Orientation Affects Growth and Harvest Yield of *Ocimum basilicum* 'Cardinal' L. Grown on a Novel, Inexpensive Vertical Structure

by

Jennifer Joy Derrow

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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
J. David Williams, Elbert A. and Barbara L. Botts Endowed Professor of Horticulture and Department Head

Abstract

Cardinal basil (*Ocimum basilicum* ‘Cardinal’ L.) was grown on a novel, inexpensive, A-frame vertical structure developed at Auburn University. The structures were built from treated lumber with cattle fencing on each of the two panel faces. One cattle fencing panel held 15, square pots [15.2 cm (6.5 in) wide × 16.5 cm (6 in) tall] with one plant per pot. One structure with two vertical panels facing opposite directions occupied 1.5 m^2 (16 ft^2) of horizontal greenhouse space, as did the traditional, horizontal greenhouse bench treatment used for comparison in this work. The objective of this research was to compare how structure orientation and season affected growth and biomass harvested for basil grown on vertical structures compared to a bench. The treatments were a north-south (N-S) oriented vertical structure, an east-west (E-W) oriented vertical structure, and a bench (control). All pots received drip irrigation. Basil plants were harvested to three remaining nodes per plant every 4 weeks for a total of two harvests per seasonal experiment, to mimic typical foliar harvests. Leaf number (LN), leaf fresh weight (LFW), and leaf dry weight (LDW) were recorded at each harvest. The two panel vertical structures produced the greatest LFW and LDW of basil on a greenhouse square foot basis. Regardless of orientation or season, both the N-S and E-W vertical structures produced a similar biomass of basil. The south orientation panel (0.75 m^2 (8 ft^2) horizontally) produced similar LFW, LDW, and LN compared to the bench [1.5 m^2 (16 ft^2)]. The east and west orientations produced similarly to the south orientation. The north orientation consistently produced the smallest basil biomass. The E-W oriented structure is recommended based on similar biomass produced and the implementation of similar cultural practices.

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N-S	Plants grown on north - south (N-S) oriented A-frame vertical structure.
E-W	Plants grown on east-west (E-W) oriented A-frame vertical structure.
Fall	Experimental run #1
Spring	Experimental run #2
Summer	Experimental run #3
LFW	Leaf Fresh Weight
LDW	Leaf Dry Weight
LN	Leaf Number

CHAPTER 1

Literature Review

History

The use of vertical gardens is not a new, trendy idea. It is actually a practice that has been around for centuries. Approximately 2,000 years ago, the Mediterranean region of the world was implementing such ideas (Köhler 2008). The slender, confined back yards of palaces in the region became the home to vertical gardens, laced with vines of all types. Vertical gardens provided shade for those who enjoyed the use of the garden, the plants cooled the area, and they provided the palace with more economic value from fruit plants being grown on the walls. The majestic Hanging Gardens of Babylon, created about 700 BC and labeled as one of the Seven Wonders of the World, is also an example of how far back vertical gardening dates (Living Walls and Vertical Gardens 2012). It was reported that grapevines and climbing roses were grown on the villa walls in Babylon. The Taj Mahal in India, built in 1632 CE, is another example of early vertical gardening (Köhler 2008).

Interest in incorporating plants into an increasingly urbanized environment has continued throughout history. The dramatic changes people experienced living through the Industrial Revolution gave birth to the Arts and Crafts movement of the late 1800s. Designers during this period sought to unify the house with the garden – most using a rather simplistic, yet highly colorful, style. They aimed to create a harmonious relationship between house and garden, making the garden an essential component of a house rather than an added bonus (Old House Online 2009). The philosophy behind the Arts and Crafts Movement was to reject using products in mass production at the time and to return to an individual style using locally made materials

(The Cultural Landscape Foundation 2016). After the massive increase in city dwellers caused by the Industrial Revolution, the next big movement that occurred was the Garden City Movement that began in the early 1900s. Led primarily by town planner Ebenezer Howard, the movement stemmed from a need to improve the quality of urban life due to uncontrolled growth that came with the Industrial Revolution. The main principles of the Garden City Movement were to establish a compact town around a wide rural belt, have residents, industry, and agriculture within the town, and limit the growth of the town. Howard felt the Revolution separated people from agriculture and the nature around them, so one of the key elements in his designs was a park in the city center – just another example of how much humans desire to have nature around them (Encyclopedia Britannica 1998).

The creation of parks and landscapes during this time of industrialization was a prominent topic, but there was also documented use of more vertical plant production during this time as well. In the early 1920's Europe and North America cities encouraged city dwellers to use woody climbers, such as English Ivy, as covers for simple brick facades in place of ornamental brick to enhance the visual appeal of the city structures (Köhler 2008). Then, in the 1980's in Central European cities, people began to move into the larger cities rather than choosing to live in the rural countryside. This led to growing interest in and research on environmental issues. The concern over losing touch with nature led to efforts to bring nature into urban environments. Among the topics of research during this time were how plant use reduced dust in the house, how plants helped with evaporative cooling, and how plants created habitat for wildlife. In German cities, incentive programs were developed to encourage citizens to take advantage of having plants and maintaining climbers in their backyards. On German mill houses the entire brick façade was covered with climbing plants as an additional insulation layer to reduce outside heat absorption, because the operation of heavy machinery inside the building created heat. Köhler reported that between 1983 and 1997 these incentive programs resulted in approximately 245,584 m^2 (2,643,444 ft^2) of green material being installed in German cities.

Vertical Gardening Today

Today, many countries including the United States, Canada, and Japan continue to show interest in the green wall movement (Wong et al. 2010). Japan is currently the global leader in developing living wall systems. Canada is not far behind with the implementation of a vertical gardening system called VertiCrop. One example is located in Vancouver, Canada where a greenhouse was constructed on top of a multi-level parking garage. This VertiCrop technology occupies a 370 m^2 (3,982 ft^2) space, but uses the large vertical space of the greenhouse to produce 453.59 to 680.39 kg (1,000 to 1,500 lbs) of fresh leafy green vegetables each week using hydroponics. The fresh produce is delivered to local restaurants in the Vancouver area (Berman 2013). With more than half of the world's population living in industrial cities, architects, designers, and planners are looking for the best way to add plants to a world dominated by a concrete infrastructure (Living Walls and Vertical Gardens 2012).

According to Future Directions International, land is a key component of agriculture and the production of enough food to feed the world (Campbell 2011). The relationship between having enough arable land and producing the amount of food the world requires is worth serious consideration and research. The Food and Agricultural Organization of the United Nations (FAO) projects that by the year 2050, the world will have to feed approximately 9 billon individuals (FAO 2015). This represents a 40% increase from today's (circa 2011) population.

Arable land is land suitable for the cultivation of edible crops. This usually refers to land either already in cultivation or the land that has the potential to be cultivated. This type of land is usually not inhabited by large-scale human settlement or protected by any land right laws (Campbell 2011). The FAO states that nearly 25% of the world's arable land is degraded (FAO 2015). Degraded land includes crop land, pastures, forests, and woodlands (Campbell 2011). Asia, Latin America, and Africa have the highest amount of degraded agricultural land because these revenue-poor countries pursue well-paid deforestation policies. However, deforestation is not the only reason for the decrease in arable land. Climate, environment, and human factors all play a part in the degradation of arable land worldwide. Furthermore, issues with irrigation, desertification, terracing, landfill, topology, and urban encroachment all play a crucial part in the loss of land used to grow crops that feed the world. The solution to the problem of arable land disappearing is multi-faceted. The problem can be corrected by producing land that is more arable, using the arable land we do have more productively, or conserving arable land from further degradation. The use of vertical growing systems might be one way to use the arable land that we do have more efficiently.

Environmental Advantages

Living green roofs and walls offer significant environmental benefits (Environmental Landscape Technologies 2015). Green roofs have been shown to lower the temperature of buildings on hot summer days. This in turn requires less energy to cool the building. The reason green roofs have a lower temperature compared to a regular roof is because plant systems loose water through evapotranspiration, shade the building, and increase insulation. Living walls can be used in an exterior or interior planting system, and water can easily be captured and recycled on a vertical growing structure. Living wall structures provide habitats for wildlife such as butterflies, beetles, bees, spiders, and leafhoppers. Living walls also provide sound barriers for busy city life. Additionally, incorporating edibles into the landscape of a living green wall can bring about economic development and educational opportunities to the city using these innovative structures (Oberndorfer et al. 2007).

Psychological Advantages

In addition to environmental impacts, plants have a powerful influence on the human psyche. The earliest records of human history include the creation of gardens for social pleasure and/or political and social functions. In 384 BCE, Aristotle introduced the literary term *Locus amoenus* that is Latin for “pleasant place.” This term refers to a place of safety or comfort with three basic elements – trees, grass, and water. The creation of both private and public gardens in society are an expression of the basic human need to connect with the living world, a term called biophilia. The hypothesis of biophilia suggests that humans subconsciously seek out nature around them (Rakow and Lee 2011).

Plants possess therapeutic benefits as well. Ulrich (1983) conducted a study using hospital patients to determine how quickly they recovered when given a room with a view of trees versus a room with a view of a brick wall. He reported that patients who viewed trees from the hospital room had a shorter postoperative stay, received fewer negative comments from nurses regarding behavior, and requested fewer analgesic doses compared to those viewing a brick wall. People not only desire to be near nature, when they cannot, they bring nature to themselves. Heerwagon and Orians (1986) found that employees who were unable to have a workspace with a view of nature were more likely to decorate their office space with scenes of nature, thus supporting that humans desire to have nature around them. Ulrich (1979) conducted another study using college students who were under stress while taking an exam. The study found that the sight of plants in the test area increased positive feeling, and reduced stress, fear, and anger. The use of plants around us not only makes the area more aesthetically pleasing, but also provides us with mental benefits.

Growing Basil

Basil is one of the most popular culinary herbs grown, used primarily for its aromatic leaves that can be eaten fresh or dried. Basil, in the genus *Ocimum*, is in the Lamaceae (mint) family, and is native to southern Asia. Basil is best grown in a location receiving 6-8 hours of sun daily, but can tolerate partial shade. Plants prefer a moist, well-drained soil with a pH of 6.0-7.0. Typically, sown seeds are spread evenly on top of a propagation mix, then covered with vermiculite to retain humidity around the seed for germination. Germination usually occurs 5-7 days after sowing (Univ. of Minnesota Extension 2007). Once the seedlings have their first set of true leaves, liquid fertilization should be applied every second or third watering cycle with 100-150 ppm N using a 20N-10P-20K fertilizer. Harvesting of the leaves can begin any time by pinching them off. Pruning the basil plant back periodically is important from a culinary perspective because if not pruned stems become woody and the plant will go to flower, decreasing leaf yields (Hamrick 2003). Basil is a relatively pest-free plant, with occasional issues from aphids, slugs, or Japanese beetles. However, the main threat to basil is root rot, so planting in a well-drained substrate and not over watering is key. Leaves can be used fresh, dried, frozen, or infused in vinegar or oil (Bonnie Plants 2017).

Greenhouse Orientation for Maximum Solar Radiation

Unfortunately, very little data has been published on the production of plants using vertical growing systems. However, research has been conducted on the orientation of the greenhouse for optimum solar absorption. El-Maghlany et al. (2015), found that south facing greenhouses capture the maximum amount of solar energy. Further, Dragicevic (2011) found the optimal orientation for a greenhouse to absorb the most solar energy throughout the entire year was actually an E-W (East-West) orientation. The E-W orientation allowed maximum solar absorption during the winter, but reduced solar radiation, keeping the greenhouse slightly cooler during the summer growing season. In the same study, a N-S (North-South) orientation received more solar energy absorption during the summer months, but not as much during the winter months compared to an E-W orientation. Therefore, an E-W orientation allowed for more constant solar radiation absorption that in turn allowed the producer to spend less on heat during the winter months and less on cooling during the summer months.

Orientation of a greenhouse affects solar absorption, as seen above, which then affects plant growth. Stanton et al. (2010) found that *Spiraea alba* grown under shade produced larger leaves compared to those produced in full sun. Plants grown in 40% to 80% shade had increasing specific leaf area from 15% to 60% as compared to plants grown in full sun. For any vertical A-frame production structure to produce efficiently, it should be oriented in a direction that allows for the most solar absorption and maximum plant growth for year-round production in a greenhouse.

Growing on a Novel, Inexpensive A-frame Vertical Structure

Although little research has been published on vertical production, Heath (2015) reported research findings on growing different herbaceous plants on a novel, inexpensive A-frame growing structure. The A-frame vertical structure was constructed of 5.1 cm × 10.2 cm × 2.4 m (2 in × 4 in × 8 ft) and 2.5 cm × 10.2 cm × 2.4 m (1 in × 4 in × 8 ft) treated wood boards, galvanized steel carriage bolts, nuts, and washers, galvanized metal cattle fencing, fencing staples, and galvanized steel nails. The cattle fencing functioned as the wall panels for both sides of the vertical A-frame structure. The wood boards framed each row of the fencing and served as a source of stability for the pots when placed in the cells of the cattle fencing. Each pot was at about a 35° angle in the cattle fencing. Each side of the vertical structure had a wall that was 1.2 m (4 ft) wide and 1.8 m (6 ft) high holding 15 pots each, for a total of 30 pots per structure.

Heath (2015) stated that the vertical growing structure occupied 1.5 m^2 (16 ft^2) which was the same amount of horizontal space occupied by the traditional greenhouse bench used in her work. Therefore, the structure doubled the plant material to be grown in the same amount of horizontal space as the greenhouse bench used as a control treatment. The herbaceous species used in the study were *Ocimum basilicum* ‘Cardinal’ L. (basil), *Amaranthus tricolor* L. (amaranth), and *Beta vulgaris* L. (sugar beet). Treatments were vertical structure panels facing north and south, and a horizontal greenhouse bench as control. The south facing panel produced the most biomass compared to the north facing panel or bench control. For basil and amaranth, the south facing panel yielded the greatest plant height and growth indices (GI). The substrate solution electrical conductivity (EC) was measured every 2 weeks until the termination of the study, and at each date vertical structure ECs were almost triple those for pots on the greenhouse bench. Heath speculated that it might be possible to decrease the amount of fertilizer applied to the plants grown on the vertical structure, but in the end still produce the same quality plant as those plants grown on a greenhouse bench.

Research Objectives

Based on Heath's (2015) work evaluating the A-frame structure used in our work and work by El-Maghlany et al. (2015) on optimum greenhouse orientation, the objective of this study was to evaluate plant performance on the vertical structure in three seasons (fall, spring, and summer) with respect to production structure orientation (N-S and E-W) for container-grown basil and biomass harvested compared to the a horizontal, greenhouse bench. The A-frame vertical structure occupies 1.5 m^2 (16 ft^2), however, one panel of the A-frame structure occupies half [0.74 m^2 (8 ft^2)] the space of the traditional greenhouse bench. Therefore, one A-frame structure panel accommodates the same number of plants as the traditional greenhouse bench space used in this study, but uses half the horizontal square footage. We can then compare the panel orientation to the traditional greenhouse bench to see if any or all panels produce similarly to the greenhouse bench. By comparing the results of the collected data with the direction of the vertical wall orientation, we can determine how orientation affects basil grown on this A-frame structure to identify which panel orientation (N-S or E-W) is most efficient in terms of biomass produced compared to the horizontal bench.

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CHAPTER 2

Significance to Industry

Vertical gardening systems possess the capabilities to use the limited space we have in an efficient way to grow fresh produce. This study evaluated container-grown herbaceous crops on an inexpensive, vertical A-frame production structure compared to growing on the traditional, horizontal greenhouse bench. This vertical structure occupied the same greenhouse footprint [1.5 m^2 (16 ft^2)] as the horizontal greenhouse bench. Results from this work indicate the E-W (East-West) orientation of the vertical structure is best versus the N-S (North-South) orientation or bench, because both east and west oriented panels produced similar crops over the three seasons evaluated. This is in contrast to the north and south panels where the crop from the south oriented panel was larger than the north. Because the E-W oriented structure had similar biomass production, it should make cultural management easier for irrigation, fertilization, and harvest schedules compared to the N-S structure.

Introduction

The practice of vertical gardening has been around for centuries. Humans are constantly seeking ways to use the limited space we have in a more efficient manner. One potential way to achieve this goal may be through the use of vertical growing systems. Not only are they space efficient for the amount of plant product produced, but with more than half of the world's population living in industrial cities, architects, designers, and planners are looking for the best ways to add plants to a world dominated by a concrete infrastructure (Living Walls and Vertical Gardens 2012). The desire for nature and plants to be brought into our urban lives was the driving force behind many topics of research throughout history, such as how plants play a part in environmental and psychological issues (Köhler 2008). Today, many countries including the United States, Canada, and Japan still show a growing interest in the Green Wall Movement (Wong et al. 2010). Campbell (2011) reported that land is a key component of agriculture and producing enough food to feed the world. The Food and Agricultural Organization of the United Nations (FAO) projected that by the year 2050, the world will have to feed approximately 9 billion mouths (FAO 2015). This would be a 40% increase from today's (circa 2011) population (Campbell 2011). Finding ways to increase food production on the land we have dedicated to growing the world's food supply is worth serious consideration and research.

Little research is published on the topic of growing plants on A-frame vertical growing structures. However, Auburn University has designed a novel, inexpensive vertical A-frame growing structure described by Heath (2015). Heath evaluated the structure using three different herbaceous plant species on the structure. She also did a cost analysis of the structure, and found it was more cost efficient than some vertical growing systems currently on the market. The research focused on how *Amaranthus tricolor* L., *Ocimum basilicum* 'Cardinal' L., and *Beta vulgaris* L. grew on the vertical A-frame structures with north and south facing panels compared to a traditional, horizontal greenhouse bench control. For all three genera, plants on the south facing panel either had similar growth to the bench or were greater in plant height, growth indices (GI) [(height + width 1 + width 2) ÷ 3], and fresh and dry weight of foliage and shoots. The north facing panel produced the least compared to plants grown on the south facing panel or the bench, regardless of plant species. Thus, the study showed the south facing structure panel produced the most growth in half the horizontal space [0.75 m^2 (8 ft^2) versus 1.5 m^2 (16 ft^2)] compared to the bench. Additionally, substrate solution electrical conductivity (EC) and pH were monitored during the study. Container ECs were almost triple for the structure panels (north and south facing) compared to the bench. Based on her work, Heath (2015) theorized that fertilizer could be decreased but still grow a similar quality plant on the vertical structure compared to the bench.

The purpose of this research was to evaluate plant performance on a cost effective and space efficient A-frame growing structure using two orientations (N-S and E-W) compared to growing on a traditional, horizontal greenhouse bench and biomass harvested monthly during three seasons of the year. *Ocimum basilicum* ‘Cardinal’ L. was used in the study. The specific objectives of this work were to (1) determine which A-frame panel orientation (N-S or E-W) was the most efficient production structure orientation when compared to the horizontal greenhouse bench on a square footage of horizontal production space occupied and biomass produced, and to (2) determine differences in A-frame panel orientation (north, south, east, or west) on plant growth. In the end, by the evaluation of an innovative and versatile, space efficient vertical A-frame production structure, we speculate the outcomes of this research could have applications to produce a large amount of plant biomass in a smaller production area than horizontal space currently allows.

Materials and Methods

Fall Experiment

Three experiments were performed, each in three separate seasons: fall, spring, and summer (the three experimental runs will be referred to as such from this point forward). All experiments took place at the Auburn University, AL 36849 Paterson Greenhouse Complex. On

17 Sept. 2015, cardinal basil (*Ocimum basilicum* 'Cardinal') seed (Park Seed Company, Hodges, SC) were sown in #606 cell packs [50 ml (1.7 oz)] volume; 5.72 cm (2.3 in) tall) containing Fafard 3B substrate (Sun Gro Horticulture, Agawam, MA). Seed were germinated and grown until transplanting in an 8 mm twin-wall polycarbonate covered greenhouse. Heat setting was 18.3 C (65 F) and evaporative cooling began at 25.6 C (78 F). Seed were uniformly hand watered once daily until transplanting using a mist nozzle producing 18.9 L·minute^{-1} (5 gal·minute). Once the seedlings had their first set of true leaves, they were fertilized once before transplanting with a 20N-4.4P-16.5K fertilizer at 200 mg·L^{-1} (0.19 oz·ft^{3}) N (Plant Marvel Nutriculture 20-10-20 Plus, Plant Marvel Laboratories, Inc., Chicago Heights, IL).

On 14 Oct. 2015, 4 weeks after sowing, seedlings at the second leaf stage were transplanted into 15.2 cm (6 in) wide × 16.5 cm (6.5 in) tall (3845 ml (130 oz) volume)) black, square, plastic pots (Magnum Square, Belden Plastics, St. Paul, MN) filled with Fafard 3B substrate amended with a 12N-5.2P-9.9K 4-mo. control release fertilizer product containing minor elements (12-12-12, Harrell's Fertilizer, Lakeland, FL). The Fafard 3B substrate was amended with 6.32 kg (13.9 lbs) of the 12-12-12 fertilizer product per 1.1 m^{3} (1.5 yd^{3}) of substrate. After transplanting, the seedlings were placed in a double-layer polyethylene covered greenhouse, for the duration of the study. The evaporative cooling system in the greenhouse was set to 25.6 C (78 F) and the heat setting at 21.1 C (70 F). At the time of transplanting, each basil plant had the terminal bud pinched to promote lateral shoot growth. Pots containing the seedlings were placed in the cattle fencing that served as the frame wall panels for the vertical structures. According to Heath (2015), the A-frame vertical structures were designed by Ag Land Management of the Alabama Agriculture Experiment Station. The structures were constructed of 5.1 cm × 10.2 cm × 2.4 m (2 in × 4 in × 8 ft) and 2.5 cm × 10.2 cm × 2.4 m (1 in × 4 in × 8 ft) treated wood boards, galvanized steel carriage bolts with nuts and washers, galvanized metal cattle fencing, fencing staples, and galvanized steel nails. The cattle fencing functioned as the wall panels for both sides of the structures. The wood boards framed each row of the fencing and served as a source of stability for the pots when placed in the cells of the cattle fencing. Each pot was at about a 35° angle in the cattle fencing. Each side of the vertical structure wall was 1.2 m (4 ft) wide and 1.8 m (6 ft) high and held 15 pots, for a total of 30 pots per structure (Heath 2015). Each vertical structure and greenhouse bench occupied 1.5 m^2 (16 ft^2) of horizontal growing space in the greenhouse.

The study was a randomized complete block design having four blocks each having three production structures. The three structures were:

1. Plants grown on north - south (N-S) oriented A-frame vertical structure.
2. Plants grown on east-west (E-W) oriented A-frame vertical structure.
3. Plants grown on a traditional horizontal greenhouse bench (control).

Drip irrigation was installed on each vertical structure and horizontal bench on 12 Oct. 2015. Each structure was wrapped in 1.3 cm (0.5 in) polyethylene tubing fitted with 15 emitters (Rain Bird XB20PC Xeri-Bug Emitters, Rain Bird, Azusa, CA) [producing 7.57 $L \cdot h^{-1}$ (2 gal/hour)] per side with 0.32 cm (0.1 in) micro tubes (Landscape Products™ Micro Tubing, Landscape Products, Tolleson, AZ) running to each pot. Holes were drilled into the center top wall of each pot using an electric drill with a 0.6 cm (13/65 in) bit so the micro tubing fit tightly through the pot wall. Irrigation lines were then placed directly into the sides of all plastic pots. The plants were irrigated four times each day at 8:00 AM, 11:30 AM, 2:00 PM, and 5:00 PM for 1 minute at each time. On 26 Oct. 2015 irrigation was decreased to two times daily (8:00 AM and

2:00 PM) and run for 1 minute per time. This change was due to seasonal decreases in outside temperatures and day lengths.

Substrate leachate electrical conductivity (EC) and pH were measured bi-weekly (8 Nov. 2015, 23 Nov. 2015, and 7 Dec. 2015), starting at transplanting and continuing until termination of the study. This was done by placing a 3.8 L (1 gallon) size plastic bag over the bottom of each container, held in place by a rubber band. Irrigation was then run for a 3 minutes and pots allowed to drain for 30 minutes to collect leachates in the plastic bag. Leachate EC and pH were measured using a pH-EC meter (HACH PocketPro+ Meter, HACH, Loveland, CO).

At each harvest, all plants were pruned back to three nodes. Data collection was taken from three randomly selected plants on each orientation (north, south, each, west, and bench) on every production structure. Leaf fresh (LFW) and dry weight (LDW), and leaf number (LN) were recorded at each harvest for each plant. Samples were dried for 48 hour in an oven (Grieve Shelf Oven, Grieve, Round Lake, IL). The first of two harvests was performed on 10 Nov. 2015. The second and final harvest was performed on 8 Dec. 2015. The study was terminated at the completion of this second harvest.

Data were analyzed two different ways for each season. The first analyses compared the north + south panel exposures to the east + west panel exposures to the bench (control) for leaf fresh weight (LFW), leaf dry weight (LDW), leaf number (LN), and substrate solution pH and EC. This was done to compare biomass produced between the structures and the bench, each occupying 1.5 m^2 (16 ft^2) of horizontal space. The second analyses compared all the panel exposures (north, south, east, and west) and the bench for the same responses. This was done to give an accurate representation based on the fact that each sun orientation (north, south, east, west panels, and horizontal bench) held the same number of plants (15), but, one vertical structure panel occupied ½ the square footage compared to the bench.

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a split plot with exposure treatments blocked in the main plot and sample date in the sub-plot. Where residual plots and a significant COVTEST statement using the HOMOGENEITY option indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Linear and quadratic trends over harvest dates were tested using orthogonal polynomials for pH and EC. For the remaining responses, differences between dates least squares means were tested using main effects F-tests when only the main effect was significant, or using the simulated method when the interaction was significant. All significances were at $\alpha = 0.05$.

Spring Experiment

On 2 Feb. 2016, *Ocimum basilicum* ‘Cardinal’ (basil) seed (Park Seed Company, Hodges, SC) were sown in #606 cell packs containing Fafard 3B (Sun Gro Horticulture, Agawam, MA). As in fall, liquid fertilization began 3 weeks after seeding on 27 Feb. 2016 when the first set of true leaves had emerged. One week later, on 5 Mar. 2016, seedlings were fertilized for a second and final time before transplanting. Using the same substrate described in fall, seedlings were transplanted on 10 Mar. 2016 into the same square plastic pots.

The study had the same treatments as in fall. Irrigation was twice daily (8:00 AM and 2:00 PM) for 1 minute at each time from 10 Mar. to 4 Apr. 2016. Leachates were taken every 2 weeks after transplanting on 26 Mar., 8 Apr., and 22 Apr. 2016. The first of two harvests were on 4 Mar. 2016. After the first harvest, irrigation was increased to four times per day at 1 minute per time due to increased outside temperatures and day lengths. During the week of 26 Mar. to 28 Mar. 2016 irrigation was turned off due to extended cloudy and rainy weather conditions making the substrates stay excessively wet. The second, and final, harvest was 4 weeks after the first on 2 May 2016. The study was terminated after the second harvest. On 9 Apr. 2016, aphids and whitefly insects were observed and on 13 Apr. 2016 plants were treated with Kontos® (OHP, Mainland, PA), a greenhouse and nursery insecticide, according to label directions. Statistical analyses of data were run as described for fall.

Summer Experiment

On 25 May 2016, *Ocimum basilicum* ‘Cardinal’ seed (Park Seed Company, Hodges, SC) were soaked in a 10% bleach solution for 5 minutes and then rinsed with tap water to wash off the bleach. This was done at the recommendation of an Alabama Extension Plant Diagnostic Lab because in spring bacterial wilt was noticed on a portion of the plants once they were growing on the vertical structures. After cleaning, seed were sown in the same substrate as fall and spring in a 72 cell pack [45 ml (1.5 oz] volume; 5.72 cm (2.3 in) tall) and placed in a germination chamber. Liquid fertilization of seedlings was started on 4 June 2016 when the first set of true leaves emerged using the same fertilizer and rate as in fall and spring. Seedlings were fertilized an additional two times on 10 June and 16 June 2016.

Seedlings were transplanted on 17 June 2016 as described in fall. Irrigation was run twice daily for 1 minute at 8:00 AM and 2:00 AM. On 10 July 2016 the irrigation was increased to four times per day (8:00 AM, 11:30 AM, 2:00 PM, and 5:00 PM) for 1 minute per time. Data were recorded and analyzed as in the fall and spring. The first of two harvests occurred on 20 July 2016 and the final harvest on 23 Aug. 2016. Leachates were determined on 30 June, 13 July, 27 July, and 17 Aug. 2016. The study was terminated following the second harvest.

Results

Leaf Fresh Weight (LFW)

There was an interaction between structure orientation (N-S, E-W, and bench) and harvest weeks after initiation (WAI) for LFW in all three seasons. In fall, LFW at 4 WAI for the N-S vertical structure was greatest, bench the least, and E-W vertical structure was similar to both other treatments (Table 1). At 8 WAI, the vertical structures produced more LFW than the bench (at least 33% more on a square foot basis) regardless of orientation. In spring, LFW at 4 and 8 WAI was greater with the two vertical structures regardless of orientation than the bench. At 8 WAI, in the same horizontal footprint, there was 94% and 81% more LFW for the N-S and E-W vertical structures than the bench, respectively. As in spring, results for LFW in summer at 4 and 8 WAI showed the two vertical structures had the highest LFW compared to the bench for the same horizontal footprint. At 8 WAI, the E-W and N-S vertical structures produced 67% and 50% more biomass than the bench, respectively. For all three seasons, LFW increased from the 4- to 8-WAI regardless of production structure.

When comparing the five orientations, only the structure orientation main effect was significant for LFW in fall and spring (Table 2). LFW was greatest for the south and east panels, and the bench while the north panel had the least, but was similar to the west panel. LFW increased about 75% from the 4- to 8-WAI regardless of structure orientation (data not shown). In spring, LFW was greatest for the south, east, west, and bench orientations and least for the north orientation. From the 4- to 8-WAI harvest, LFW increased 136% in spring regardless of structure orientation (data not shown). For the LFW group comparisons for both fall and spring, there were no differences between east and west, but the south panel was greater than the north panel (Table 2). Unlike the fall and spring, summer had an interaction between structure orientation and WAI for LFW (Table 3). Regardless of structure orientation, LFW increased from the 4- to 8-WAI. For both harvests, the bench had the greatest LFW. At 4 WAI, north, south, east, and west LFW was similar. However, at 8 WAI, north, south, and east orientations were similar and the least compared to the bench while the west orientation was similar to all others. For the paired comparisons there was no difference between east and west on either harvest date, but the south LFW was greater than north orientation on both harvest dates (Table 3). Although not compared statistically, LFW in the summer was the greatest, followed by spring (48% less) and then fall (217% less).

Leaf Number (LN)

As with LFW, there was an interaction between structure orientation and harvest date for LN for all three seasons (Table 4). In fall, LN at both 4 and 8 WAI harvests and for both vertical structures had higher LN than the bench on a square foot basis. Calculations were made by dividing the LN by the horizontal growing space to see the average amount of leaves produced per 1.5 m^2 (16 ft^2). For fall at 8 WAI, the N-S structure produced an average of 496 leaves·m^2 (46 leaves·ft^2) and the E-W produced 450 leaves·m^2 (42 leaves·ft^2), but the bench produced only 290 leaves·m^2 (27 leaves·ft^2). For spring on the 4 WAI, the E-W produced the highest LN, the bench had the least, and the N-S was similar to both other treatments. At 8 WAI, the vertical structures had the greatest LN when compared to the bench regardless of orientation. At 8 WAI during the spring, the N-S vertical structure produced an average of 696 leaves·m^2 (65 leaves·ft^2) and the E-W produced 656 leaves·m^2 (61 leaves·ft^2), but the bench produced only 396 leaves·m^2 (37 leaves·ft^2). Regardless of production structure, in fall and spring, LN increased from the 4- to 8-WAI. In summer, LN for the N-S structure was greatest while the bench was least at 4 WAI harvest. At 8 WAI, there was no difference in LN among structures. When comparing 4 to 8 WAI, the N-S structure LN decreased while LN for the bench increased. LN was similar for the E-W structure regardless of harvest date. At 8 WAI in summer, there were no differences among treatments, but the N-S structure produced an average of 726 leaves·m^2 (68 leaves·ft^2) and the E-W produced 803 leaves·m^2 (75 leaves·ft^2), and the bench produced only 696 leaves·m^2 (65 leaves·ft^2).

In fall and summer, LN had an interaction between production structure and WAI for the different orientations (Table 5). Only the orientation main effect was significant for spring (Table 6). Regardless of orientation, LN in fall increased 106% from the 4- to 8-WAI harvest. In fall, the bench produced the greatest LN, the north panel the least, with the south, east, and west panels being similar to all other orientations 4 WAI. At 8 WAI, the south panel had the greatest LN and the north panel the least, while the east panel orientation was similar to all other orientations. For the paired comparisons in fall at 4 WAI and 8 WAI, there was no difference between east and west, but the south panel LN was greater than the north (Table 5). In spring, the bench had the greatest LN, north the least, with south and west being similar to all other orientations (Table 6). For the paired comparisons there was no difference between east and west, but the south was greater than the north. For summer at 4 WAI, the south panel was greatest, and the north and west panels the least. The bench LN was similar to both the south and east panels. At 8 WAI, the south panel showed a decrease in LN compared to the 4 WAI harvest. The west panel and the bench had an increase in LN from the 4- to 8-WAI, while north and east were similar. The bench had the greatest LN at 8 WAI, while the north, south, east, and west panels were less and similar. For the paired comparisons there were no differences between east and west regardless of harvest date, but south LN was greater than north at 4 WAI (Table 5). There was no difference between the north and south panels for LN at 8 WAI.

Leaf Dry Weight (LDW)

Unlike LFW and LN, LDW in fall showed only a production structure main effect significance. LDW for the N-S structure produced the greatest LDW, the bench produced the least, and the E-W structure was similar to both other structures (Table 7). In spring and summer, there was an interaction between production structure and WAI for LDW (Table 8). In spring at 4 WAI, there was no difference in LDW between production structures. However, in summer, the N-S structure had the greatest LDW at 4 WAI while the E-W structure and the bench were least. At 8 WAI for both spring and summer, the N-S and E-W structures were similar, while the bench had the least. In spring, LDW biomass was 67% and 50% more, for the N-S and E-W vertical structures, respectively, than the bench. The N-S and E-W vertical structures produced 34% and 56% more LDW biomass in summer when compared to the bench. Lastly, for all three seasons LDW was greater (by at least 117%) at the 8 WAI than the 4 WAI (fall data not shown; spring and summer, Table 8) regardless of production structure.

Fall was the only experiment of the three seasons to have an interaction between structure orientation and WAI in LDW for the five exposures (Table 9). Regardless of orientation, LDW increased from the 4- to 8-WAI harvest. The south panel had the greatest LDW at 4 WAI, north the least, and east was similar to the west and north panels, and the bench. The west panel LDW at 4 WAI was similar to the north panel and the bench. At 8 WAI, the bench had the greatest LDW with the south and east panels being similar. The north panel had the least LDW with the west panel being similar. For paired comparisons there was no difference between east and west at 4 WAI, however there was a difference in fall at 8 WAI. Regardless of harvest date, south had greater LDW than north (Table 9).

Only the orientation main effect was significant for LDW in spring and summer (Table 10). For both seasons, LDW was greatest for the bench. The north, south, east, and west panels were similar to each other in spring and summer. The only exception was in spring, where the south panel was similar to the bench as well as all other orientations. In spring, LDW increased 150% from the 4- to 8-WAI (data not shown). There was a 98% increase in LDW from 4- to 8-WAI during summer (data not shown). For both spring and summer, there were no differences between east and west in paired comparisons, but south was only greater than north in spring. There were no differences between panel orientations for fall and summer (Table 10).

pH and Electrical Conductivity

Over all three seasons, only the WAI main effect was significant for container substrate pH and EC (Table 11). In fall, both pH and EC had a quadratic model over time regardless of production structure. The pH decreased from 4- to 6-WAI followed by an increase at 8 WAI. EC increased from 4- to 6-WAI, then decreased at 8 WAI. For spring, pH was not different over time. The EC followed a similar model to fall with a quadratic model over time. EC was highest at 4 WAI, decreased at 6 WAI, and then increased at 8 WAI. In summer, both the pH and EC decreased quadratically over time.

Discussion

Results from this work showed the A-frame vertical structures used produced greater amounts of *Ocimum basilicum* ‘Cardinal’ L. foliage on a square foot of greenhouse floor space basis than the horizontal greenhouse bench regardless of panel orientation or production season.

Among the different panel orientations, the south panel orientation produced just as well as the bench in most cases. The east and west panel orientations were similar to the south panel for LFW, LN, and LDW. When making direct paired comparisons between east and west orientations, and north and south orientations, there was no difference in production between the east or west orientations, but production between the north and south orientations were vastly different in all cases except LFW at the 4 and 8 WAI harvests during summer. The importance of these findings is that by orienting the structures E-W, growers can implement similar cultural practices such as irrigation, fertilizer rates, and harvest schedules. Orienting the structures N-S would require more work for a grower because water would have to be monitored more frequently (the south panel would dry out faster than the north) and harvest schedules could be different due to the south panel growing faster than the north panel, as seen by the differences in harvest magnitude. Dragicevic (2011) supports the idea that the E-W structure was the optimum orientation. The E-W orientation should allow maximum solar interception during the winter, but reduced solar interception in the summer. In the same study, a N-S orientation received more solar interception during the summer months, but not as much during the winter months compared to an E-W orientation. Therefore, an E-W orientation allowed more constant solar interception that in turn allowed the producer to spend less on heat during the winter months and on cooling during the summer months.

In all three seasons, LFW, LDW, and LN increased from the 4- to 8-WAI harvests. This was likely in response to the plants being pruned back to three nodes per plant, thus breaking apical dominance and leading to more lateral shoot growth. The exception was LN in summer where there was a decrease for the N-S structure, but no differences for the E-W structure (Table 4). It was noted that during the 8 WAI harvest, plants grown on the vertical structures appeared to produce larger leaf sizes and longer internodes compared to bench plants. Stanton et al. (2010) found that *Spiraea alba* grown under shade produced larger leaves compared to those produced in full sun. Plants grown in 40% to 80% shade had increased specific leaf area from 15% to 60% as compared to plants grown in full sun. Although not compared statistically, LFW per leaf for summer was calculated by dividing LFW by LN. Each vertical structure panels had at least 20 g more LFW per leaf than the bench. This calculation supports the observation at 8 WAI that leaves appeared larger on plants grown on the vertical structures than on the bench. These observations, along with Stanton's (2010) findings, explain the decrease in LN, or very little change, from 4- to 8-WAI, while increased LFW and LDW between harvests. Even though leaf number decreased, weight did not possibly because leaf area could have been increasing due to less solar interception. The decrease in LN could have been due to the plants grown on the vertical structures during the summer season were growing faster than the plants grown on the greenhouse bench. Heath (2015), supports the observation that plants grown on the vertical structures appeared to have longer internodes with data where basil plants grown on the vertical structure (both north and south panels) were taller compared to plants on the bench.

Additionally, Heath's (2015) work reported a dramatic increase in substrate solution EC from containers on the vertical structures compared to the bench. The results from this work found no differences in substrate solution ECs for the vertical structures and the bench. However, growth data was similar for the two production structures used in both Heath's (2015) work and the work presented here. Heath (2015) reported for both *Ocimum basilicum* 'Cardinal' L. (basil) and *Amaranthus tricolor* L. (amaranth) at the end of the study, that plants on the south panel and bench had greater growth (plant height and growth index), than those on the north panel. Basil grown on the south panel had the highest shoot and foliar dry weight compared to plants on the north panel. Fresh weight followed a similar trend as dry weight. Heath's (2015) results were similar to those found in the current study, where the south panel was similar to the bench for LFW, LDW, and LN. The current study also found that the east and west panels were also similar to the south panel for most observations. A comparison can be made with respect to season between Heath's (2015) work and this research. Heath (2015) harvested basil after 5 weeks of production time while the current work had two harvests' at 4 week intervals. Heath's (2015) work and the summer experiment of this work took place during the same season. Heath (2015) found that the south panel and bench had greater or similar LN, while the north panel had the least. The current work follows the same trend at 4 WAI for LN, but also showed that the east panel was similar to the bench (Table 5).

In conclusion, the vertical A-frame production structure used in this study is a space efficient, alternative method for the container production of *Ocimum basilicum* 'Cardinal' L. compared to using a traditional, horizontal greenhouse bench, where both occupied the same greenhouse square footage. Furthermore, this work indicates the E-W orientation of the vertical structure would be best, because both east and west oriented panels produced similar crops over the three seasons evaluated. This is in contrast to the north and south panels where the crop from the south oriented panel was larger than the north. Because the E-W oriented structure had similar biomass production, it should make cultural management easier for irrigation, fertilization, and harvest schedules compared to the N-S structure.

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Table 1. Leaf fresh weight for *Ocimum basilicum* 'Cardinal' L. over time based on production structure, Fall, Spring, and Summer.

		Leaf fresh weight (g)[z]		
	WAI[y]	N-S[x]	E-W	Bench
Fall				
	4	186 bA[w]	146 bAB	113 bB
	8	288 aA	304 aA	188 aB
Spring				
	4	246 bA	273 bA	182 bB
	8	684 aA	638 aA	352 aB
Summer				
	4	671 bA	590 bA	464 bB
	8	888 aA	989 aA	594 aB

[z] Production structure by harvest date interaction was significant, α = 0.05.

[y] Weeks After Initiation (WAI): Fall: 4 WAI - first harvest, 10 Nov. 2015, 8 WAI - second harvest, 8 Dec. 2015; Spring: 4 WAI - first harvest, 4 Apr. 2016, 8 WAI - second harvest, 2 May 2016; Summer: 4 WAI- first harvest, 7 July 2016, 8 WAI - second harvest, 23 Aug. 2016.

[x] Production Structure: N-S – A-frame vertical structure with north and south oriented panels; E-W- A-frame vertical structure with east and west oriented panels; Bench - horizontal bench (control).

[w] Least squares means comparisons between harvest dates (lower case in columns) using F-test, α = 0.05. Least squares means comparisons among production structures (upper case in rows) using the Simulated Method, α = 0.05.

Table 2. Leaf fresh weight for *Ocimum basilicum* 'Cardinal' L. based on orientation, Fall and Spring.

	Leaf fresh weight (g)[z]				
	North[y]	South	East	West	Bench
Fall[x]	83 c[w]	153 a	129 ab	99 bc	153 a
Spring[v]	203 b	262 ab	229 ab	232 ab	271 a

[z] Only the orientation main effect was significant, α = 0.05.

[y] Orientation: North - A-frame panel facing north; South - A-frame panel facing south; East - A-frame panel facing east; West - A-frame panel facing west; Bench – horizontal bench (control).

[x] Fall - least square means comparisons among orientation pairs (East vs. West = 0.0720; North vs. South = <0.0001) estimated using the Simulated Method, α = 0.05.

[w] Least squares means comparisons among orientations using the Simulated Method, α = 0.05.

[v] Spring - least square means comparisons among orientation pairs (East vs. West = 0.9999; North vs. South = 0.0102) estimated using the Simulated Method, α = 0.05.

Table 3. Leaf fresh weight for *Ocimum basilicum* 'Cardinal' L. over time based on orientation, Summer.

	Leaf fresh weight (g)[z]				
WAI[y]	North[x]	South	East	West	Bench
4[w]	330 bB[v]	342 bB	313 bB	288 bB	460 bA
8	473 aB	496 aB	468 aB	530 aAB	595 aA

[z] Orientation by harvest date interaction was significant, α = 0.05.

[y] Weeks After Initiation (WAI): 4 WAI - first harvest, 7 July 2016, 8 WAI - second harvest, 23 Aug. 2016.

[x] Orientation: North - A-frame panel facing north; South - A-frame panel facing south; East - A-frame panel facing east; West - A-frame panel facing west; Bench – horizontal bench (control).

[w] Least square means comparisons among orientation pairs (East vs. West = 0.8998 (4 WAI) and 0.0083 (8 WAI); North vs. South = 0.0155 (4 WAI) and <0.0001 (8 WAI)) estimated using the Simulated Method, α = 0.05.

[v] Least squares means comparisons between harvest dates (lower case in columns) using F-tests, α = 0.05. Least squares means comparisons among orientations (upper case in rows) using the Simulated Method, α = 0.05.

Table 4. Leaf number for *Ocimum basilicum* 'Cardinal' L. over time based on production structure, Fall, Spring, and Summer.

		Leaf number[z]		
	WAI[y]	N-S[x]	E-W	Bench
Fall	4	360 bA[w]	320 bA	225 bB
	8	745 aA	675 aA	435 aB
Spring	4	440 bAB	500 bA	330 bB
	8	1,045 aA	985 aA	595 aB
Summer	4	1,365 aA	1,105 nsB	715 bC
	8	1,090 bNS	1,205	1,045 a

[z] Production structure by harvest date interaction was significant, α = 0.05 each.

[y] Weeks After Initiation (WAI): Fall: 4 WAI - first harvest, 10 Nov. 2015, 8 WIA - second harvest, 8 Dec. 2015; Spring: 4 WAI - first harvest, 4 Apr. 2016, 8 WAI - second harvest, 2 May 2016; Summer: 4 WAI - first harvest, 7 July 2016, 8 WAI - second harvest, 23 Aug. 2016.

[x] Production Structure: N-S – A-frame vertical structure with north and south oriented panels; E-W- A-frame vertical structure with east and west oriented panels; Bench - horizontal bench (control).

[w] Least squares means comparisons between harvest dates (lower case in columns) using F-test, α = 0.05. Least squares means comparisons among production structures (upper case in rows) using the Simulated Method, α = 0.05.

Table 5. Leaf number for *Ocimum basilicum* 'Cardinal' L. over time based on orientation, Fall and Summer.

		Leaf number[z]				
	WAI[y]	North[x]	South	East	West	Bench
Fall[w]	4	145 bB[v]	215 bAB	170 bAB	155 bAB	225 bA
	8	255 aC	485 aA	365 aABC	310 aBC	430 aAB
Summer[u]	4	530 nsC	840 aA	615 nsBC	500 bC	715 bAB
	8	545 B	645 bB	600 B	620 aB	1,045 aA

[z] Orientation by harvest date interaction was significant, α = 0.05.

[y] Weeks After Initiation (WAI): Fall: 4 WAI - first harvest, 10 Nov. 2015, 8 WAI - second harvest, 8 Dec. 2015; Summer: 4 WAI - first harvest, 7 July 2016, 8 WAI - second harvest, 23 Aug. 2016.

[x] Orientation: North - A-frame panel facing north; South - A-frame panel facing south; East - A-frame panel facing east; West - A-frame panel facing west; Bench – horizontal bench (control).

[w] Fall - least square means comparisons among orientation pairs (East vs. West = 0.8104 (4 WAI) and 0.5104 (8 WAI); North vs. South = 0.0346 (4 WAI) and <0.0001 (8 WAI)) estimated using the Simulated Method, α = 0.05.

[v] Least squares means comparisons between harvest dates (lower case in columns) using F-tests, α = 0.05. Least squares means comparisons among orientations (upper case in rows) using Simulated Method, α = 0.05. "ns" = not significant.

[t] Summer - least square means comparisons among orientation pairs (East vs. West = 0.3741 (4 WAI) and 0.9618 (8 WAI); North vs. South = 0.0004 (4 WAI) and 0.2970 (8 WAI)) estimated using the Simulated Method, α = 0.05.

Table 6. Leaf number for *Ocimum basilicum* 'Cardinal' L. based on orientation, Spring.

Leaf number[z]				
North[yx]	South	East	West	Bench
300 c[w]	445 ab	365 bc	380 abc	460 a

[z] No interaction between orientation and harvest date, α = 0.05.

[y] Orientation: North - A-frame panel facing north; South - A-frame panel facing south; East - A-frame panel facing east; West - A-frame panel facing west; Bench – horizontal bench (control).

[x] Least square means comparisons among orientation pairs (East vs. West = 0.9106; North vs. South = 0.0002) estimated using the Simulated Method, α = 0.05.

[w] Least squares means comparisons among orientation using the Simulated Method, α = 0.05.

Table 7. Leaf dry weight for *Ocimum basilicum* 'Cardinal' L. based on production structure, Fall.

Leaf Dry Weight (g)[z]		
N-S[y]	E-W	Bench
4.5 a[x]	3.8 ab	3.1 b

[z] No interaction between production structure and harvest date, α = 0.05.

[y] Production Structure: N-S – A-frame vertical structure with north and south oriented panels; E-W- A-frame vertical structure with east and west oriented panels; Bench - horizontal bench (control).

[x] Least squares means comparisons among production structures using the Simulated Method, α = 0.05.

Table 8. Leaf dry weight for *Ocimum basilicum* 'Cardinal' L. over time based on production structure, Spring and Summer.

		Leaf Dry Weight (g)[z]		
	WAI[y]	N-S[x]	E-W	Bench
Spring	4	23 bNS[w]	28 b	20 b
	8	74 aA	65 aA	45 aB
Summer	4	57 bA	50 bB	44 bB
	8	99 aA	115 aA	74 aB

[z] Production structure by harvest date interaction was significant, α = 0.05 each.

[y] Weeks After Initiation (WAI): Spring: 4 WAI - first harvest, 4 Apr. 2016, 8 WAI - second harvest, 2 May 2016; Summer: 4 WAI - first harvest, 7 July 2016, 8 WAI - second harvest, 23 Aug. 2016.

[x] Production Structure: N-S – A-frame vertical structure with north and south oriented panels; E-W- A-frame vertical structure with east and west oriented panels; Bench - horizontal bench (control).

[w] Least squares means comparisons between harvest dates (lower case in columns) using F-test, α = 0.05. Least squares means comparisons among production structures (upper case in rows) using the Simulated Method, α = 0.05. “NS” = not significant.

Table 9. Leaf dry weight for *Ocimum basilicum* 'Cardinal' L. over time based on orientation, Fall.

WAI[y]	Leaf Dry Weight (g)[z]				
	North[x]	South	East	West	Bench
4[w]	5 bC[v]	10 bA	7 bBC	6 bBC	9 bAB
8	9 aD	21 aAB	17 aABC	11 aCD	22 aA

[z] Orientation by harvest date interaction was significant, α = 0.05.

[y] Weeks After Initiation (WAI): 4 WAI - first harvest, 7 July 2016; 8 WAI - second harvest, 23 Aug. 2016.

[x] Orientation: North - A-frame panel facing north; South - A-frame panel facing south; East - A-frame panel facing east; West - A-frame panel facing west; Bench – horizontal bench (control).

[w] Least square means comparisons among orientation pairs (East vs. West = 0.8998 (4 WAI) and 0.0083 (8 WAI); North vs. South = 0.0155 (4 WAI) and <0.0001 (8 WAI)) estimated using the Simulated Method, α = 0.05.

[v] Least squares means comparisons between harvest dates (lower case in columns) using F-tests, α = 0.05. Least squares means comparisons among orientations (upper case in rows) using the Simulated Method, α = 0.05.

Table 10. Leaf dry weight for *Ocimum basilicum* 'Cardinal' L. based on orientation, Spring and Summer.

	Leaf Dry Weight (g)[z]				
	North[y]	South	East	West	Bench
Spring[x]	21 b[w]	29 ab	23 b	24 b	33 a
Summer[v]	41 b	44 b	40 b	45 b	59 a

[z] Only the orientation main effect was significant, α = 0.05.

[y] Orientation: North - A-frame panel facing north; South - A-frame panel facing south; East - A-frame panel facing east; West - A-frame panel facing west; Bench – horizontal bench (control).

[x] Spring - least square means comparisons among orientation pairs (East vs. West = 1.0000; North vs. South = 0.0191) estimated using the Simulated Method, α = 0.05.

[w] Least squares means comparisons among orientations using the Simulated Method, α = 0.05.

[v] Summer - least square means comparisons among orientation pairs (East vs. West = 0.5915; North vs. South = 0.8310) estimated using the Simulated Method, α = 0.05.

Table 11. Bi-weekly substrate solution pH and electrical conductivity (EC) for *Ocimum basilicum* ‘Cardinal' L. over time, Fall, Spring, Summer.

	Fall		Spring		Summer	
WAI[z][y]	pH	EC (μS/m)	pH	EC (μS/m)	pH	EC(μS/m)
2	-	-	-	-	5.7	2223
4	6.4	583	6.4	790	5.4	858
6	6.0	751	6.3	511	5.2	758
8	6.6	333	6.3	548	5.1	288
Significance	Q***[x]	Q***	NS	Q***	Q***	Q***

[z] Time main effect was significant, α = 0.05. No significant difference between production structures or orientation for A-frame structures.

[y] Weeks After Initiation (WAI): Fall: 4 WAI - 8 Nov. 2015, 6 WAI - 23 Nov. 2015, 8 WAI – 7 Dec. 2015; Spring: 4 WAI – 26 Mar. 2016, 6 WAI – 8 Apr. 2016, 8 WAI – 22 Apr. 2016; Summer: 2 WAI – 30 June 2016, 4 WAI – 13 July 2016, 6 WAI – 27 July 2016, 8 WAI – 17 Aug. 2016.

[x] Significant quadratic (Q) trends over time using orthogonial polynumerals, α = 0.001 (***). “NS” = not significant.

CHAPTER 5

Final Discussion

The purpose of this work was to examine how *Ocimum basilicum* ‘Cardinal’ L. (basil) plants responded to growing at different production structure orientations (N-S, E-W, and bench) and how that affected the biomass harvested on a monthly basis when grown on an A-frame vertical structure that utilized greenhouse space in an efficient manner. This work demonstrated that, regardless of orientation, the 2-panel A-frame vertical structure produced more LFW and LDW biomass compared to the horizontal, greenhouse bench occupying the same square footage.

Future research with vertical growing structures should include work with the drip irrigation system. Even though the system provided a uniform way to water each individual plant, the water stream tended to create divots or lines in the substrate after many irrigation cycles, washing away substrate and exposing roots close to the surface. Solutions might include the use of spray stakes, drip irrigation rings, or lower volume emitters, but increasing irrigation time.

Although previous work reported higher substrate solution ECs for pots on the A-frame structures compared to the horizontal bench, our work found no difference in ECs due to structure (Heath 2015). Heath reported EC levels three times greater in the vertical pots compared to the bench pots. This difference between Heath’s work and this current work may be due to better irrigation management in the current study. In Heath’s (2105) work, the irrigation was run three times daily for 3 minutes with no changes being made during the experiments. Water requirements during the current study were monitored on a daily and changes were made depending on the saturation level of the substrate. Additional work should investigate how irrigation frequency and duration impact the vertical structure pot ECs compared to pots on the benches. Fertilizer rates and EC levels should also be examined because this could lead to a decrease in the amount of fertilizer required for plants grown on the vertical structure while producing the same quality plant compared to the horizontal, greenhouse bench.

Plant pallet should be expanded to include more edibles and then ornamental, flowering plants. Research into how flowering plants, possibly even small shrubs, respond to being grown on the A-frame structure compared to being grown horizontally. The use of perennials, and how they respond to going dormant on the A-frame structure should also be included in future work. Expanding the plant pallet could lead to evaluation of plant performance on the structure when it is located outside, because up to this point all research conducted with the vertical A-frame production structure has been inside the greenhouse. Bringing the structure outside for experimentation could lead to the use of more woody type plant material in research.

Based on the fact that the plants grown on the A-frame structure grew vertically at about a 35° angle coming out of the pot, these A-frame structures are not ready to be used in major greenhouse production operations. However, future experimentation should be conducted on how the plants, once grown on the space efficient structure and are market ready, respond to having their pots reoriented vertically, like they would in a retail setting waiting to be purchased. Future work might include addressing: how long it takes for various plants to respond to phototropism, so the purchaser would never know the plant was grown on a vertical structure, making it identical to a plant grown on a traditional greenhouse bench. If marketable, the plant material a greenhouse grower could produce for the same square footage might be increased drastically.

While this novel, inexpensive, vertical growing structure should be used in future research before recommending it to major production growers as an alternative to the greenhouse bench, it could be appropriate for grower production in a small scale setting. Restaurant chefs with kitchen gardens might incorporate this structure into a garden setting for fresh produce. This inexpensive A-frame structure offers an innovative way to use a small amount of space in a big way, as proved by this research. This research demonstrates that the structure could be applied in growing herbs that would be harvested every few weeks. Outdoor classrooms in schools offer another venue in which this structure could be utilized. Schools could use this structure as a novel way to teach multiple subjects such as history, math, art, science, and horticulture all while doing so on a small footprint. Assisted living facilities could use this structure as a horticulture therapy tool for residents as a way to bring them outside into nature. The height and ease of access makes the structure a practical tool to facilitate participation in a gardening activity by those that are wheel chair bound or otherwise limited in mobility. Finally, the homeowner/renter with limited space, or a homeowner/renter desiring to use space more efficiently, would be well suited to use this A-frame vertical growing structure.

This novel A-frame growing structure, through further research and modifications, offers potential as an innovative tool for commercial growers. Hopefully the insight gained through this research, as well as future work, will aid not only greenhouse growers, but also introduce restaurant chefs, homeowners/renters, school teachers, landscape designers, builders, and horticulture therapist to a versatile, space efficient and simple vertical growing structure that offers the capacity to be used efficiently in a variety of ways.

Literature Cited

Heath, H. 2015. Evaluation of an A-frame vertical growing structure using: *Amaranthus tricolor*, *Beta vulgaris* ‘Detroit Dark Red’, and *Ocimum basilicum* ‘Cardinal’. Auburn Univ., Auburn, M.S. Thesis.