et al. (2009) demonstrated that total fruit yield increased by increasing nitrogen rate whereas the marketable fruit yield did not. Cockshull et al. (1992) found that shade affects greenhouse tomato production by increasing time to first fruit harvest and reducing average fruit size. In contrast, excessive light levels in greenhouse tomato production were shown to cause uneven fruit ripening.

Heath (2016) found vertical production structures provided an efficient manner for container production of three herbaceous species in the same area as traditional bench production. More information is needed on a variety of potential horticultural crops, such as cherry tomato, for vertical production and whether optimal fertilizer input varies from traditional horizontal bench container production. In conclusion, there is need to evaluate the cherry tomato production on an A-frame vertical structure by comparing fruit yield and plant growth as affected by different vertical structure orientations, fertilizer rates, and irrigation schedules.

Summary

To address global hunger and malnutrition, innovative and sustainable solutions are required to feed current and future populations, while promoting consumption of healthy, nutritional food. Due to increased urbanization and continued challenges for limited space, the development of innovative, ecofriendly and sustainable technologies, which provide efficient, productive and nutritionally safe agricultural commodities, is highly desirable. As one type of low-space production system, vertical production shows great promise in urban agriculture.

Vertical gardening systems have a long history and recently were shown to provide a number of economic and environmental benefits in modern urban settings. The advantages to vertical crop production are giving a new meaning to this old technique. Vertical gardening in the past was mainly for ornamental or botanical applications, while modern vertical growing systems focus on creating sustainable and resourceful approaches to provide high quality, fresh, locally available food, and cleaner environments in the urban setting.

Research literature is limited for vertical crop production systems. Most vertical systems are used to enhance the urban landscape with flowers and foliage. Vertical crop production in greenhouses has focused on herbs or small leafy green vegetables. More recently, Heath (2016) evaluated three types of edible herbaceous crops on an A-frame structure in a greenhouse environment. A-frame structures used proved to be durable, eco-friendly, resource efficient, and adaptable. Additionally, they are cost efficient (costing about $60 per structure without automated irrigation), flexible, and space efficient.

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CHAPTER 2

Effect of Fertilizer Rate and Panel Orientation on Growth and Fruit Yield of Sweet 'n' Neat Cherry Tomato in Greenhouse Vertical Production

Additional index words. cherry tomato production, vertical gardening, urban agriculture, world hunger and malnutrition.

Abstract. This study evaluated container production of Sweet 'n' Neat cherry tomato (*Solanum lycopersium* L.) using a novel, inexpensive A-frame vertical structure compared to a traditional horizontal bench production system in a greenhouse setting. The objective of this research was to compare how three plant orientations (south facing A-frame panel, north facing A-frame panel and horizontal bench) and three controlled release fertilizer (CRF) rates [2.8, 4.1, and 5.4 kg/m^3 (4.7, 7.0, and 9.3 lb/yd^3)] affect cherry tomato fruit yield. There were two experiments conducted. The experimental design for each was a randomized complete block design. All plants received pre-plant incorporated CRF and drip irrigation. Data collection included growth indices, total fruit yield, marketable fruit yield, days to first flower and fruit, foliage nitrogen (N) content, shoot dry weight, and substrate solution EC and pH. The two vertical panels produced more marketable fruit when compared to the horizontal bench regardless of CRF rate, while each vertical panel only occupied half the greenhouse growing space compared to the horizontal bench. The peak harvest time for cherry tomato on the A-frame structure was 90 to 100 days after transplanting (DAT) compared to 90 DAT on the horizontal. The south panel produced more total fruit while the north panel had greater foliar N content and shoot dry weight. Fewer days to first fruit occurred on the south facing panel than the north panel. CRF rate had little affect of marketable fruit yield but did

affect fruit ripening. The only interaction between CRF rate and plant orientation was in experiment 1 for cherry tomato at the four different maturity stages. Earliest red fruit was harvested on the south panel receiving low CRF rate. Both production orientation and CRF rate had little impact on container substrate EC or pH.

Introduction

Vertical gardening systems have a long history and there is great interest with developing urbanization. The importance of nature and plants for urban living has become a popular research topic, such as how gardens benefit both the environment and people's health (Köhler, 2008). In the past 20 years, vertical systems have been popular in United States, Canada, and Japan (Wong et al., 2010). The Food and Agriculture Organization of the United Nations (2009a) estimates that the world population will grow to 9 billion by 2050. Unfortunately, there are increasing environmental issues, such as limited arable land and climate change, affecting food production's ability to feed our current and future world population. Malnutrition is estimated to cost 3.5 trillion US dollars per year worldwide, and the demand for nutritional food to meet nutritional needs is increasing (Food and Agriculture Organization of the United Nations, 2015). Thus, it is necessary to develop innovative, ecofriendly, and sustainable technologies to help provide efficient, productive, and nutritionally safe agricultural products for both urban and rural areas of the world (Food and Agriculture Organization of the United Nations, 2009b). Currently, crops for vertical production have been limited to herbs and leafy vegetables, and there has been little research on vertical crop production systems and other potential crops to be used. As a highly nutritional and important fresh food product, cherry tomato makes up more than 25% of the produce market for the Mediterranean region of the world (Leonardi et al, 2000).

Heath (2016) evaluated three types of edible herbaceous crops (*Amaranthus tricolor* L., *Ocimum basilicum* L. 'Cardinal Basil', and *Beta vulgaris* L. 'Detroit Dark Red') on an A-frame structure to compare south and north panel orientations with traditional horizontal bench production in a greenhouse environment. For all three species, plants on the south facing panel had similar or greater heights, growth indices, and foliage or shoot fresh and dry weights compared to the horizontal bench, while the north facing panel had the least. In subsequent work, Derrow (2017) evaluated *Ocimum basilicum* 'Cardinal Basil' foliage production on the same vertical structures to compare south, north, east and west panel orientations with horizontal benches. Plants on the horizontal benches had the greatest leaf number, and leaf fresh and dry weight, but in most cases the south panel had similar yields. The north panel orientation had the least yields. In addition, vertical production on two panels, regardless of orientation, had greater produce compared to the horizontal bench occupying similar greenhouse floor area.

Heath (2016) found that container substrate solution electrical conductivity (EC) for the vertical structures was triple that of the horizontal bench using the same fertilizer rate. The author theorized that the vertical structure may require less fertilization in producing a similar product compared to the horizontal bench. However, in follow up work by Derrow (2017) using the same vertical system, there were no differences in container EC among the five production orientations evaluated using the same fertilizer rate.

This study used 'Sweet 'n' Neat' cherry tomato due to its compact plant size, high fruit yield, and sweet flavor. This is a vine indeterminate tomato but people often use it in production as a determinate tomato because of its short vine length. The objectives of this study were: 1) determine the suitability of using an A-frame structure for cherry tomato (*Solanum lycopersium* L. 'Sweet 'n' Neat') production, 2) determine vertical production fruit yield compared to a traditional horizontal bench, and 3) determine differences in controlled release fertilizer (CRF) rates on fruit yield and quality as well as container substrate EC and pH.

Materials and Methods

Two experiments were conducted at the Paterson Greenhouse Complex on the Auburn University campus in Auburn, AL 36849 USA using a double–layer, polyethylene-covered greenhouse. The cooling set temperature was 26.7 ℃ (80 ℉), and ventilation started at 6:00 PM. A-frame vertical structures with irrigation systems, as described by Heath (2016), were used. experiments 1 and 2 were initiated on 15 Sept. 2015 and 30 Jan. 2016 and terminated 27 Jan. 2016 and 5 July 2016, respectively.

Cherry tomato (*Solanum lycopersicum* L. ‘Sweet ‘n’ Neat’) seed (Harris Seeds; Rochester, NY USA) were germinated in 806 cell packs, each cell was 117 cm^3 and 5.4 cm deep, containing Fafard 3B substrate (Sun Gro Horticulture; Agawam, MA USA). During germination, seed was irrigated using a hand held mist nozzle producing 18.9 L per min, once daily until the first two cotyledon leaves emerged. Seedlings were fertilized once per week with a 20N-4.4P-16.6K at 200 ppm N water soluble liquid fertilizer (20-10-20 plus Minors: Plant Marvel Laboratories, Inc., Chicago, IL USA) following sowing and until transplanting. Seedlings were transplanted on 13 Oct. 2015 and 2 Mar. 2016 for the two experiments, respectively.

The experimental design for experiment 1 was a randomized complete blocks design with four blocks, seven treatments per block, and 18 pots per treatment per block for a total 504 plants. The treatment design was an augmented 3 × 2 factorial of CRF rate and production orientation. The seventh treatment was a traditional, horizontal bench serving as a control receiving only the high CRF rate (Table 1). Each A-frame structure occupied 1.5 m^2 of horizontal growing space, but provided 4.8 m^2 of vertical growing space. In contrast, the traditional greenhouse bench control occupied the same 1.5 m^2 of horizontal growing space as the one A-frame structure (both panels). The seven treatments were randomly placed in the greenhouse as illustrated in Figure 1. The 18 pots on each vertical structure panel were arranged in three plant columns with six plants in each column. The experiment required 12 A-frame structures and four horizontal benches.

Seedlings were transplanted into 3812 cm^3 black, square plastic pots having a 16.5 cm height (Belden Magnum, Belden Plastics; St. Paul, MN USA) containing Fafard 3B growing substrate containing three CRF rates. The CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of a 12N–5.3P–10K 3 to 4 month CRF (Harrell's 12-12-12, Harrell's LLC, P.O. Box 807, Lakeland, FL USA). Fertilizer rates were based on the bag label rate and previous work by Heath (2016).

Irrigation system emitters were Rain Bird® 7.6 L per hour drip emitters. At experiment initiation, transplants were irrigated twice daily at 8:00 AM and 12:00 AM for 2 min per cycle. The experiment irrigation schedule was adjusted according to weather conditions and plant growth stage by adjusting irrigation duration, frequency, or both. The highest irrigation volume was a duration of 3 min, four times per day, and the lowest volume was 1 min, once per day.

Growth indices (GI) were measured at 14, 28, and 42 days after transplanting (DAT). Six samples were randomly chosen from the 18 pots within each treatment per block to determine GIs. GI was calculated as (height + first width + second width)/3. Height was measured from the substrate surface to the top stem node. The first width was measured at the visually widest canopy point, and the second width was perpendicular to the first.

Substrate solution EC and pH were determined using a pH/EC probe (Pocket Pro+ Multi1 Tester, Hach; Loveland, CO, USA). Two samples were randomly chosen from the 18 pots within each treatment per block. Leachates were collected weekly beginning two weeks after transplanting, at 27, 41, 55, 69, and 85 DAT. Substrate solution leachates from a 2 min irrigation cycle were collected using rubber bands to tie 3.8 L plastic bags on the bottom of each pot prior to leachate collection. After collection, leachate samples were allowed to reach room temperature of 26℃ before determining solution EC and pH.

Days to the appearance of first flower and first fruit were recorded. First flower was determined as when yellow petals were visible. First fruit was when the diameter of the first fruit was 2 mm or greater. The date recorded was when six pots of the 18 within each treatment per block reached first flower or first fruit.

Fruit were harvested from all pots for each vertical panel and the horizontal bench, and sorted into one of four maturity stages; red, turning, pink or green according to Cantwell (2000) for future fruit nutritional quality analyses. Harvest dates were 5 Jan. 2015 (84 DAT) and 25 Jan. 2016 (104 DAT) based on seed package label information and objective observation. Harvested fruit had a minimum diameter of 15 mm. The weight and number of fruit for each maturity stage were recorded from each treatment and block.

At the termination of experiment 1, foliar samples were taken to determine nitrogen (N) content. Two samples of six leaves were randomly collected from the 18 pots within each treatment and block for a total of eight samples per treatment. Leaves were collected from the first three plant nodes. The fresh leaf tissue was sent to the Auburn University Soil Testing Lab (ALFA Building, Auburn University, AL 36849) for analyses.

Experiment 2 was a randomized complete block design with four blocks and nine treatments (Figure 2). The treatment design was a 3 × 2 factorial CRF rate and production orientation (Table 2). There were 18 pots in all treatments on the vertical panels, and six pots per treatment on the horizontal bench for a total of 504 plants. The same 12 A-frame vertical structures and four horizontal benches were used in both experiments. Seedlings were transplanted on 2 Mar. 2016 as described in experiment 1. Pre-transplant irrigation and fertilization were also the same as in experiment 1.

Data collected in experiment 2 included substrate solution EC and pH, and days to first flower (DFL) and fruit (DFR) as described in experiment 1. Substrate solution leachates were collected at 15, 29, 41, 56, 65, and 82 DAT. In experiment 2, fruit were harvested differently. Only fruit at the red maturity stage were harvested from all pots on each vertical panel and horizontal bench. Six harvests were conducted at 64, 80, 90, 96, 103 or 110 DAT. Fruit from each harvest were sorted into marketable and unmarketable fruit.

At experiment termination, plant shoot dry weight was determined using six samples randomly chosen from each treatment and block. Plant material harvested was the entire plant canopy from the substrate surface, including all stem and leaf tissue. The fresh plant material was put into a drying oven (Grieve Shelf Oven, Grieve, Round Lake, IL) on 27 Jun. 2016 at 72℃ for 72 h.

An Analysis of Variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). All response variables were analyzed using the normal probability distribution except the fruit number which was analyzed using the negative binomial distribution. Least squares means differences among directions were determined using the simulated method. Linear or quadratic trends over fertilizer rate and harvest time were determined using orthogonal polynomials. All significances were at $\alpha = 0.05$.

Results

Experiment 1, three plant production orientations at high CRF rates

There were three significant 2-way interactions for tomato fruit number in experiment 1; plant orientation by harvest date, plant orientation by maturity stage, and harvest date by maturity stage (Table 3).

When comparing plant orientation on harvests 1 and 2, both the horizontal bench and south panel produced more total fruit at harvest 1 than harvest 2 (Table 4). North panel fruit numbers were similar between harvests. On harvest 1, the horizontal bench and the south panel produced more total fruit than the north panel. However, on harvest 2, there were no differences between the three plant orientations.

When comparing plant orientation and fruit maturity stage, there was more fruit harvested from the south panel and horizontal bench than from the north panel for green, pink, and red maturity stages (Table 5). For turning fruit, a greater total fruit number was harvested from the horizontal bench compared to either the north or south panels. For the horizontal bench, greater fruit numbers of green and red fruit were harvested than pink or turning. On the horizontal bench, there was 46.4% green and 30% red fruit harvested. For the north panel, green fruit (58.2 %) was almost triple the number of red fruit, and about five times more than the pink or turning fruit. On the south panel, total green fruit was the most (54.3%) and turning fruit the least (4.2%). Red fruit was about 28% of the fruit harvested. There were twice as many green fruit as red, four times more green than pink, and over 13 times more green than turning on the south panel.

When comparing total fruit numbers based on maturity stage, more pink and turning fruit were harvested at harvest 1 than harvest 2 (Table 6). Green and red numbers were similar for the two harvests. At both harvests, green fruit had the most fruit harvested, 49% and 58% on harvest

1 and 2, respectively, and turning fruit the least, 7% and 6% on harvest 1 and 2, respectively. Red fruit comprised 25% of harvest 1 and 45% of harvest 2.

Only production orientation affected DFR, but not DFL (Table 7). DFL was 9 days across all treatments (data not shown). Plants on the north panel took longer to fruit, 38 days, compared to those on the horizontal bench (28 DFR), and the south panel (30 DFR).

Only plant production orientation affected foliar nitrogen content (data not shown). Foliar nitrogen was greatest for plants on the north panel (4.1%), compared to the horizontal bench (2.3%) and the south panel (2.2%).

Only the collection date main effect was significant for EC (Table 8). There was a quadratic decrease in EC over collection dates (Table 9). Although there were a few differences in container substrate pH, all pH's were within an acceptable range (6.1 or above) for greenhouse-grown tomato (Rutledge, 2015). The substrate solution pH ranged from 6.9 to 7.3, averaging 7.2.

Experiment 1, two plant production orientations at three CRF rates.

For fruit numbers in experiment 1, two three-way interactions were significant; plant orientation by CRF rate by maturity stage and plant orientation by harvest date by maturity stage (Table 10).

More green fruit was harvested from the north panel than the south panel for plants receiving the low CRF rate, while more green fruit was harvested from the south panel than the north panel at the high CRF rate (Table 11). There was no difference between the two panels for green fruit numbers at the medium CRF rate. There was no difference in turning fruit numbers between the two panels at any CRF rate. For pink fruit harvested, there was no difference between the two panels at the low CRF rate however, more pink fruit was harvested from the south panel than the north at the medium and high CRF rates. More red fruit was harvested from the south panel than the north panel at each of the three CRF rates.

Green fruit numbers increased linearly as CRF rate increased for the south panel, which comprised 21.7%, 39.9%, and 54.3% of the total fruit harvested at the low, medium and high CRF rates, respectively (Table 11). Red fruit number decreased linearly with increasing CRF rate, making up 57.5%, 43.8% and 28.6% of the total fruit harvested at the low, medium and high CRF rates, respectively. However, no trends over CRF rate were found for turning or pink fruit, nor were any trends found for all maturity stages for the north panel. For the south panel, more green fruit than red was harvested at the high CRF rate, and turning and pink fruit numbers were lower than green and red. Red and green fruit number was similar at the medium CRF rate, and turning and pink fruit numbers were lower than green and red. Plants on the south panel receiving the low CRF rate had almost three times more red fruit than green, while green, turning, and pink fruit numbers were not different. On the north facing panel, over 50% of the fruit was at the green maturity stage and about 20% was at the red maturity stage regardless of CRF rate. Red and green fruit numbers were similar at the low CRF rate, and turning and pink fruit numbers were lower than green and red. For the medium and high CRF rates, there were more green fruit than fruit at any other maturity stage, and turning, pink, and red fruit numbers were not different. The total yield of green and red maturity stage fruit was over 80% of the total fruit yield regardless of plant orientation or CRF rate.

There was more green fruit harvested from the north panel than the south on harvest 2; conversely, more green fruit was harvested from the south panel than the north on harvest 1 (Table 12). There were no differences in turning fruit numbers between plant orientations for either harvest. More pink fruit was harvested on harvest 1 than 2 from both panel orientations. Percent pink maturity fruit of total fruit harvested was greater on harvest 1 (16.7%) than 2 (9.7%). There was no difference in harvests 1 and 2 on the north panel, but more red fruit was harvested on harvest 1 than 2 on the south panel. There was more green fruit harvested than any other maturity stages from the north panel regardless harvest date. Red fruit number was less than half the green fruit number on the north panel. Green and red fruit were similar on the south facing panel for both harvest dates, and turning and pink fruit numbers were less than red and green.

There was no difference in total fruit number, regardless of fruit maturity stage, between harvests 1 and 2 for the north facing panel (Table 13). More total fruit was harvested on harvests 1 than 2 on the south panel. On harvest 1, total fruit was greater for the south panel than north, but there was no difference between the panels on harvest 2.

There were no affects of plant orientation or CRF rate on DFL (data not shown). Plant orientation affected DFR (Table 14). Plants on the north panel took 36 DFR while those on the south panel took only 29 DFR (data not shown).

Plant orientation and CRF rate main effects were significant for foliar N (Table 15). Foliar N content was greater for plants on the north panel (3.1%) than the south (1.8%). Foliar N content showed an increasing quadratic response with increasing CRF rate (data not shown).

There was an interaction between CRF rate and collection date for substrate solution EC (Table 16). Regardless of CRF rate, there was a quadratic change in EC over collection dates (Table 17). For all CRF rates, EC decreased up to collection date 4, and then increased at collection date 5. EC increased linearly with increasing CRF rate on the first three collection dates. There were no trends in EC over CRF rate on collection dates 4 and 5. EC collected from the north panel was higher (230.8 μs) than from the south panel (184.3 μs) regardless of CRF rate or collection date (data not shown). Although there were a few differences in container substrate pH, all pH's were within and acceptable range for greenhouse-grown tomato (Rutledge, 2015). The substrate solution pH ranged from 6.7 to 7.7, with an average pH of 7.2.

Experiment 2, three plant production orientations and three CRF rates

There were two two-way interactions for fruit number per pot; plant orientation by harvest date and harvest date by CRF rate (Table 18). Fruit number per pot showed a quadratic change over harvest dates for all plant orientations with maximum fruit numbers per pot at harvest date 3 for the horizontal bench and the south panel, and at harvest date 4 for the north panel (Table 19). Over the first three harvests, the greatest fruit number was harvested from the horizontal bench and over the last three harvests, greatest fruit number was harvested from the north vertical panel.

There was a quadratic change in fruit numbers per pot over harvest dates for all CRF rates with maximum fruit numbers at harvest date 3 (Table 20). On harvest 1, fruit number per pot decreased linearly with increasing CRF rate, while on harvest 5, fruit number per pot increased linearly. There were no trends for CRF rate for the remaining harvest dates.

Both the main effects of plant orientation and CRF rate affected total fruit number. Greatest total fruit number occurred for the horizontal bench, followed by the south panel, and the north panel was the least (Table 21). However, total fruit number of the two vertical panels was 1.5 times that of the horizontal bench when using the same horizontal greenhouse square footage. Total fruit number increased linearly as CRF rate increased (data not shown). Total fruit number receiving the low CRF rate was 33 fruit, the medium CRF rate was 40 fruit, and at the high CRF rate was 42 fruit.

For total marketable fruit, there was an interaction between plant orientation and harvest date (Table 22). Greatest total marketable fruit occurred for the south facing panel on harvest 3, and the north panel and horizontal bench had the least (Table 23). Fruit number for the horizontal bench showed a quadratic trend, while fruit number decreased linearly for both vertical panels over harvest date. During harvests 4 through 6, marketable fruit was greatest for both the north and south facing panels and the least for the horizontal bench. Percent marketable fruit decreased linearly over the four harvest dates for the horizontal bench (Table 24). For both the north and south panels, percent marketable fruit over the harvest dates showed quadratic trends with both having the highest percent marketable fruit on harvest 4.

There was an interaction between harvest date and CRF rate for total marketable fruit. Total marketable fruit numbers decreased linearly over harvest dates for all CRF rates (Table 25). Total marketable fruit increased linearly with increasing CRF rates on harvest 5 and 6, but there was no CRF rate affect on harvests 3 and 4. There was a large decrease in total marketable fruit after harvest 4 for all CRF rates.

Only plant orientation affected DFL (Table 26). Plants from the north panel took 21 DFL, which was 5 days longer than the south panel or the horizontal bench (data not shown).

Both production orientation and CRF rate main effects affected DFR (Table 27). Plants from the north panel took 43 DFR, which was 8 days longer than for the south panel, or the horizontal bench (data not shown). DFR increased with increasing CRF rate (data not shown).

There was an interaction between plant orientation and CRF rate for shoot dry weight (Table 28). Shoot dry weights for plants on the vertical panels were greater than those on the horizontal bench at the low CRF rate, but there were no differences in plant orientations at the medium or high CRF rates (Table 29). Shoot dry weight increased linearly with increasing CRF rate on all plant orientations.

There were plant orientation by collection date and collection date by CRF rate interactions for container substrate solution EC (Table 30). There were quadratic changes in EC over collection dates for all plant orientations (Table 31). EC values decreased from the highest values at collection date 1 to the lowest values at collection date 5 and increased thereafter for all plant orientations. ECs for the horizontal bench were higher than both vertical panels on collection dates 1 and 2, but not different on collection dates 3 through 7. There were quadratic changes in EC over collection dates for all three CRF rates (Table 32). EC values decreased from the highest values at collection date 1 to the lowest values at collection date 5 and increased thereafter for the low and medium CRF rates. The lowest EC value occurred on collection date 3 at the high CRF rate. EC increased linearly with increasing CRF rate only on collection date 1, thereafter there were no differences in EC among the CRF rates. Container substrate leachate pH ranged from 6.7 to 7.3, the average pH was 7.0 (data not shown). All pH's were within the recommended pH range for greenhouse tomato production (Rutledge, 2015).

Discussion

This research showed that vertical production of ‘Sweet 'n' Neat’ cherry tomato using an A-frame vertical structure can be an efficient production method in a greenhouse setting. Cherry tomato yield on vertical structure panels produced more fruit compared to the traditional horizontal bench when occupying half the horizontal greenhouse space. Additionally, different CRF rates impacted fruit ripening, but had little affect on marketable fruit yield.

Among different production orientations, the south panel produced greater fruit numbers than the north panel regardless of CRF rate over the two harvest dates of experiment 1, while the south panel and horizontal bench produced similar fruit numbers at the high CRF rate. In experiment 2, total tomato yield was the most for the horizontal bench, followed by the south panel, and the north panel produced the least. When looking at marketable fruit yield, the south panel produced the most over the final four harvests, followed by the north panel, and the horizontal bench produced the least. In experiment 2, peak harvest time for the horizontal bench was about 90 DAT, while the peak harvest time for both vertical panels was about a week longer, 90-100 DAT. The south panel (90-96 DAT) had a peak harvest time that was almost a week earlier compared to the north panel (96-100 DAT).

The importance of these findings is that both vertical panels produced more marketable fruit from the same number of plants but only occupied half of the greenhouse growing area. Furthermore, cherry tomato on the vertical structure had a longer harvest season by producing over an extended period compared to the traditional greenhouse bench. By extending the harvest season for cherry tomato, vertical production may be more efficient and economical by reducing the cost of plant material needed for replanting as often compared to horizontal benches. Derrow (2017) reported an east-west orientated A-frame structure produced similar foliar harvests for basil over time for each of the two panels. The east-west oriented structure might give more uniform ripening of tomato fruit between the two panels (east-west) compared to the north-south orientation in this work.

Earlier fruit was harvested from the south facing panel receiving the low CRF rate in experiment 1. There were fewer days required to reach the red fruit maturity stage for plants on the south panel compared to the north panel or horizontal bench. In experiment 2, though total fruit number increased with increasing CRF rate, there was no difference in fruit number due to CRF rate during the two peak harvests. CRF rate had little impact on cherry tomato fruit yield. Consequently using a lower CRF rate could reduce fertilizer production costs as well as reduce potential environmental concerns over nutrient leaching. For a cherry tomato grower, it is possible to use lower CRF rates with vertical structures to get fruit ready for market earlier than with higher CRF rates. Based on marketable fruit yield and fruit maturity timing, the medium CRF is still recommended for this type vertical production.

As Heath (2016) and Derrow (2017) found growing *Amaranthus tricolor, Ocimum basilicum* 'Cardinal Basil', and *Beta vulgaris* 'Detroit Dark Red' on these A-frame vertical structures, yield was greater than the horizontal bench by combining both vertical panels which would require the same horizontal foot print. Additionally, Heath (2016) reported container substrate solution ECs from vertical structures were greater than the horizontal bench. However, the ECs for the horizontal bench in this study were similar to the vertical panels. Derrow (2017) found a similar EC trend when compared to this study. There was no difference in container substrate ECs among the plant orientations. However, pre-planted incorporated CRFs may be not the best option for container cherry tomato production over the entire production period due to difficulties in maintaining desired concentrations of the nutrients at the different tomato growth stages. Liquid fertilization, which is common in commercial production, needs to be evaluated for this vertical system.

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Figure 1. Plant orientations and controlled release fertilizer rates experimental layout for Sweet 'n' Neat cherry tomato produced on a vertical, A-frame growing structure or traditional greenhouse bench, experiment 1.

<table>
<tr><td>B5/B4[z]</td><td>B7</td><td>B1/B6</td><td>B3/B2</td><td>D3/D2</td><td>D1/D6</td><td>D5/D4</td><td>D7</td></tr>
<tr><td>C1/C6</td><td>C5/C4</td><td>C3/C2</td><td colspan="5" rowspan="3">Unused space</td></tr>
<tr><td>C7</td><td></td><td>A7</td></tr>
<tr><td>A5/A4</td><td>A3/A2</td><td>A1/A6</td></tr>
</table>

[z]Four experimental blocks were A-D;

Treatments were: 1) north oriented vertical panel, 12N–5.3P–10K controlled release fertilizer (CRF) pre-plant incorporated at 5.4 kg/m^3 of substrate; 2) south oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 5.4 kg/m^3 of substrate; 3) north oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 4.1 kg/m^3 of substrate; 4) south oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 4.1 kg/m^3 of substrate; 5) north oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at of 2.8 kg/m^3 of substrate; 6) south oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 2.8 kg/m^3 of substrate; 7) horizontal bench, 12N–5.3P–10K CRF pre-plant incorporated at 5.4 kg/m^3 of substrate. / = vertical structure.

Figure 2. Plant orientations and controlled release fertilizer rates experimental layout for Sweet 'n' Neat cherry tomato produced on a vertical, A-frame growing structure or traditional greenhouse bench, experiment 2.

B8/B7[z]	B1-2-3	B4/B9	B6/B5	D6/D5	D4/D9	D8/D7	D1-2-3
C4/C9	C8/C7	C6/C5					
C1-2-3		A1/2/3			Unused space		
A8/A7	A6/A5	A4/A9					

[z]Four experimental blocks were A-D;

Treatments were 1) horizontal bench, 12N–5.3P–10K controlled release fertilizer (CRF) pre-plant incorporated at 5.4 kg/m^3 of substrate; 2) horizontal bench, 12N–5.3P–10K CRF pre-plant incorporated at 4.1 kg/m^3 of substrate; 3) horizontal bench, 12N–5.3P–10K CRF pre-plant incorporated at 2.8 kg/m^3 of substrate; 4) north oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 5.4 kg/m^3 of substrate; 5) south oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 5.4 kg/m^3 of substrate; 6) north oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 4.1 kg/m^3 of substrate; 7) south oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 4.1 kg/m^3 of substrate; 8) north oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at of 2.8 kg/m^3 of substrate; 9) south oriented vertical panel, 12N–5.3P–10K CRF pre-plant incorporated at 2.8 kg/m^3 of substrate. / = vertical structure, - = horizontal bench.

Table 1. Plant orientations and controlled release fertilizer rates for Sweet 'n' Neat cherry tomato produced on a vertical, A-frame structure or traditional greenhouse bench, experiment 1.

Treatment	Plant orientation[z]	Fertilizer rate (kg/m^3) [y]
1	North panel	2.8
2	South panel	2.8
3	North panel	4.1
4	South panel	4.1
5	North panel	5.4
6	South panel	5.4
7	Horizontal bench	5.4

[z]North or south refers to panel orientation of A-frame structure vertical panels as described by Heath (2016). The horizontal bench orientation served as an industry standard.

[y]Rate of 12N–5.3P–10K, 3-4 month controlled release fertilizer pre-plant incorporated into the substrate.

Table 2. Plant orientations and controlled release fertilizer rates for Sweet 'n' Neat cherry tomato produced on a vertical, A-frame structure or traditional greenhouse bench, experiment 2.

Treatment	Plant orientation[z]	Fertilizer rate (kg/m^3) [y]
1	North panel	2.8
2	South panel	2.8
3	Horizontal bench	2.8
4	North panel	4.1
5	South panel	4.1
6	Horizontal bench	4.1
7	North panel	5.4
8	South panel	5.4
9	Horizontal bench	5.4

[z]North or south refers to panel orientation of A-frame structure vertical panels as described by Heath (2016). The horizontal bench orientation served as an industry standard.

[y]Rate of 12N–5.3P–10K, 3-4 month controlled release fertilizer pre-plant incorporated into the substrate.

Table 3. Analysis of variance for Sweet 'n' Neat cherry tomato total fruit number based on plant orientations, harvest dates, and fruit maturity stages when the substrate had 5.4 kg/m^3 of controlled release fertilizer, experiment 1.

Source of variance	F value	Pr > F
Orientation (O)[z]	39.41	0.0001
Harvest date (H)[y]	26.54	0.0001
Maturity stage(M)[x]	106.03	0.0001
O × H	8.21	0.0006
O × M	3.10	0.0093
H × M	4.93	0.0036
O × H × M	2.02	0.0742

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

[y]Harvest dates were 84 and 104 days after transplanting on 13 Oct. 2015.

[x]Maturity stages were green, turning, pink, or red (Cantwell, 2000).

Table 4. Total fruit number for Sweet 'n' Neat cherry tomato as affected by three plant orientations on two harvest dates when the substrate had 5.4 kg/m^3 of controlled release fertilizer, experiment 1.

	Harvest	
Plant orientation[z]	1[y]	2
H[x]	65aA[w]	55nsB
N	47bNS	51
S	61aA	54B

[z]The plant orientation by harvest date interaction was significant at $\alpha = 0.05$.

[y]Harvests 1 and 2 were 84 and 104 days after transplanting on 13 Oct. 2015.

[x]H=horizontal bench, N=north facing vertical panel, and S=south facing vertical panel.

[w]Least squares means comparisons among orientations (lower case in columns) and among harvests (upper case in rows) using the simulated method, $\alpha = 0.05$. NS or ns= not significant.

Table 5. Total fruit number for Sweet 'n' Neat cherry tomato at four fruit maturity stages when the substrate had 5.4 kg/m^3 of controlled release fertilizer at three plant orientations, experiment 1.

Fruit maturity stage[z]	Plant orientation		
	H[y]	N	S
Green	201aA[x]	109aB	218aA
Turning	35bA	17cB	16dB
Pink	67bA	22bcB	49cA
Red	126aA	38bB	113bA

[z]The fruit maturity stage by plant orientation interaction was significant, $\alpha = 0.05$.

[y]H=horizontal bench, N=north facing vertical panel, and S=south facing vertical panel.

[x]Least squares means comparisons among fruit maturity stages (lower case in columns) and among harvest dates (upper case in rows) using the simulated method, $\alpha = 0.05$.

Table 6. Total fruit number for Sweet 'n' Neat cherry tomato at four fruit maturity stages when the substrate had 5.4 kg/m^3 of controlled release fertilizer on two harvest dates, experiment 1.

	Harvest	
Fruit maturity stage^z	1^y	2
Green	178aNS^x	159a
Turning	27cA	17cB
Pink	67bA	26cB
Red	92bNS	72b

^{z}The fruit maturity stage by harvest date interaction was significant, α = 0.05.

^{y}Harvests 1 and 2 were 84 and 104 days after transplanting on 13 Oct. 2015.

^{x}Least squares means comparisons among fruit maturity stages (lower case in columns) and among harvest dates (upper case in rows) using the simulated method, α = 0.05. NS = not significant.

Table 7. Analysis of variance of Sweet 'n' Neat cherry tomato for days to first flower (DFL) and days to first fruit (DFR) based on plant orientations when the substrate had 5.4 kg/m^3 of controlled release fertilizer, experiment 1.

Source of variance		F value	Pr > F
Plant orientation [z]	DFL	0.36	0.7105
	DFR	9.11	0.0152

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

Table 8. Analysis of variance for Sweet 'n' Neat cherry tomato container substrate solution electronic conductivity based on plant orientations and collection dates when the substrate had 5.4 kg/m^3 of controlled release fertilizer, experiment 1.

Source of variance	F Value	Pr > F
Plant orientation (O)^z	2.54	0.1375
Collection date (C)^y	15.60	0.0001
O x C	0.20	0.9898

^{z}Plant orientations were horizontal bench and north and south facing vertical panel.

^{y}Collection dates were 27, 41, 55, 69, or 85 days after transplanting on 13 Oct. 2015.

Table 9. Container substrate leachate solution electrical conductivity (EC) for Sweet 'n' Neat cherry tomato when the substrate had 5.4 kg/m^3 of controlled release fertilizer as affected by collection dates, experiment 1.

Collection date[z]	EC (µs)
1	373.8
2	243.3
3	215.5
4	165.6
5	196.3
Sign.	Q***[y]

[z]Collection dates were 27, 41, 55, 69 or 85 days after transplanting on 13 Oct. 2015.

[y]Significant (Sign.) quadratic (Q) trend using orthogonal polynomials at $\alpha = 0.001$ (***).

Table 10. Analysis of variance for Sweet 'n' Neat cherry tomato total fruit number as affected by plant orientations, controlled release fertilizer (CRF) rates, harvest dates, and fruit maturity stages, experiment 1.

Source of variance	F value	Pr > F
Orientation (O)[z]	34.06	0.0001
Fertilizer rate (F)[y]	0.57	0.5669
Harvest date (H)[x]	15.27	0.0002
Maturity stage (M)[w]	139.25	0.0001
O × F	3.47	0.0357
O × H	18.27	0.0001
F × H	0.25	0.7783
O × M	23.38	0.0001
F × M	3.71	0.0030
H × M	9.62	0.0001
O × F × H	1.42	0.2474
O × F × M	3.54	0.0042
O × H × M	8.63	0.0001
F × H × M	1.32	0.2592
O × F × H × M	1.02	0.4175

[z]Plant orientations were north or south facing vertical panels.

[y]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

[x]Harvest dates were 84 and 104 days after transplanting on 13 Oct. 2015.

[w]Maturity stages were green, turning, pink, or red (Cantwell, 2000).

Table 11. Total fruit number for Sweet 'n' Neat cherry tomato at four fruit maturity stages (FMS) as affected by two plant orientations and three controlled release fertilizer (CRF) rates, experiment 1.

	Plant orientation							
	North[y]				South			
FMS[z]	L[x]	M	H	Sign.[w]	L	M	H	Sign.
Green	120aA[v]	155aNS	112aB	NS	67bB	137a	226aA	L***
Turning	17cNS	13bNS	17bNS	NS	14b	15c	17d	NS
Pink	34bcNS	22bB	23bB	NS	49b	45bA	56cA	NS
Red	67abB	44bB	41bB	NS	180aA	157aA	116bA	L*

[z]The fruit maturity stage by fertilizer rate by plant orientation interaction was significant, α = 0.05.

[y]North=north facing vertical panel and South=south facing vertical panel.

[x]CRF rates were L= 2.8, M=4.1 , and H= 5.4 kg/m^3 of substrate pre-plant incorporated.

[w]Non-significant (NS) or significant linear (L) trends using orthogonal polynomials, α = 0.05 (*) or 0.001 (***).

[v]Least squares means comparisons among fruit maturity stages (lower case in columns) and among harvest dates (upper case in rows) using the simulated method, α = 0.05. NS = not significant.

Table 12. Total fruit number for Sweet 'n' Neat cherry tomato at four fruit maturity stages (FMS) as affected by two plant orientations over two harvest dates, experiment 1.

	Plant orientation			
	North[y]		South	
FMS[z]	Harvest 1[x]	Harvest 2	Harvest 1	Harvest 2
Green	112aB[w]	146aA	173aA	114aB
Turning	18cNS	13c	15cNS	15c
Pink	36bcA	17bcB	65bA	34bB
Red	51bNS	50b	202aA	100aB

[z]The fruit maturity stage by plant orientation by harvest date interaction was significant, $\alpha = 0.05$.

[y]North=north facing vertical panel and South=south facing vertical panel.

[x]Harvests 1 and 2 were 84 and 104 days after 13 Oct. 2015

[w]Least squares means comparisons among fruit maturity stages (lower case in columns) and among harvest dates (upper case in rows) using the simulated method, $\alpha = 0.05$. NS = not significant.

Table 13. Total fruit number for Sweet 'n' Neat cherry tomato as affected by two plant orientations on two harvest dates, experiment 1.

Plant orientation^{z}	Harvest 1^{y}	Harvest 2
North^{x}	217bNS^{w}	226ns
South	456aA	263B

^{z}The plant orientation by harvest date interaction was significant, α = 0.05.

^{y}Harvests 1 and 2 were 84 and 104 days after transplanting on 13 Oct. 2015.

^{y}North=north facing vertical panel and South=south facing vertical panel.

^{w}Least squares means comparisons between directions (lower case in columns) and between harvests (upper case in rows) using the simulated method, α = 0.05. NS or ns = not significant.

Table 14. Analysis of variance for Sweet 'n' Neat cherry tomato days to first fruit as affected by plant orientations and controlled release fertilizer (CRF) rates, experiment 1.

Source of variance	F value	Pr > F
Orientation (O)[z]	13.06	0.0025
Fertilizer rate (F)[y]	0.55	0.5864
O × F	0.09	0.9127

[z]Plant orientations were north or south facing vertical panels.

[y]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incoporated.

Table 15. Analysis of variance for Sweet 'n' Neat cherry tomato foliar nitrogen content as affected by plant orientations and controlled release fertilizer (CRF) rates, experiment 1.

Source of variance	F Value	Pr > F
Orientation (O)^{z}	53.19	0.0001
Fertilizer rate (F)^{y}	14.34	0.0001
O × F	2.74	0.0796

^{z}Plant orientations were north or south facing vertical panels.

^{y}CRF rates were 2.8, 4.1, or 5.4 kg/m^{3} of substrate pre-plant incorporated.

Table 16. Analysis of variance for Sweet 'n' Neat cherry tomato container substrate solution electronic conductivity as affected by plant orientations, collection dates, and controlled release fertilizer (CRF) rates, experiment 1.

Source of variance	F value	Pr > F
Orientation (O)^{z}	8.04	0.0221
Collection date (C)^{y}	43.51	0.0001
Fertilizer rate (F)^{x}	7.94	0.0036
O × F	1.12	0.3478
O × C	1.53	0.2010
F × C	2.45	0.0179
O × F × C	0.91	0.5112

^{z}Plant orientations were north or south facing vertical panels.

^{y}Collection dates were 27, 41, 55, 69, or 85 days after transplanting on 13 Oct. 2015.

^{x}CRF rates were 2.8, 4.1, and 5.4 kg/m^{3} of substrate pre-plant incorporated.

Table 17. Container substrate solution electrical conductivity (EC) for Sweet 'n' Neat cherry tomato as affected by three controlled release fertilizer (CRF) rates over five collection dates, experiment 1.

	CRF rate			
Collection date[z]	L[y]	M	H	Sign.
1[x]	211.9	320.4	406.3	L***[w]
2	193.9	217.2	256.7	L**
3	132.8	151.9	223.4	L***
4	131.8	129.9	179.0	NS
5	181.3	166.6	210.2	NS
Sign.	Q*	Q***	Q***	

[z]The CRF rate by collection date interaction was significant, $\alpha = 0.05$.

[y]CRF rates were L= 2.8, M=4.1, or H= 5.4 kg/m^3 of substrate pre-plant incorporated.

[x]Collection dates were 27, 41, 55, 69 or 85 days after transplanting on 13 Oct. 2015.

[w]Non-significant (NS) or significant linear (L) or quadratic (Q) trends using orthogonal polynomials at $\alpha = 0.05$ (*), 0.01 (**), or 0.001 (***).

Table 18. Analysis of variance for Sweet 'n' Neat cherry tomato fruit number per pot based on plant orientations, harvest dates, and controlled release fertilizer (CRF) rates, experiment 2.

Source of variance	F value	Pr > F
Orientation (O)[z]	10.13	0.0002
Harvest date (H)[y]	70.56	0.0001
Fertilizer rate (F)[x]	3.25	0.0468
O × H	20.93	0.0001
O × F	0.44	0.7784
H × F	7.23	0.0001
O × H × F	0.87	0.6258

[z]Plant orientations were horizontal bench or north or south facing vertical panels.

[y]Harvest dates were 64, 80, 90, 96, 104 and 110 days after transplanting on 2 Mar. 2016. Only red fruit was harvested in experiment 2.

[x]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

Table 19. Fruit number per pot for Sweet 'n' Neat cherry tomato as affected by three plant orientations over six harvest dates, experiment 2.

Harvest date[z]	Plant orientation		
	H[y]	N	S
1[x]	3a[w]	0b	3a
2	8a	1c	5b
3	25a	8c	15b
4	8c	16a	12b
5	2b	3a	2ab
6	2a	3a	1b
Sign.	Q***[v]	Q***	Q***

[z]The plant orientation by harvest date interaction was significant, $\alpha = 0.05$.

[y]H=horizontal bench, N=north facing vertical panel, and S=south facing vertical panel.

[x]Harvest dates were 64, 80, 90, 96, 103, and 110 days after transplanting 2 Mar. 2016. Only red fruit was harvested in experiment 2.

[w]Least squares means comparisons among plant production orientation (lower case in rows) for each harvest date using the simulated method, $\alpha = 0.05$.

[v]Significant (Sign.) quadratic (Q) trends using orthogonal polynomials, $\alpha = 0.001$ (***).

Table 20. Fruit number per pot for Sweet 'n' Neat cherry tomato as affected by three controlled release fertilizer (CRF) rates over six harvest dates, experiment 2.

Harvest date[z]	CRF rate			
	L[y]	M	H	Sign.
1[x]	3	2	1	L***[w]
2	5	5	4	NS
3	14	17	17	NS
4	9	13	14	NS
5	1	2	3	L***
6	1	2	3	NS
Sign.	Q***	Q***	Q***	

[z]The harvest date by CRF rate interaction was significant, $\alpha = 0.05$.

[y]CRF rates were L= 2.8, M=4.1, or H= 5.4 kg/m^3 of substrate pre-plant incorporated.

[x]Harvest dates were 64, 80, 90, 96, 103, and 110 days after transplanting on 2 Mar. 2016. Only red fruit was harvested in experiment 2.

[w]Significant (Sign.) linear (L) or quadratic (Q) trends using orthogonal polynomials, $\alpha = 0.001$ (***). NS = not significant.

Table 21. Fruit number per pot of Sweet 'n' Neat cherry tomato as affected by three plant orientations, experiment 2.

Plant orientation[z]	Total fruit number[y]
H[x]	47a[w]
N	31c
S	38b

[z]The plant orientation main effect was significant, $\alpha = 0.05$.

[y]Only red fruit was harvested in experiment 2.

[x]H=horizontal bench, N=north facing vertical panel, and S=south facing vertical panel.

[w]Least squares means comparisons among orientations using the simulated method, $\alpha = 0.05$.

Table 22. Analysis of variance for Sweet 'n' Neat cherry tomato total marketable fruit number based on plant orientations, harvest dates, and controlled release fertilizer (CRF) rates, experiment 2.

Source of variance	F value	Pr > F
Orientation (O)[z]	86.13	0.0001
Harvest date (H)[y]	186.24	0.0001
Fertilizer rate (F)[x]	19.98	0.0001
O × H	14.7	0.0001
O × F	0.91	0.4637
H × F	2.3	0.0395
O × H × F	0.55	0.8744

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

[y]Harvest dates were 90, 96, 103 and 110 days after transplanting on 2 Mar. 2016. Only red fruit was harvested in experiment 2, and there was no marketable red fruit at 64 or 80 days after transplanting on 2 Mar. 2016.

[x]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

Table 23. Total marketable fruit for Sweet 'n' Neat cherry tomato as affected by three plant orientations over four harvest dates, experiment 2.

Plant orientation[z]	Harvest				
	3[y]	4	5	6	Sign.
H[x]	149b[w]	42b	8b	11b	Q***[v]
N	138b	281a	50a	48a	L***
S	269a	216a	37a	16a	L***

[z]The plant orientation by harvest date interaction was significant, $\alpha = 0.05$.

[y]Harvest 3, 4, 5, and 6 were at 90, 96, 103 and 110 days after transplanting on 2 Mar. 2016. Only red fruit was harvested in experiment 2, and there was no marketable red fruit at 64 or 80 days after transplanting, 5 May 2016 (harvest 1) or 21 May 2016 (harvest 2), respectively.

[x]H=horizontal bench, N=north facing vertical panel and S=south facing vertical panel.

[w]Least squares means comparisons between directions (lower case in columns) using the simulated method, $\alpha = 0.05$.

[v]Significant (Sign.) linear (L) or quadratic (Q) trends using orthogonal polynomials at 0.001 (***).

Table 24. Percent total marketable fruit for Sweet 'n' Neat cherry tomato as affected by three plant production orientations over four harvest dates, experiment 2.

Plant orientation[z]	Harvest				
	3[y]	4	5	6	Sign.
H[x]	86.3a[w]	77.2b	54.5b	67.8ns	L**[v]
N	64.9b	94.6a	84.5a	65.2	Q***
S	69.6b	90.8a	81.0a	62.9	Q***

[z]The plant orientation by harvest date interaction was significant, α = 0.05.

[y]Harvest 3, 4, 5, and 6 were at 90, 96, 103, and 110 days after transplanting on 2 Mar. 2016, respectively. Only red fruit was harvested in experiment 2, and there was no marketable red fruit at 64 or 80 days after transplanting, 5 May 2016 (harvest 1) or 21 May 2016 (harvest 2), respectively.

[x]H=horizontal bench, N=north facing vertical panel and S=south facing vertical panel.

[w]Least squares means comparisons among directions (lower case in columns) for each harvest date using the simulated method, α = 0.05. ns = not significant.

[v]Significant (Sign.) linear (L) or quadratic (Q) trends using orthogonal polynomials at α = 0.01 (**) or 0.001 (***).

Table 25. Total marketable fruit number per pot for Sweet 'n' Neat cherry tomato as affected by three controlled release fertilizer (CRF) rates over four harvest dates, experiment 2.

	Harvest				
CRF[z]	3[y]	4	5	6	Sign.
L[x]	161	97	15	13	L***[w]
M	193	152	32	21	L***
H	179	173	42	30	L***
Sign.	NS	NS	L***	L**	

[z]The harvest date by CRF rate was significant, $\alpha = 0.05$.

[y]Harvest 3, 4, 5, and 6 were at 90, 96, 103 and 110 days after transplanting on 2 Mar. 2016. Only red fruit was harvested in experiment 2, and there was no marketable red fruit at 64 or 80 days after transplanting, 5 May 2016 (harvest 1) or 21 May 2016 (harvest 2), respectively.

[x]CRF rates were L= 2.8, M=4.1, or H= 5.4 kg/m^3 of substrate pre-plant incorporated.

[w]Significant (Sign.) linear (L) or quadratic (Q) trends using orthogonal polynomials at $\alpha = 0.01$ (**) or 0.001 (***). NS = not significant.

Table 26. Analysis of variance for Sweet 'n' Neat cherry tomato days to first flower as affected by plant orientations and controlled release fertilizer (CRF) rates, experiment 2.

Source of variance	F value	Pr > F
Orientation (O)[z]	48.45	0.0010
Fertilizer rate (F)[y]	1.07	0.3582
O × F	0.38	0.8234

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

[y]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

Table 27. Analysis of variance for Sweet 'n' Neat cherry tomato days to first fruit as affected plant orientations and controlled release fertilizer (CRF) rates, experiment 2.

Source of variance	F value	Pr > F
Orientation (O)[z]	86.74	0.0010
Fertilizer rate (F)[y]	5.58	0.0130
O × F	1.33	0.2962

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

[y]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

Table 28. Analysis of variance for Sweet 'n' Neat cherry tomato shoot dry weight as affected by plant orientations and controlled release fertilizer (CRF) rates, experiment 2.

Source of variance	F value	Pr > F
Orientation (O)[z]	0.68	0.538
Fertilizer rate (F)[y]	69.96	0.001
O × F	3.90	0.0050

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

[y]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

Table 29. Shoot dry weight for Sweet 'n' Neat cherry tomato as affected by plant orientations and controlled release fertilizer (CRF) rates, experiment 2.

	CRF rate			
Plant orientation[z]	L[y]	M	H	Sign.
H[x]	19.8b[w]	26.1ns	37.2ns	L***[v]
N	24.4a	27.8	33.4	L***
S	24.3a	29.7	33.5	L***

[z]The plant orientation by CRF interaction was significant, $\alpha = 0.05$.

[y]CRF rates were L= 2.8, M=4.1, or H= 5.4 kg/m^3 of substrate pre-plant incorporated.

[x]H=horizontal bench, N=north facing vertical panel, and S=south facing vertical panel.

[w]Least squares means comparisons among directions (lower case in columns) for each fertilizer rate using the simulated method, $\alpha = 0.05$. ns = not significant.

[v]Significant (Sign.) linear (L) trends using orthogonal polynomials at $\alpha = 0.001$ (***).

Table 30. Analysis of variance for Sweet 'n' Neat cherry tomato container substrate solution electronic conductivity as affected by plant orientations, collection dates, and controlled release fertilizer (CRF) rates, experiment 2.

Source of variance	F value	Pr > F
Orientation (O)[z]	4.85	0.0512
Collection date (C)[y]	95.61	0.0001
Fertilizer rate (F)[x]	4.19	0.0280
O × F	1.56	0.2257
O × C	2.68	0.0021
F × C	3.01	0.0006
O × F × C	1.35	0.1361

[z]Plant orientations were horizontal bench and north and south facing vertical panels.

[y]Collection dates were 15, 29, 41, 56, 65, 82 or 96 days after transplanting on 2 Mar. 2016.

[x]CRF rates were 2.8, 4.1, or 5.4 kg/m^3 of substrate pre-plant incorporated.

Table 31. Container substrate solution electrical conductivity (EC) for Sweet 'n' Neat cherry tomato as affected by three plant orientations over seven collection dates, experiment 2.

Collection date[z]	Plant orientation		
	H[y]	N	S
1[x]	588.1a[w]	430.3b	394.6b
2	189.5a	115.3b	97.6b
3	97.6ns	92.7	103.7
4	107.9ns	91.0	92.1
5	92.8ns	83.3	88.8
6	108.3ns	104.8	96.1
7	114.5ns	113.5	113.9
Sign.[v]	Q***[v]	Q***	Q***

[z]The plant orientation by collection date interaction was significant, $\alpha = 0.05$.

[y]H=horizontal bench, N=north facing vertical panel, and S=south facing vertical panel.

[x]Collection dates were 15, 29, 41, 56, 65, 82, or 96 days after transplanting on 2 Mar. 2016.

[w]Least squares means comparisons among directions (lower case in rows) for each date using the simulated nethod, $\alpha = 0.05$. ns = not significant.

[v]Significant (Sign.) quadratic (Q) trends using orthogonal polynomials at $\alpha = 0.001$ (***).

Table 32. Container substrate solution electrical conductivity (EC) for Sweet 'n' Neat cherry tomato as affected by three controlled release fertilizer (CRF) rates over seven collection dates, experiment 2.

Collection date[z]	CRF rate			
	L[y]	M	H	Sign.[x]
1	404.0	408.8	600.3	L***[w]
2	128.7	125.0	148.7	NS
3	89.3	112.4	92.2	NS
4	84.3	99.5	107.2	NS
5	79.1	83.5	102.3	NS
6	108.8	98.6	101.8	NS
7	112.4	107.9	121.5	NS
Sign.	Q***	Q***	Q***	

[z]The collection date by CRF interaction was significant, $\alpha = 0.05$. Collection dates were 15, 29, 41, 56, 65, 82 or 96 days after transplanting on 2 Mar. 2016.

[y]CRF rates were L= 2.8, M=4.1, and H= 5.4 kg/m^3 of substrate pre-plant incorporated.

[x]Non-significant (NS) or significant (Sign.) linear (L) or quadratic (Q) trends using orthogonal polynomials, $\alpha = 0.001$ (***).

Chapter 3

Final Discussion

The purpose of this work was to examine how ‘Sweet 'n' Neat’ cherry tomato (*Solanum lycopersium* L.) fruit yield responded using three plant production orientations (A-frame south and north facing panels, and horizontal bench) and three rates of controlled release fertilizer (CRF) rates in a greenhouse setting. This work indicated that regardless of CRF rate, vertical panels produced more marketable fruit than the horizontal bench occupying the same greenhouse floor space.

Based on concerns over substrate being washed out of the pots from the drip irrigation system in Heath’s (2016) work, changes were made in irrigation design and application methods for this work. To modify the system, the end of each drip tube was cut at an angle. The face of the cut tube was placed to face the substrate, causing the water to be distributed at the base of the plant stem. Additionally, the irrigation run times were reduced to 1 min and frequencies increased to 3 times per day compared to Heath’s work using. Total irrigation amounts were kept similar between the two studies. Despite the irrigation adjustments to this work, some substrate was still washed out of the pot. Future research should include adding a drip tip inserted into the substrate along the side of the pot or the addition of mist stakes to the drip line end. Another potential option would be to reduce irrigation pressure reducing the drip rate to provide a more efficient irrigation system.

Using the current irrigation system and application rates, there were fruit harvested with surface cracks. The Missouri Botanical Garden (2017) indicates cracks in tomato fruit may be due to uneven soil moisture levels causing differences in water movement into plant. During the summer for our study, when container substrates were drying out quicker, irrigation was increased both by run time to 2 min and frequency up to 5 times per day. Fruit cracks could have been caused by adjustments in the irrigation run times and frequencies. Future research on cherry tomato production should evaluate increasing irrigation run times and frequencies slowly to prevent a sudden increase in water to tomato plants and ultimately fruit.

UMass Extension (2017) recommends commercial greenhouse tomatoes be fertilized using water soluble liquid fertilizer via an injector system or by a bulk tank system. Using this system, the nitrogen (N) application rate is adjusted over two different periods after transplanting. The first period, transplant to second fruit cluster set, requires 100-125 ppm N; the second period, second fruit cluster to topping, should receive 125-200 ppm N. In our study, tomatoes were harvested earlier at the lower controlled release fertilizer (CRF) rate, while total fruit yield was greater at the higher CRF rate, but many of the fruit with the high CRF rate were unmarketable due to yellow shoulder disorder. The Missouri Botanical Garden (2017) indicates this disorder may be caused by nutrient stress. This may explain why increasing CRF rate increased total fruit yield but reduced marketable fruit yield. Further research on cherry tomato fruit production should look at using a low CRF rate as a starter fertilizer then using liquid fertilizer through an injection system during the later stage production. Actual nutrient levels should be looked at as well by doing a qualitative nutrient profile on container solution throughout the study.

In our work, there was unmarketable fruit with yellow shoulder disorder harvested from the top of the vertical panels and from the horizontal bench. The Missouri Botanical Garden (2017) indicates that this disorder could also be caused by adverse weather conditions, such as high sun exposure. In our study, fruits were harvested from the whole panel with no regard for panel location.

Future work should look at fruit quality and yield from different positions of each vertical panel orientation while recording light levels from these different positions. Derrow (2017) recommended an east-west A-frame structure orientation for ‘Cardinal Basil’ production because of a greater total combined foliar yield for both panels compared to the horizontal bench. Although the combination of the east-west and north-south A-frame structure orientations produced similar total foliar amounts of ‘Cardinal Basil’, harvest time and yields were uneven between the north and south panels. The south panel produced the most and north panel the least in her work. It is possible that the uneven harvest yield for the north-south orientation was due to uneven light levels for the two panels compared to the east-west orientation. There is further research needed for cherry tomato production looking at different panel orientations as well as locations up and down each panel. Another study could look at the addition of wheels to the A-frame structure, allowing the panel orientation to be rotated during production to even out sun exposures for the panel orientations.

Further work also needs to be done evaluating other potential crops for use on this A-frame structure. Some that might have potential are ornamental chili pepper, strawberry, and edible flowers like daylily. The A-frame structure used in our work made harvesting tomatoes easier compared to from the bench plants. Additionally, mixed crop production could be evaluated in the future potentially reducing concerns over different light levels up and down panels or even panel orientation. Different crop species require different cultural requirements and harvest times. Research is needed to grow these potential crops in different positions on the panel as a combination to find the best production mix. For example, cherry tomato, chili pepper and strawberry could be placed at one of the three sections (upper two rows, middle two rows and bottom two rows).

There is more research needed before recommending this A-frame structure to large scale commercial greenhouse producers. However, the A-frame vertical production system could be suitable for small scale greenhouse production. The height and ease of access with the A-frame structure makes harvest and maintenance simpler for producers. This A-frame system doubles the number of pots and plants to be produced in the same greenhouse space compared to a horizontal bench. As an inexpensive system, the structure is easy to build requiring little expertise.

In conclusion, this A-frame vertical system has potential as a production method for small scale commercial growers and with future research and modifications potentially large scale growers. This novel plant growing system might also be used for education and therapy functions because of its low cost and ease to construct.

Literature Cited

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