Evaluation of an A-frame Vertical Growing Structure Using: *Amaranthus tricolor, Beta vulgaris 'Detroit Dark Red',* and *Ocimum basilicum 'Cardinal Basil'*

by

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Abstract

Vertical gardening systems represent innovative, dynamic, and space efficient methods for producing fresh and nutrient-dense produce within highly populated cities and rural areas in a sustainable and economically efficient manner. The purpose of this work was to evaluate a novel, wood A-frame vertical structure that optimizes greenhouse production space compared to traditional bench-top greenhouse production. Three nutrient rich, herbaceous species were evaluated in this study: *Amaranthus tricolor*, *Ocimum basilicum* 'Cardinal Basil', and *Beta vulgaris* 'Detroit Dark Red'. Experiments were conducted in May and July 2014 comparing the A-frame to traditional, horizontal greenhouse bench-top production methods using *Amaranthus tricolor* and *Ocimum basilicum* 'Cardinal Basil'. *Amaranthus tricolor* plants grown on the south facing panel of the A-frame structure performed best with respect to plant height, growth indices (GI), total leaf area, and total shoot and foliar fresh weights. Similarly, with *Ocimum basilicum* 'Cardinal Basil' plants grown on the south facing vertical panel had higher values for plant height, leaf area index, and total shoot fresh and dry weights when compared to those grown on the horizontal bench-top or north facing panel of the vertical structure. Plants for both species grown on the north facing vertical panel of the A-frame structure yielded larger leaves than those of plants on the south facing panel or horizontal bench-top. Experiments using *Beta vulgaris* 'Detroit Dark Red' were conducted in May 2014 and February 2015 using the same A-frame structures and greenhouse benches. In Experiment 1, *Beta vulgaris* 'Detroit Dark Red', plants grown on the south facing panel of the A-frame structure were greater than or similar to plants grown on the bench-top with respect to plant height, GI, beetroot dry and fresh weights, and root width and circumference. During the second experiment, plants grown on the south facing panel of the A-frame structure had the greatest plant height, GI, total leaf area, foliage and beetroot fresh and dry weights, beetroot width, beetroot length, and beetroot circumference compared to plants grown on the north facing panel of the vertical structure or those on the bench-top. For all species in all experiments, substrate electrical conductivity (EC) readings were higher for containers that were on the A-frame structure, regardless of exposure, compared to bench-top pots.

This document also provides the instructions and components required to build the wood A-frame vertical growing structure evaluated in this study. A current cost estimate and comparison to two commercially available vertical structures was completed, and are discussed.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Global shortage of arable land, a continuous increase in population, and prevalent hunger around the world are major indicators expressing the necessity for researching and establishing alternative methods for growing food crops in a sustainable manner. The Food and Agricultural Organization's (FAO) (2014) estimates concerning global hunger indicate that the number of chronically undernourished people has decreased by more than 100 million over the past decade. Despite the decrease in global hunger, there are currently 805 million people that suffer from chronic hunger throughout the world, and this number is continuing to increase due to economic and political systems in the world (World Food Programme, 2015A). The majority of those that suffer from chronic hunger reside in under developed countries. Furthermore, the World Food Progamme (WFP) states that hunger and malnutrition are the world's leading health risks. Both hunger and malnutrition contribute to higher death rates each year than AIDS, malaria, and tuberculosis combined (World Food Programme, 2015B). World hunger is a problem that can be solved, and vertical gardening is one innovative and sustainable approach that can provide an accessible, inexpensive, and space efficient method for producing a variety of edible, nutritious food crops.

Growing plants vertically is not a new and trending idea, it is actually an ancient practice used throughout human history. The Hanging Gardens of Babylon, which dates back to the 6th century BC, is still recognized as one of humanity's greatest accomplishments owing to it's sophisticated engineering and extensive labor in regards to design and maintenance (Rakow and Lee, 2011). The term "vertical gardening" encompasses various forms of vertical greenery systems (VGS) such as green facades, green walls or living walls, and various vertical-growing structures. VGS are separated into two categories: green facades and living wall systems (LWS). The difference between the two categories is determined by the manner in which the plant material is grown (Perini and Rosasco, 2013). A green façade supports the growth of climbing plants, vining plants, and cascading ground covers (Growing Green Guide, 2015). Plant roots are established in the ground and are located at the base of a façade or supporting structure. LWS consist of various types of growing substrates that contain plant roots, which are suspended above ground and extend upward within a living wall system or structure. Typically, the structure or support system that holds the growing substrate and plant material is attached to a wall, hence the common term "living wall system."

With traditional vertical gardening, plant roots grow and extend underground. Several examples of traditional vertical gardening systems and structures include green facades, trellises, arbors, pergolas, and espaliers. In each of these traditional VGS, plant roots are located in the ground and near or at the base of a supportive structure, such as a building facade. The structure provides stability and support for the plant to cling and grow upward.

The major contributors to the increasing interest in vertical gardening focus on the following issues noted world wide: environmental enhancement of urban areas, an innovative method for providing readily available and fresh produce, maximizing limited outdoor space, and conserving arable land. The WFP states that there is enough food in the world for all people to receive the nourishment required for a healthy and productive life (World Food Programme, 2015A). Despite the fact that there is enough food in the world to feed the entire human population, food availability, which is an imperative aspect in food security, is hindered by income, food prices, gender, and infrastructure, such as railways and paved roads, especially in under-developed countries (Food and Agricultural Organization: Hunger Dimensions, 2012).

Concepts derived from urban and sustainable agriculture provide innovative methods that aim to combine food, production, and design in order to provide fresh, readily available food in and on buildings within urban areas (Specht et al., 2013). VGS are a form of urban, sustainable agriculture (Specht et al., 2013), and such systems can provide solutions for two major global issues: shortage of arable land and limited food availability. VGS have been utilized for the past 2,000 years for aesthetic and economic purposes, and food production (Köhler, 2008). VGS can help meet the needs of world hunger and limited food availability by maximizing limited space in order to provide readily available, fresh produce and vegetation that is produced in a cost and space efficient manner. By supplying under-developed and developing countries, and highly populated cities with an innovative and versatile LWS that can be easily manipulated and designed to meet consumer's needs, food supply may increase, along with human health.

The concept of vertical gardening requires additional research for current and future urban societies and cities, especially since a wide range of professional and academic disciplines have recently become interested in the topics of sustainable agriculture and urban food production (Specht et al., 2013). Many forms of VGS utilized today are far more advanced than systems used merely forty years ago. Köhler (2008) states that green facades have been a topic of discussion for 100 years, but nonetheless, numerous research inquiries and opportunities still exist. A few areas of vertical gardening that require supplementary research include: establishing educational and interpretational awareness of VGS (Wong et al., 2010), utilizing irrigation to improve evaporative cooling in green facades (Köhler, 2008), and establishing a business model based on the concept of vertical farming-growing plants in greenhouses that extend upward and are built atop buildings (Fletcher, 2012).

Presently, there is no published research concerning the production of food crops on a cost and space efficient A-frame VGS. The purpose of this work is to introduce and evaluate the performance of a wood, A-frame vertical growing structure that is durable, eco-friendly, resource-efficient, and adaptable. Researchers are seeking alternatives for food production systems since there is increasing competition for land and water resources (Specht et al., 2013). VGS, specifically the system used in this study, offer potential solutions for future food production, especially since such individuals view VGS as the future of sustainable agriculture.

Definition of Terms

The following terms are given and operationally defined in order to assist in clarification for this study:

1. Undernourishment: an insufficient amount of food intake not meeting the dietary energy requirements for an active and healthy life (Food and Agricultural Organization, 2014A).
2. Arable land: land that is suitable for the cultivation of crops (Campbell, 2011).
3. Urban agriculture: the practice of cultivating, processing, and distributing food crops and occasionally raising animals within a small space in a village, town, or city for immediate consumption or sale in local markets (Ahronowitz, 2003).
4. Zero-acreage Farming (ZFarming): represents numerous sub-types of urban agricultural methods geared towards food production, such as rooftop gardens, rooftop farms, rooftop greenhouses, indoor farms, edible green walls, and vertical farms built as multistory greenhouses (Specht et al., 2013).
5. High-density vertical growing systems (HDVGS): area sustainable alternatives to traditional agriculture production methods that are designed to grow plants vertically, or

stacked, in order to increase production yield large in a limited amount of space (Okumura, 2014).

6. Living wall system: plants that are grown vertically in a structure fastened to an indoor or outdoor wall surface that contains layers of vegetation within a waterproof membrane, which is located between the wall surface (Dunnett and Kingsbury, 2008).
7. Horticulture: the cultivation of a garden, orchard, or nursery; the cultivation of flowers, fruits, vegetables, ornamental plants, the science and art of cultivating such plants, from hort (us) garden + (agr) iculture (Dictionary.com, 2013).
8. Hydroponics: the method of growing plants by way of balanced essential nutrient solutions providing the plant with the necessary mineral and water requirements (Dunnett and Kingsubry, 2008).

LITERATURE REVIEW

The literature reviewed in this chapter focuses on the topic of vertical gardening, particularly the history and evolution of vertical gardening, followed by the benefits of vertical gardens. VGS designs and trends, as well as world hunger and arable land is also discussed. The final section is comprised of a summation of the literature reviewed, which encourages the implementation of VGS into societies around the globe as an approach to aid in global hunger and promote human and environmental well being.

1. History of Vertical Gardening
2. The Evolution of Vertical Gardening: Designs and Trends
3. Benefits of Vertical Gardens
4. Arable Land and World Hunger
5. Summary of Literature

History of Vertical Gardening

Overview: The earliest recorded gardens date back to the year 2065 BC, while the earliest record of importing plants from one country to another is documented as early as 1100 BC (Robinson and Zajicek, 2005). Ancient gardens were created and designed by monarchs and rulers, religious and elite figures with political power and wealth. Approximately 2,000 years ago, in the Mediterranean region, the earliest form of vertical gardening was utilized in small, confined yards of palaces, which were covered in vines (Köhler, 2008). Several of the earliest gardens are recognized as "wonders of the world," such as the Hanging Gardens of Babylon in Nineveh, created in 700 BC, and the Taj Mahal in India, created in 1632 CE. In Central Europe, 500 years ago, the most popular climbing plants in castles and villages were woody vines, along with fruit espaliers and climbing roses (Köhler, 2008). For thousands of years, vertical gardens have continued to serve as a source of food, educational and medicinal purposes, or economic value.

The notion of growing vegetation on walls and supportive structures is documented throughout history, and continues to produce positive influences on human welfare and the environment. Modernized vertical gardens, such as LWS, have progressed and changed since the early 1900s (Living Walls and Vertical Gardens, 2011). In the 1920s, the British and Americans encouraged a garden city movement involving the integration and utilization of plants and garden features, such as pergolas, trellis structures, and self-climbing plants into their respective societies. During the early 1980s and onward, Central Europe exhibited a growing interest in environmental issues, which resulted in the vision of entwining nature within urban areas (Köhler, 2008). In many German cities, for example, the development of incentive programs for green facades arose; some of which supported tenant initiatives for establishing and maintaining climbers in backyards and on facades. Since the 1980s, research on VGS tends to focus on: plants ability to mitigate dust particles, evaporative cooling effects of plants, the insulating effects of plants on building facades, as well as creating habitats for urban wildlife- birds, spiders, and beetles. According to Köhler and Schmidt (1997), between 1983 and 1997, the incentive programs resulted in the installation of about 2,643,444 ft^2 (245,584 m^2) of green facades. During this time frame, the interest in VGS was seemingly limited to urban areas across Europe.

In Europe, vertical greenery systems are no longer considered to be a novel idea within their society and urban areas. Köhler (2008) hints that the once plentiful, ongoing research activities involving VGS is now waning in Europe. Fortunately, there are many countries, such as the U.S., Canada, and Japan, showing increasing interest in the idea of these systems. Presently, Japan is the global leader in developing VGS (Wong et al., 2010).

Horticulture provides essential and indispensible benefits for the entire world. VGS can continue to serve the present and future societies of the world, and many systems do so by combining horticultural science with urban planning, design and architecture, ecology and landscape planning, and economic and social sciences (Specht et al., 2013). With such a diverse range of disciplines involved in urban agriculture and vertical gardening, the designs and techniques of living wall systems vary greatly.

The Evolution of Vertical Gardening: Designs and Techniques

Vertical gardening systems have progressively evolved throughout time. Such systems began as a form of aesthetic luxury, but the benefits and potential of vertical systems were realized early on, and our ancestors began to test and develop a multitude of uses for vertical greening and vertical food production. The evolution of vertical gardening began with green facades and support structures (trellises, pergolas, arbors). By 500 BC, fruit espaliers were created (Köhler, 2008). During the early 1920s, Europe and America "resurrected" the use of green facades for the purpose of enhancing the visual appeal of urban areas and to benefit the environment. During the 1980s, green facades began to be used for ecological enhancement within cities. The use of green facades in urban areas led to the emergence of numerous types of living walls, fences, and structures that are now designed and constructed from an assortment of materials, such as metals, woods, plastics, and wires. The development of vertical indoor farms or greenhouses, along with food production on LWS and structures is a very recent form of urban agriculture. As a result, there is very little research about vertical greenhouses and living wall systems, especially in relation to food yields, suitable plant material, urban and rural benefits, and so on. However, many benefits of vertical walls and farms outweigh current disadvantages, and it seems the world is in need of a novel and sustainable form of agriculture that requires little or no land in order to provide fresh, nutritious food in areas with little to no cultivatable land.

Green facades, trellises, arbors, pergolas, and espaliers represent the oldest and most traditional style of all vertical garden systems and designs. A green façade is a system that allows for and supports the growth of climbing plants, vining plants, and cascading ground covers (Growing Green Guide, 2015). Plant roots are established in the ground and are located at the base of a façade or supporting structure. Trellises, arbors, and pergolas are used in a similar fashion. Each of these traditional methods can be constructed with wood, metal, plastic and fiberglass, rope, cable, and/or wire (Köhler, 2008). Espaliers also use plant material that is established and grown in the ground, but the main difference in this system is the framework, which is designed to train tree trunks and branches to grow a certain way (Dictionary.com, 2015). Traditionally, fruit trees and shrubs were used for espaliers, but today's society also uses ornamental trees and shrubs.

The key difference between a green facades and a living wall system (LWS) is defined by the manner in which the plants are grown (Perini and Rosasco, 2013). Green façades provide stability and support for climbing plants or hanging shrubs to cling to and grow upward. Plants grown on green facades are either established directly in the ground or in containers placed at the base of the structure, or in containers on a wall or building facade (Feng and Hewage, 2014). LWS, or green walls, grow and establish plant material using various techniques. LWS can be designed with planter boxes or modular panels, where each planter box contains its own growing substrate, or each modular panel is pre-vegetated using substrate (Ottéle et al., 2011). Such systems are attached to a structure or wall frame (Feng and Hewage, 2014). Green facades represent the traditional method of vertical gardening, while LWS utilize various contemporary growing methods differing in appearance and design techniques. Examples of actual wall materials that can be utilized for growing vegetation vertically include: dry stonewalls, modular and stacked construction walls, mortared walls, and vegetation mats (Dunnett and Kingsbury, 2008). Living walls, and plants in general, possess the ability to soften vast amounts of infrastructure and hardscapes. For instance, The Rubens at the Palace, a 1912 luxury hotel in London, implemented a rather large living wall system designed by Green Roof Consultancy, a company based in London. The living wall covers nearly 3,768 ft^2 (350.06 m^2) and contains plantings of ferns, ivy, and flowering plants. In addition to the immense size of this living wall, it is quite amazing that a framework of planters weighing 16 tons could be installed on the brick walls of a hotel built in 1912. According to engineering reports, the brick walls were quite capable of supporting the heavy framework, and no additional reinforcement was required prior to installation (Wilcox, 2013).

One of the newest, and seemingly subtle forms of vertical gardening is the vertical indoor farm, or vertical greenhouse. A vertical farm is basically a stacked greenhouse production facility that is typically built on top of an existing building, but can also be built at ground level and stand-alone. Vertical farms are located in various areas around the world such as Sweden, Singapore, the United Kingdom, and the United States. Many of these farms are supported by non-profit organizations hoping to stimulate environmental causes and create local jobs while others are for-profit businesses aiming to meet the demand for local produce or are subsidized by governments trying to improve domestic food security (Fletcher, 2012). One prime example of a vertical greenhouse is the Local Garden, located in Vancouver, Canada. The vertical greenhouse is built on top of a city-owned multi-story parking garage that occupies twenty-two parking spaces and grows crops via a patent-pending Verticrop conveyor system. The patent pending system allows four hectares worth of produce to be grown on approximately 3,982 ft^2 (0.037 ha) (Berman, 2013). The company produces 1,000 to 1,500 pounds (453.59 to 680.39 kg) of hydroponically grown leafy green vegetables every week, year round. Once the produce is harvested, it is delivered to local restaurants and retailers within 24 hours.

The examples of vertical gardening designs and techniques represent a mere fraction of the versatile, advancing systems that exist. The chief principle of modern vertical growing systems focus on striving to create sustainable and resourceful approaches that provide agricultural advancement, fresh food, clean environments, and also introduce and connect people to nature and beauty. Vertical gardens are no longer a thing of the past; they are becoming an integral part of society’s future.

Benefits of Vertical Gardening

Vertical gardening is an innovative and versatile, space efficient method for growing edible and ornamental plants that continues to reveal numerous benefits for human health and welfare, the environment, and economies worldwide. Researchers, innovators, green industry companies, manufacturers, and consumers are realizing why urban agriculture, sustainable agriculture, and living wall systems are becoming so popular. These companies and individuals are realizing the innumerable benefits of growing plants vertically. Vertical gardening systems can provide sustainable alternatives for food production, increase food availability in urban areas (Specht et al., 2013), as well as under-developed countries, and enhance urban environments, to name a few.

Human health and welfare benefits: Humans have been reaping the benefits of gardening for thousands of years. During ancient times, gardens were considered to be a luxury, a space of beauty and relaxation for the wealthy and elite, such as rulers, religious leaders, and political figures (Rakow and Lee, 2011). Research indicates that the gardening process produces unintentional, beneficial effects on a person's feelings, thoughts, and emotions (Lewis, 1996). These benefits are especially realized for people who live in highly industrialized cities that contain large populations, traffic noise, and construction, which can cause mental fatigue.

Furthermore, the emotional benefits of gardening create therapeutic aspects for people (Kaplan and Kaplan, 1982; Relf, 1992; Ulrich and Parsons, 1992). In urban areas, vegetation greatly improves the visual and physical environment. The most visible portions of infrastructure in urban settings are building facades and roads. In addition to street trees and areas of turf, living wall systems can further enhance the visual appeal of urban areas, benefit people, and the environment, as well as encourage plant and people interactions that foster human connections to gardening and nature.

Introducing greenery into urban areas is commonly recognized as a therapeutic benefit to humans. Take for instance hospital patients. Ulrich (1983) discovered that hospital patients able to view a tree from the nearest window recuperated quicker than patients who could not view a tree from the closest window.

In regards to general welfare benefits, such as public health, plant health and aesthetic benefits, LWS exhibit various advantages; however, many advantages are based on the time of year, plant material utilized, relationships between plants, and placement and orientation of the systems (Valesan and Sattler, 2008). Dr. Manfred Köhler's research illustrates numerous benefits attributed to vertical gardening that relate to human and environmental welfare such as the removal of car exhaust particles in city air, reducing annual dust fall by 4%, and generating energy conservation on north facing green faces by up to 25% (Priesnitz, 2006).

A sense of self-sufficiency and empowerment can come from growing one's own food. LWS, as well as other types of VGS, are capable of producing local, fresh food to urban, suburban, and rural areas around the world. Increased access to fresh, nutritious foods promotes human health and well-being, which can lead to a more productive economy. The availability and access to fresh food persists as a global issue, especially for recovering economies and developing countries. Even if adequate food supplies are available and accessible, specific population groups continue to suffer from acute undernourishment (Food Agricultural Organization, 2010). According to the Food Agricultural Organization (2010), an abundance of food that is easily accessible does not always resolve all effects of undernourishment. Nutrient-dense foods such as grain crops, roots, and tubers, fruits, coupled with timely detection are the two treatments for undernourishment and acute malnutrition (World Hunger Organization, 2015B). It is important to remember that the chronically hungry, undernourished people can be found all over the world, and not just in rural, developing countries. LWS can help provide the 805 million people suffering from chronic hunger (World Food Programme, 2015A) with a sustainable cost efficient, method for producing edible crops that possess high nutritional value.

Environmental benefits: Living walls impart a wide variety of private and public benefits, which in turn enhance the ecosystem. LWS also help to conserve energy in urban areas and reduce the negative effects of urbanization (Environmental Landscape Technologies, 2015). The use of LWS, and plants in general, create positive impacts for both interior and exterior environments. This is especially beneficial to urban areas exposed to high amounts of air pollution. The major components of air pollution from vehicles and factories are heavy metals that are toxic in low concentrations. Ozone, which is a major component of smog that is formed on hot, sunny days, causes an increase in temperatures and is a byproduct of highly urbanized areas (Dunnett and Kingsbury, 2008).

By introducing LWS into urban areas, vegetation can help purify the air by filtering out or absorbing airborne particles that land onto surfaces of leaves and stems. Gaseous pollutants are absorbed and sequestered inside plant tissues, thus, removing and isolating air particles (Dunnett and Kingsbury, 2008). Additional air contaminants removed by vegetation include formaldehyde, nitrogen dioxide, benzenes, and carbon monoxide (Wolverton et al., 1989).

In addition to toxic air pollution, the urban heat island effect is another problematic result of urbanization. As the amount of infrastructure increases in an area, a "specific urban climate" is formed and is defined by higher night temperatures and humidity, which is an effect of restricted airflow, polluted air, and heightened concentrations of air particles (Dunnett and

Kingsbury, 2008). When temperatures increase, the probability of smog increases, which can result in health disorders such as asthma and additional respiratory issues. Urban heat island effect is caused by many factors. A few examples include large quantities of structures with heat absorbing capabilities, lack of evaporative cooling surfaces and vegetation, cumulative surface runoff, and air pollution (Dunnett and Kingsbury, 2008), along with heat produced by vehicles, air conditioners, and factories (Wong et al., 2010). All of these factors create higher urban air temperatures than those in suburban or rural areas (Dunnett and Kingsbury, 2008).

Fortunately, the beneficial impact of LWS and other uses of vegetation on buildings can accrue to enhance an entire city's environment (Dunnett and Kingsbury, 2008). In a green façade study by Thönnessen (2002) the dispersal of micro and macronutrients on and in leaves of Boston ivy were exposed to air pollutants within an inner city street in Düsseldorf, Germany. The study tested emissions from car exhaust and fine dust from car brakes and tires. Leaf samples were taken from five different height levels of the façade (2.0, 4.5, 7.5, 10.5, and 13.5 meters above ground, or 6.6 ft., 14.8 ft., 24.6 ft., 34.4 ft., 44.3 ft.). Results showed that the greatest amount of pollution accumulated on leaves located at 2 m (6.6 ft.) above ground during the fall months and in the 7.5 m (24.6 ft.) above ground area as well. More importantly, the research showed that the green facades are highly effective for capturing dust in urban environments.

Green roofs and LWS are also sources of sound insulation and can protect roof or wall membranes. Vegetation, trapped air, and growing medium can also heighten the efficacy of sound insulation on buildings by absorbing or reflecting sound frequencies (Environmental Landscape Technologies, 2015). According to Environmental Landscape Technologies Inc. (2015), living wall systems and green roofs can improve thermal performance by reducing the amount of heat that travels through a roofing system by 70-90% during the summer and 10-30% in the winter.

Although, one must recognize that such benefits are dependent upon the type of vegetation and the depth of growing medium (Environmental Landscape Technologies, 2015). The effectiveness of differing types of vegetation also varies during the winter and summer (Dunnett and Kingsbury, 2008). Of course, this limitation, and many other issues may change in the future since alternative and sustainable solutions for horticultural crop production continue to advance.

Economic advantages: Various LWS provide resourceful, versatile, and sustainable design capabilities that enable them to be used for many applications and require involvement from a wide range of career fields. The idea of growing vegetation vertically has increased over the past 20 years due to the evolution of realistic design techniques (Fletcher, 2012), making vertical gardening a more practical and economical growing method.

Growing vegetation vertically positively influences economic issues such as reducing the cost of transporting food, providing fresh, local produce to consumers, and effectively reducing the heating and cooling costs of buildings in urban areas. Owing to the flexibility of numerous design techniques, vertical gardening can be a scalable, efficient method for producing crops and vegetation for green facades. Contrary to some critics, several vertical farms and LWSdo not require expensive equipment and can be designed to suit commercial and non-commercial needs. This type of production can help utilize certain vacant areas and are designed to save space. Many vertical systems are designed for hydroponic and aeroponic systems, which eliminate the need for soil (Fletcher, 2012).

As for food production, vertical gardening systems, along with other sustainable agriculture systems, exemplify a new approach for contributing to the provision of fresh, healthy produce for consumers (Brock, 2008). One study that reinforces VGS as a resourceful form of urban agriculture explains how Zero-acreage Farming (ZFarming) contributes to sustainable urban food production, coupled with climate mitigation and efficient use of resources (Specht et al., 2013). The term “ZFarming” is a subtype and specification for general urban agriculture that represents numerous types of agricultural methods geared towards food production, such as rooftop gardens, rooftop farms and rooftop greenhouses, indoor farms, edible green walls and vertical farms (Specht et al., 2013). The International Union for Conservation of Nature’s (IUCN) was referenced for the description of sustainability (2006), which involved examining three overlapping “pillars” (environmental, social, and economic), with sustainable development serving as the focus of the three pillars. The study collected and reviewed 96 articles involving rooftop gardens/farms, rooftop greenhouses, and indoor farms. The articles were quantitatively and qualitatively analyzed. Results revealed that ZFarming is a very new subject matter, and it is currently in the preliminary stages of research, conception, and application. Literature also showed that the main goal and motivation of ZFarming is food production. Ultimately, the study found that current literature suggests that ZFarming holds great promise for each of the environmental, social, and economic pillars, and requires knowledge and input from diverse career fields.

Another advantage of VGS involves connecting consumers to food production. Consumers desire fresh, local produce and more participation in the food production chain (American Planning Association, 2007). In spite of this, the perpetual increase of industrialization and agribusiness has caused the distance between farms and markets to increase (Specht et al., 2013). Fortunately, vertical gardening can help reduce the distance between farms and consumer markets. According to Laumer (2008), high-density VGS (HDVGS) are diverse, and can be utilized in urban and suburban areas, as well as rural, and even desert areas. Laumer (2008) also claims that HDVGS can produce about 20 times more produce than the average field crop production. This is a significant increase in food production that could help provide fresh produce to urbanites and to the millions of individuals that reside in underdeveloped countries suffering from chronic hunger. Nevertheless, one must recognize that food production and yield is dependent upon the design type and scale of a HDVGS, as well as the plant material, type of substrate (Environmental Landscape Technologies, 2015), and environmental conditions. For instance, most VGS are used to enhance and soften hardscapes in urban areas and consist of foliage or flowers. Other VGS are designed and used specifically for greenhouse production. Herbs and small leafy-greens, both of which are grown for foliage, are typically produced in a greenhouse setting.

Constraints and Limitations of Vertical Gardening

Despite the benefits and advantages vertical farms and systems provide there are constraints and limitations. Many of the limitations are dependent upon the type of vertical system, such as a vertical greenhouse or living wall. The point is that not all VGS have the same constraints and limitations, and not all have the same benefits and advantages.

For some VGS, the overall weight of a structure can be problematic. For example, a vertical greenhouse farm may or may not be able to meet the required load bearing capacity of the building or foundation on which it is to be placed. Similarly, load-bearing capacity of older buildings especially, may be an issue for implementing living walls. In most cases, it is quite costly to re-construct a building’s supportive framework. Also, the total weight of a structure includes the substrate, plant material, water, irrigation system, and in some cases, wind velocity and snow load (Dunnett and Kingsbury, 2008).

Budget development and cost estimations epitomize another drawback for many forms of VGS (Carpenter, 2008). Hans Hassle, the chief executive of Plantagon (a vertical farm company) states that “it’s much more expensive, of course, to build a greenhouse vertical than to build a normal greenhouse” (Fletcher, 2012). To help counteract the building costs, this vertical farm is equipped with energy saving measures, which helps to reduce energy consumption by 30%-50% (Fletcher, 2012). In regards to green facades and LWS designed for outdoor areas, energy costs are generally not an issue. The costs associated with LWS are mainly attributed to installation costs, including methods, project, scale, and watering methods (Wong et al., 2010). In Wong’s study (2010) involving the perception of vertical greenery systems in Singapore, five groups of participants (architects, landscape architects, developers, government agencies, building occupants) in a survey questionnaire rated concerns of vertical greenery systems. Survey responses indicated that high maintenance costs were major barriers to the expansion of vertical greenery systems.

Current research on suggested plant material for vertical systems is extremely limited, but is essential for properly designing and developing LWS (Mårtennson et al., 2014). Presently, green facades represent a large portion of available research and literature, most of which is dominated by botanical descriptions (Köhler, 2008). Additionally, the type of vegetation used is also limited to the type of vertical system. For example, vertical farms tend to produce leafy greens and herbs, while the majority of LWS serve as support systems for climbing plants or lightweight plants, and are typically designed to hold plants with shallow root systems. Subsequently, distorted growth may occur in plants that are grown vertically. For example, stems and leaves are phototropic and geotropic (Dunnett and Kingsbury, 2008). Thus, stem bending can be an issue. Additionally, plant material and plant performance will vary based on climate, region, and environment.

Köhler (2008) argues that a large portion of technical and research literature is fixed upon problematic issues that arise from improper planning or implementation, and how these issues could be avoided for VGS. Respectively, the research associated with vertical systems is still in its initial stages (Specht et al., 2013). As this topic of interest continues to develop, particularly for sustainable urban food production, future research will address many disadvantages or constraints for various types of VGS.

World Hunger and Arable Land

A major concern that propels the notion of urban food production comes from diminishing access and availability of arable land (Specht et al., 2013). The shortage of arable land is caused by a number of social and environmental issues comprised of climate change, soil constraints and degradation, urbanization and unequal distribution of arable land (Campbell, 2011). Approximately 2.7 billion hectares (6.67 billion acres) of potentially cultivatable land exists, and the majority of this land is located in Sub Saharan Africa, and South and Central America. Out of the 2.7 billion hectares (6.67 billion acres) of potential cropland, 1.8 billion hectares (4.45 billion acres) concentrated in only seven developing countries: Angola, Argentina, Brazil, Bolivia, Colombia, Democratic Republic of Congo, and Sudan. Therefore, one can conclude that the Sub-Saharan and South and Central Americas possess the greatest potential for developing and preserving over half of the world's most profitable land (Campbell, 2011).

For smaller or less densely populated areas worldwide, available land or space is not an issue, but for many large cities, open spaces are rare. Many highly urbanized areas that have limited available space must often decrease or restrict the size of food production units, which results in smaller production yields. Fortunately, the use of low-space technologies holds great opportunity for producing food in confined areas (Dubbeling, 2011). These low-space technologies can also be utilized in developing countries experiencing poor accessibility or a shortage of arable land, and can help to conserve arable land. Latin American countries, for instance, are burdened by unequal land distribution, which often leads to the uneven distribution of food since produce is frequently exported for profit instead of giving inhabitants the opportunity to buy locally grown food (Campbell, 2011). Furthermore the FAO (2012) states that the majority of food consumption comes from locally grown food, but the problem is not everyone has access to locally grown foods or sufficient and steady income to purchase local or imported foods. Economic affordability, food prices, food availability, and physical access are major factors that either help or hinder food accessibility and security (Food and Agricultural Organization, 2012). What's more, global food and agricultural trade has increased by almost five fold throughout the past 50 years. Thus, when local production does not meet the demands of the local areas, economic trade is utilized to help compensate, which means poor countries must import high priced foods in order to supply residents. Much like the unequal distribution of global arable land, trade is also unevenly distributed, and this is one major contributor to world hunger (Food and Agricultural Organization, 2014B).

In order to eliminate world hunger, a unified tactic is needed and requires the following: increased investments from public and private sectors to increase agriculture production; improved access to inputs, services, technologies and markets; promoting rural development; specific nutrition programs, especially for children and mothers with micro-nutrient deficiencies (Food and Agricultural Organization, 2015). This plausible solution can also be modified and applied to hungry individuals that reside in developed countries. Domestic agriculture production continues to be the chief provider of employment, income, and food in rural areas worldwide, which demonstrates the importance for developing sustainable forms of food production (Food and Agricultural Organization, 2014B). Adequate food sources have been and will likely always be a serious issue. Aid from existing and future research that is coupled with the development and implementation of sustainable forms of urban and rural agriculture production can significantly help feed the hungry, increase human and environmental health, improve economic prosperity, and conserve remaining arable land.

LWS possess a considerable amount of innovative potential, particularly in areas with limited or non-existent arable land, or in areas where arable land or flat space is at a premium (Dunnett and Kingsbury, 2008). Furthermore, LWS can be designed to suit the needs of urban and rural areas, and can be constructed with a variety of materials that are cost efficient and recyclable. Most importantly, these systems can help conserve valuable land and water resources, reduce food miles, and produce 20 times more yield than the normal yield from field crops (Laumer, 2008).

Summary of Literature Review

Over 7 billion people exist in a world that encompasses merely 2.7 billion hectares (6.67 billion acres) of potentially cultivatable land. By 2030, the United Nations (2015) estimates that the world population will increase to 8.5 billion. A multitude of solutions are needed to feed current and future populations. One of the most important solutions involves research that is focused on developing sustainable forms of agricultural production that can be modified and employed to suit the needs of urban and rural areas around the globe.

VGS have shown great progress in production methods for the past two to three decades, and many of these systems are already making a difference in peoples’ lives all over the world.

LWS represent one form of vertical gardening that continues to advance and attract much interest from those in agriculture and horticulture sciences, urban planning, ecology, landscape design, architecture, economics and social sciences (Specht et al., 2013). Clearly, there is potential for LWS, and vertical farms as well, if such a wide array of researchers and educators are working together to create more sustainable and properly managed forms of agriculture for urban and rural areas. The Food and Agricultural Organization (2014B) conveys the importance of increasing investments from public and private sectors in order to increase agriculture production. Further research and literature pertaining to living walls and vertical systems can help to develop and implement sustainable forms of urban and rural agriculture production. Research that focuses on creating innovative and resourceful approaches for producing fresh and healthy food crops can help feed the 805 million hungry and undernourished people in the world, increase human health and welfare, aid in climate mitigation, benefit economies, and conserve precious natural resources.

The purpose of this study was to create, test, and compare an inexpensive wood, A-frame VGS to traditional, horizontal greenhouse bench-top production methods in order to better understand the value of growing plants vertically. Goals of the study included establishing supplemental research to previous work associated with VGS, broadening plant material selections for such systems, and most importantly exploring a resourceful agriculture production method with the ability to yield fresh, nutrient-rich produce for people in urban and rural areas around the world.

Objectives

The purpose of this study was to compare and evaluate three edible container-grown crops placed in an inexpensive A-frame vertical structure to crops grown traditionally on a horizontal greenhouse bench. A specific goal of the study was to create a more economical and sustainable method for producing edible plants within a limited amount of space. The following three treatments were examined:

1. Plants grown traditionally on raised green house benches.
2. Plants grown on an A-frame vertical structure with wall panels facing north.
3. Plants grown on an A-frame vertical structure with wall panels facing south.

Broad objectives for the entire study include: 1) comparing plant performance and yield including: visual quality, total dry weight and fresh weight of foliage, substrate solution electrical conductivity (EC) and pH of medium, and foliage color to plants grown with traditional, horizontal growing techniques, 2) creating a cost analysis for constructing an A-frame vertical growing structure, 3) comparing crop production yield of an A-frame vertical structure to the traditional growing method in respect to square footage, and 4) investigating the potential of growing edible plants vertically with the hope of providing sustainable growing methods for the horticulture and agriculture industry and to aid in human welfare.

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CHAPTER II

Evaluation of an A-frame Vertical Growing Structure for *Amaranthus tricolor* L. and *Ocimum basilicum* L. 'Cardinal Basil'.

Abstract

Vertical gardening systems represent an innovative, dynamic, and space efficient method for producing fresh and nutrient-dense produce within densely populated cities, as well as rural areas, in a sustainable and economically efficient manner. Two experiments were conducted during May and July 2014 where an A-frame vertical growing structure was evaluated and compared to traditional, horizontal greenhouse bench-top methods growing *Amaranthus tricolor* and *Ocimum basilicum* 'Cardinal Basil'. The experiments were conducted in double-wall poly greenhouses. Due to similar results, the data that was collected for Experiments 1 and 2 were combined for analyses. Results from both experiments determined the vertical structure to be a suitable method for producing *Amaranthus tricolor* and *Ocimum basilicum* 'Cardinal Basil'. A randomized complete blocks design was used and consisted of 4 blocks. One block had one vertical structure and one greenhouse bench, both of which occupied 16 ft^2 of greenhouse production space. Treatments were: 1) plants grown traditionally on raised greenhouse benches 2) plants grown on an A-frame vertical structure with wall panels facing north, and 3) plants grown on an A-frame vertical structure with wall panels facing south. Treatment 3 yielded the greatest height, growth index (GI), leaf surface area, total shoot and foliar fresh weight for *Amaranthus tricolor*. For *Ocimum basilicum* 'Cardinal Red', Treatment 3 resulted in the greatest plant height, leaf are index (LAI), and total shoot and foliar fresh and dry weight. Treatment 2 yielded the greatest LAI per leaf (leaf surface area). Treatments 2 and 3 resulted in the highest

GI, and Treatments 1 and 3 produced the highest leaf number per plant for *Ocimum basilicum* ‘Cardinal Red’.

Index words: *Amaranthus tricolor* L.*,* *Ocimum basilicum* L. ‘Cardinal Basil’, sustainable crop production.

Significance to the industry

There is a global need for evaluating and implementing alternative and sustainable agricultural production methods in order to conserve irreplaceable natural resources such as arable land. Vertical gardening systems possess the capabilities of producing fresh, nutrient-dense foods in an economically efficient and sustainable manner within limited spaces in urban and rural areas. This study evaluated and compared edible, container-grown crops using an inexpensive A-frame vertical growing structure to traditional, horizontal greenhouse bench-top production methods. The study revealed that one A-frame vertical structure was capable of increasing yields by 2 to 3 times in a 16 ft^2 production space compared to crops grown traditionally on greenhouses benches that occupied the same area. The study provides insight for those involved in agricultural sciences, urban and landscape planning, design and architecture, ecology, and consumers searching for alternative and economically sustainable production methods that can be utilized in a variety of settings.

Introduction

Vertical gardening systems exhibit great potential in serving as an alternative method for sustainable food production. Due to increasing interest and concerns for enhancing urban environments, reducing food miles by providing fresh and nutritious produce in urban areas, maximizing space, and conserving arable land, vertical gardening systems are developing all over the world (Zulu, 2013). Additionally, the availability and access to fresh, nutrient-dense foods persists as a global issue, especially for recovering economies and developing countries. Food that is abundant and easily accessible does not omit malnutrition or nutritional deficiencies (WFP, 2015); this statement applies to individuals in the United States and other developed countries as well. People who are chronically hungry and undernourished can be found all over the world, and not just in rural, under-developed countries. There are 805 million people in the world suffering from chronic hunger every day (WFP, 2015). Sustainable, high-density vertical gardening (HDVG) can help combat hunger around the world in both urban and rural settings by providing easy to grow, nutrient-dense foods. Previous work with vertical gardening systems mainly focuses on reducing climate mitigation and the urban heat island effect (Dunnett and Kingsbury, 2008), increasing building insulation (Perini and Rosasco, 2013), and conducting cost-benefit and lifecycle analyses for green facades and living wall systems on buildings (Perini and Rosasco, 2013; Feng and Hewage, 2014). Currently, there is little research available concerning the production of nutrient-rich food crops on an inexpensive, space efficient A-frame vertical gardening system. Thus, there is a need to exam food production using vertical gardening systems.

Materials and Methods

Two experiments were conducted, one beginning May 2014, and a second starting July 2014 to evaluate two edible container-grown crops, *Amaranthus tricolor* L. and *Ocimum basilicum* L. 'Cardinal Basil', using an inexpensive A-frame vertical growing structure. Both experiments were conducted in double-wall poly greenhouses at the Paterson Greenhouse Complex on the Auburn University campus in Auburn, AL 36849. *Amaranthus tricolor* L. seed was ordered from Johnny's Selected Seeds Internet website, and *Ocimum basilicum* L. 'Cardinal Basil' seed was ordered from Park Seed Company located at 3507 Cokesbury Road Hodges, SC.

Plants used in this study were specifically selected to fulfill certain requirements in order to enhance the study by achieving marketable and beneficial results for the green industry and potential consumers. Crops selected met the following requirements: high nutritional values and numerous nutritional benefits for consumers, easy to grow, rapid production time (minimal number of days to harvest, i.e. 50-65 days from seed to maturity/harvest), shallow root systems, growth habits suitable for production using the vertical structure (i.e. small herbaceous plants), potting substrate, and similar cultural requirements.

All seeds were sown in a Fafard 3B potting substrate placed in 806 black plastic cell packs on greenhouse benches. Each seed tray was covered with a clear plastic Bio Dome humidity cover (from the Park Seed Company, 3507 Cokesbury Road Hodges, SC) to aid in germination. The Bio Dome humidity cover was removed following germination. Once two sets of true leaves were present, a total of 84 seedlings were transplanted into 15.24 cm x 16.51 cm (6 inch x 6.5 inch) black, Belden Magnum Square pots, and placed into the experimental set up.

Experiment 1 was initiated May 2, 2014. The experiment was conducted over 35 days. Containers were filled with Fafard 3B substrate and top-dressed with 8 grams/0.3 ounces of Harrell's 14-14-14, 2-3 months control release fertilizer (manufactured for Harrell's LLC). Harrell's fertilizer consists of 6.9400% nitrate nitrogen and 7.0600% ammoniacal nitrogen, 14.0000% available Phosphate (P_2O_5), and 14.0000% soluble Potash (K_2O). Plants were irrigated with a drip-irrigation system. Containers were watered four times a day for three minutes at each watering. Irrigation times were set for 8:00 AM, 11:30 AM, 2:00 PM and 5:00 PM. Detailed information regarding the drip-irrigation system is discussed in chapter 4. To ensure containers on the vertical structure received adequate watering, holes were drilled into containers about one inch below the pot rim using a 15/64 inch drill bit, which allowed for irrigation tubing to be inserted in to each container.

Experiment 2 was initiated on July 14, 2014. Materials used in Experiment 2 were the same as in Experiment 1. Methods for Experiment 2 were similar to those described in Experiment 1, other than where noted. Plants were harvested 28 days after initiation (DAI) on August 11, 2014.

The experimental design for both experiments was a randomized complete block design with 4 blocks. Each block was comprised of one vertical structure that occupied a 16 ft^2 ground area, and one greenhouse bench that occupied 16 ft^2 of horizontal growing space. Each vertical structure consisted of a north and south facing metal cattle-fencing wall panel, each of which were 4 ft. x 4 ft. Experiment 1 had 7 plants (sub-samples), per species, per treatment, per block. The treatments were: 1) plants grown traditionally on raised green house benches, 2) plants grown on an A-frame vertical structure with wall panels facing north, and 3) plants grown on an A-frame vertical structure with wall panels facing south. Plant species were grouped into sub-samples of 7 and randomly placed within each treatment in each block (e.g. 7 basil plants were placed on the bottom row of the vertical structure in block A, Treatment 2, and in the middle row of the structure in block A, Treatment 3). For each species, growth indices (GI) were measured 13, 20, 27, and 34 days after the experiment was initiated (DAI) for Experiment 1. GI was calculated as follows: [(height + width 1 + width 2)÷ 3]. Container leachates were collected using the Virginia Tech Pour-Through nutrient extraction procedure (Wright, 1986) to determine soluble solution electrical conductivity (EC) and pH values. EC and pH values were determined using an Agri-meter™, model HG6/PH, (Myron L® Company, 2013) 14, 21, and 28 DAI during Experiment 1. Plants were harvested 35 DAI in Experiment 1 to determine leaf number per plant, leaf area index (LAI), LAI per leaf (leaf surface area), and fresh and dry shoot weights. According to Professor Dennis Baldocchi (2012) from the University of California Berkeley, leaf area index (LAI) is the amount of one-sided leaf area per unit of ground surface area. In order to assess LAI, a direct method was used which involved manually sampling leaves for each species' sub-sample, per treatment, per block. LAI was measured using a LI-3100C Leaf Area Meter (LI-COR, 2015). Average leaf size per plant, per sub-sample, per treatment, per block was calculated as follows: (total LAI cm^2 per plant ÷ total leaf number per plant). Once fresh foliage data was completed, plant shoots, foliage, and roots were placed in a labeled brown paper bag and dried for 48 hours at 82° Celsius in a Grieve laboratory oven.

Data that was collected for both species in each experiment were combined for analyses. An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.3 (SAS® Institute, Cary, NC). Data were analyzed as randomized complete block designs, and data recorded over time were analyzed as factorial designs with repeated measures. Experiment replications (i.e. Experiment 1 and 2) were treated as a random variable in the model in some cases. Where residual plots and a significant COVTEST statement using the HOMOGENEITY option indicated heterogeneous variance, a random statement with the GROUP option was used to correct heterogeneity. Differences among treatment least squares means were determined using the Shaffer Simulated Method. Linear and quadratic trends over weeks were tested using orthogonal polynomials in CONTRAST statements. All significances were at $\alpha = 0.05$.

Results and Discussion

Combined results from *Amaranthus tricolor* L. and *Ocimum basilicum* L. 'Cardinal Basil' are discussed in the same chapter due to both species exhibiting similar data results. Both species were evaluated in two replicated experiments, or runs. There was an interaction between treatment and weeks for *Amaranthus tricolor* L. plant height, growth indices (GI), and substrate solution electrical conductivity (EC) (Table 2.1). A quadratic trend over time showed an exponential plant height increase within each treatment. No differences between treatments occurred during week 1 or 2 for plant height. For weeks 3-4, plant height for the south facing wall panel (Treatment 3) was greater than plant height for the bench-top control (Treatment 1). Plants on the south wall panel (Treatment) 3 had the greatest plant height and were similar to plants grown on the north wall panel (Treatment 2). By week 5, Treatments 1 and 3 were similar in plant height, but both were greater than Treatment 2.

There was an interaction between treatment and weeks for GI. A quadratic trend over weeks of increasing GI for all treatments was observed (Table 2.1). There were no differences for GI among treatments during weeks 1 and 2. Week 3 and 4, GI for plants in Treatment 1 and Treatment 2 were similar, but smaller than plants in Treatment 3. By week 5, Treatments 1 and 3 had the greatest GI, compared to plants in Treatment 2.

As with plant height and GI, there was an interaction between treatment and weeks for EC (Table 2.1). For each treatment, EC had a quadratic response over time and was lowest by the 4th week of the study. In weeks 2 through 4, Treatments 2 and 3 had the greatest EC compared to Treatment 1, which had to lowest EC. Regardless of week, the EC values for Treatment 1 were consistently lower, by three fold or more, than the EC values for Treatments 2 or 3.

Table 2.2 shows the combined means for Experiments 1 and 2 post-harvest data for *Amaranthus tricolor* L.: leaf counts, leaf area indices (LAI), LAI per leaf, shoot and foliar dry and fresh weight. There was no interaction between week and treatment, but both main effects had differences. There were no differences in leaf count or leaf area indices among treatments for *Amaranthus tricolor* L. However, average LAI per leaf for plants in Treatments 2 and 3 were larger than plants in Treatment 1. The total dry weight for Treatments 1 and 3 were similar with both being greater than Treatment 2. The total fresh weight followed the same trend as total dry weight, with Treatments 1 and 3 having the greatest mass.

Table 2.3 shows substrate solution pH means of pots containing *Amaranthus tricolor* L. There was no interaction between week and treatment, but both main effects had differences. The average pH for Treatment 1 was higher than the average pH for Treatments 2 and 3 throughout both experiments. Regardless of treatment, pH increased linearly over the duration of the experiment.

Combined results from Experiments 1 and 2 for *Ocimum basilicum* L. 'Cardinal Basil' show there was a significant interaction for plant height between treatment and weeks (Table 2.4). For all treatments, there was a linear trend with plant height increasing over time. Week 1, plant heights were similar among treatments. However, in week 2, Treatment 3 had the tallest plants compared to Treatment 1. Plants in Treatment 2 were similar to Treatments 1 and 3. In weeks 3 and 4, Treatments 2 and 3 had similar plant heights, with both treatments having taller plants than Treatment 1.

There was no interaction between week and treatment for GI regarding *Ocimum basilicum* L (Table 2.5). However, treatment and week main effects were different. Treatment 1 had the smallest GI compared to plants in Treatments 2 or 3, which were similar. There was a quadratic increase over time for GI regardless of treatment.

There was no interaction between treatment and weeks for substrate solution pH or EC (Table 2.6). Substrate solution pH for Treatment 1 was greater than the pH for Treatments 2 or 3, which were similar. With respect to EC, Treatment 1 had a lower mean than Treatments 2 or 3. Both Treatments 2 and 3 had similar EC's. Over time, EC declined regardless of treatment.

Combined means of post-harvest data for *Ocimum basilicum* L. ‘Cardinal Basil’ in Treatments 1 and 3 had the greatest leaf count compared to plants in Treatment 2 (Table 2.7). Treatment 3 had the greatest LAI, while the plants in Treatment 2 had the least. LAI for Treatment 1 plants was similar to both Treatment 2 and Treatment 3. Overall, Treatment 2 had the greatest LAI per leaf compared to plants in Treatment 1. Treatment 3 produced the greatest total shoot and foliar dry weight compared to Treatment 2, but both were similar to dry weight for Treatment 1 plants. Results for total fresh weight were similar to total dry weight.

In essence, comprehensive results revealed that the south panel (Treatment 3) of the vertical structure produced similar biomass of *Ocimum basilicum* L. ‘Cardinal Basil’ when compared to control plants on the greenhouse bench (Treatment 1). The same cannot be said for the north-facing wall panel (Treatment 2), but results show that the orientation of the wall panels is important. Despite the fact that the north panel does not perform as well as the south panel, both wall panels on the vertical structure yield double the amount of plant production in a 16 ft^2 area compared to a greenhouse bench that occupies the same horizontal production area.

Conclusion

This study confirmed that the A-frame vertical growing structure is a space efficient, sustainable method for producing *Amaranthus tricolor* L. and *Ocimum basilicum* L. ‘Cardinal Basil’ when compared to traditional, horizontal container production. The study also showed that the vertical structure is capable of producing crops that are comparable to, or greater, than crops grown using traditional, horizontal greenhouse bench-top production per ft^2 of production space. The vertical structure maximizes and efficiently utilizes production space by producing two or three times more *Amaranthus tricolor* L. and *Ocimum basilicum* L. ‘Cardinal Basil’ in 16 ft^2 of production space than a greenhouse bench that occupies the same amount of horizontal space

(Table 2.2). Orientation and placement of the vertical structure does affect plant growth. For the most part, Treatment 3 (south wall panel) produced the largest plants, regardless of species. Since plants in Treatment 3 were facing south, they were able to receive more sunlight for a longer period of time due to time of year (early, mid and late summer) and location of the study (northern hemisphere). Plants in Treatment 2 (north wall panel) faced north and received more shade throughout the day unlike, Treatment 1 or 3, which was able to receive more sun. Limited sun exposure may explain why plants in Treatment 2 grew the least (regardless of species). Performance of plants grown on the greenhouse bench varied, but plants in Treatment 1 were mostly similar to Treatment 3. As for substrate solution EC values, both Treatments 2 and 3 had significantly higher EC values compared to Treatment 1, regardless of species. Higher EC values for plants on the vertical structures may be caused by the angle at which the containers rested when placed into the wall panel cells on the vertical structure. The containers rested at a 30°-40° angle on the vertical structure. Higher EC values indicate a greater amount of soluble nutrients (macro and micronutrients essential for healthy plant growth) in the substrate available for the plant to absorb through the root systems. Additionally, the container design most likely had an effect on substrate solution results. For instance, each plastic container has four small holes on the bottom of the container. If container drainage areas were designed differently, the EC results for the vertical structure could have differed. It is presumed that the orientation of the container affected the manner in which leachates drained from the containers drainage holes. In essence, less leaching may have occurred with Treatments 2 and 3 due to container orientation and container design, which resulted in less nutrient loss. Treatment 1 had lower EC values because the base of the container was sitting flat on horizontal greenhouse benches, which resulted in a greater loss of soluble nutrients.

Collectively, this study illustrates that the A-frame vertical growing structure is a space efficient, alternative growing method that can increase crop production within the same amount of production space occupied by a greenhouse bench and produce plants that are equal to, or better (in respect to plant height and growth indices), than traditional greenhouse bench-top production methods.

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Table 2.1. Combined means for plant heights, growth indices, and electrical conductivity (EC) for *Amaranthus tricolor* L., Experiments 1 and 2.

	Height (cm)				**Growth index (cm)**				**EC (millimhos/cm)**		
	Treatment				Treatment				Treatment		
Week	1[w]	2[v]	3[u]	Week	1	2	3	Week	1	2	3
1	9.5[NSx,NS]	9.9	10.5	1	11.8[NS]	11.5	12.5	2	0.41B	1.42A	1.66A
2	17.8	18.0	20.4	2	20.5[NS]	20.1	22.5	3	0.35B	1.71A	1.68A
3	31.0B	33.9AB	38.5A	3	32.0B	32.9B	35.4A	4	0.07B	0.81A	0.68A
4	58.5B	60.8AB	66.2A	4	43.9B	43.4B	47.0A				
5	87.0A	73.4B	90.3A	5	48.1A	45.6B	48.5A				
Significance	Q***[y]	Q***	Q***	Significance	Q**[y]	Q***	Q***	Significance	Q*[y]	Q**	Q**

[z] The treatment by week interaction for all percentages was significant at α = 0.05.

[x] Least square means comparisons within rows using the Shaffer Simulated Method at α = 0.05.

[y] Quadratic (Q) trends over weeks using orthogonal contrasts at α = 0.05 (*), α = 0.01 (**), and 0.001 (***).

[NS] Means are not significantly different.

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of vertical structure.

[u] Treatment 3, south wall panel of vertical structure.

Table 2.2. Combined means of leaf count, leaf area indices, average leaf area per leaf, dry and fresh shoot and foliar weight for *Amaranthus tricolor* L., Experiments 1 and 2.

Treatment	**Leaf count**	**Leaf area Index (cm^2)**	**Leaf area per leaf (cm^2)**	**Shoot and foliar dry weight (g)**	**Shoot and foliar fresh weight (g)**
1[y]	55[NS]	2137.0[NS]	39.5b	22.7a	153.5a
2[x]	52	2278.0	45.2a	18.6b	142.2b
3[w]	53	2229.7	42.7a	23.0a	158.1a
Significance	Q*	Q*	Q*	Q*	Q*

[z] Least square means comparisons within columns using the Shaffer Simulated Method at $\alpha = 0.05$ (*).

[NS] Means are not significantly different.

[y] Treatment 1, (control) plants grown on a greenhouse bench.

[x] Treatment 2, north wall panel of vertical structure.

[w] Treatment 3, south wall panel of vertical structure.

Table 2.3. Combined pH means for Experiments 1 and 2 for *Amaranthus tricolor* L.

Treatment	**pH**	Week	**pH**
1[w]	6.8a[y]	2	6.3
2[v]	6.2b	3	6.3
3[u]	6.2b	4	6.6
		Significance	L*[x,y]

[z] Only the treatment and week main effects were significant at $\alpha = 0.05$

[y] Least square means comparisons within column using the Shaffer Simulated method at $\alpha = 0.05$.

[x] Significance and Linear (L) trends over weeks using orthogonal contrasts at $\alpha = 0.05$ (*).

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of vertical structure.

[u] Treatment 3, south wall panel of vertical structure.

Table 2.4. Combined plant height means for *Ocimum basilicum* L. 'Cardinal Basil', Experiments 1 and 2.

	Treatment		Height (cm)
Week	1[w]	2[v]	3[u]
1	5.8[y, NS]	7.2	7.5
2	12.0B	13.9AB	15.1A
3	18.0B	21.8A	21.6A
4	26.0B	31.6A	32.3A
	L***[x]	L***	L***

[z] The treatment by week interaction was significant at $\alpha = 0.05$.

[y] Least square means comparisons within rows using the Shaffer Simulated Method at $\alpha = 0.05$.

[x] Significant Linear (L) trends over weeks using orthogonal contrasts at $\alpha = 0.001$ (***).

[NS] Means are not significantly different.

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of vertical structure.

[u] Treatment 3, south wall panel of vertical structure.

Table 2.5. Combined growth index means of *Ocimum basilicum* L. ‘Cardinal Basil’, Experiments 1 and 2.

Growth Index (cm)

Treatment		Week	
1[w]	13.9b[y]	1	7.5
2[v]	16.3a	2	11.9
3[u]	16.4a	3	17.8
		4	24.8
		Significance	Q***[x]

[z] Only the treatment and week main effects were significant at $\alpha = 0.05$.

[y] Least square means comparisons within column using the Shaffer Simulated Method at $\alpha = 0.05$.

[x] Significance and Quadratic (Q) trends over weeks using orthogonal contrasts at $\alpha = 0.001$ (***).

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of vertical structure.

[u] Treatment 3, south wall panel of vertical structure.

Table 2.6. Combined pH and electrical conductivity (EC) means for *Ocimum basilicum* L. 'Cardinal Basil', Experiments 1 and 2.

Treatment	**pH**[z]	Week	**pH**	Treatment	**EC (millimhos/cm)**[z]	Week	**EC**
1[w]	6.8a[y]	2	6.6	1	0.21b	2	1.00
2[v]	6.4b	3	6.3	2	1.43a	3	1.18
3[u]	6.2b	4	6.4	3	1.34a	4	0.80
Significance	Q*[x]				Significance		Q*[x]

[z] Only the treatment and week main effects were significant at $\alpha = 0.05$

[y] Least square means comparisons within column using the Shaffer Simulated Method at $\alpha = 0.05$.

[x] Significance and Quadratic (Q) trends over weeks using orthogonal contrasts at $\alpha = 0.05$ (*).

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of vertical structure.

[u] Treatment 3, south wall panel of vertical structure.

Table 2.7. Combined leaf counts, leaf area indices, leaf area index per leaf, shoot and foliar dry and fresh weight means of *Ocimum basilicum* L. 'Cardinal Basil', Experiments 1 and 2.

Treatment	**Leaf count**	**Leaf area index (cm^2)**	**Leaf area index per leaf (cm^2)**	**Shoot and foliar dry weight (g)**	**Shoot and foliar fresh weight (g)**
1[y]	185a[z]	2796.7ab	15.4b	13.8ab	134.8ab
2[x]	154b	2652.2b	17.7a	12.0b	129.2b
3[w]	183a	2982.6a	16.6ab	14.3a	143.7a

[z] Least square means comparisons within columns using the Shaffer Simulated Method at $\alpha = 0.05$.

[y] Treatment 1, (control) plants grown on a greenhouse bench.

[x] Treatment 2, north wall panel of vertical structure.

[w] Treatment 3, south wall panel of vertical structure.

CHAPTER III

Evaluation of an A-frame Vertical Growing Structure Using *Beta vulgaris* L. 'Detroit Dark Red'

Abstract

To date, there is little data on research referencing the topic of nutrient-dense food production that utilizes sustainable, space efficient vertical greening systems. Two experiments were conducted in May 2014 and in February 2015 using an inexpensive A-frame vertical growing structure. The purpose of the study was to evaluate the growth of *Beta vulgaris* L. 'Detroit Dark Red' on the vertical structure compared to traditional, horizontal greenhouse production methods. Both experiments were conducted in double-wall poly greenhouses. A randomized complete block design was used in the study, and the experimental design consisted of 4 blocks. Each block had one vertical structure and one greenhouse bench, both of which occupied 16 ft^2 of horizontal greenhouse production space. The following treatments were used in the study: 1) plants grown traditionally on raised greenhouse benches, 2) plants grown on an A-frame vertical structure with wall panels facing north, and 3) plants grown on an A-frame vertical structure with wall panels facing south. In Experiment 1, plants grown on raised greenhouse benches (Treatment 1) and plants grown on south facing wall panels (Treatment 3) performed the best having the highest values for plant height, growth indices (GI), beetroot dry and fresh weights, and root width and root circumference. In Experiment 2, plants in Treatment 3 performed the best overall, while Treatments 1 and 2 were similar. During Experiment 2, plants in Treatment 3 had the greatest plant height, average GI, and highest EC values among all treatments. Substrate solution electrical EC readings for Treatments 2 and 3 were higher than EC readings in Treatment 1, regardless of experiment. Post-harvest data from Experiments 1 and 2 were the only data combined and collectively analyzed due to similar results from each experiment. Post-harvest data collection included: leaf count, leaf area index (LAI), LAI per leaf, foliage and beet root dry and fresh weights, beet root width, length, and circumference. Findings for post-harvest data showed Treatment 3 exhibited the best plant performance, while Treatments 1 and 2 showed similar results. Results from the experiments determined the vertical structure to be a suitable method for producing *Beta vulgaris* L. 'Detroit Dark Red'.

Index words: *Beta vulgaris* L. 'Detroit Dark Red'**,** sustainable crop production.

Significance to the industry

There is an increasing demand for nutrient-dense foods for people around the world. Hunger and malnutrition exist in highly urbanized and rural areas, as well as developed and underdeveloped countries. Malnutrition is a result of insufficient energy and nutrient intake that either exceeds or does not meet an individual's needs to maintain growth, organ function and immunity (WFP, 2015). Availability and physical access to fresh produce are two major factors that influence food security (FAO, 2012). High-density vertical growing systems (HDVG) represent one possible solution that could help combat world hunger. Furthermore, such systems continue to attract much interest from the green industry, and some individuals believe vertical growing systems to be the future of sustainable agricultural production (Fletcher, 2012). This work showed that one A-frame vertical growing structure occupying 16 ft^2 of greenhouse production space was able to produce over two times the amount of *Beta vulgaris* L. foliage and nearly double the amount of root production compared to a traditional greenhouse bench occupying the same 16 ft^2 of horizontal production space.

Introduction

The World Hunger Organization (WHO, 2015) defines hunger as “the want or scarcity of food in a country.” Hunger and malnutrition are the world’s leading health risks and contribute to higher annual death rates than AIDS, malaria, and tuberculosis combined (WFP, 2015). According to the FAO (2014), hunger reduction requires a unified approach that should include the following: increased investments from public and private sectors to increase agriculture production; improved access to inputs, services, technologies and markets; promoting rural development; specific nutrition programs, especially for children below the age of five, and mothers with micro-nutrient deficiencies. The FAO (2014) also states that there is a decrease in the production and consumption of cereal crops, roots, and tubers. Fortunately, the use of low-space technologies, such as vertical gardening systems, holds great promise for producing fresh and nutritious food in confined areas (Dubbeling, 2011). Vertical gardening systems that are sustainable and economically efficient could potentially deliver higher production yields than traditional, field crop production methods (Laumer, 2008), maximize limited production space, and help provide nutrient-dense foods for people around the globe.

The red beetroot, *Beta vulgaris* L*.,* is a nutrient-packed vegetable that contains an extensive amount of folate, and is also a very good source of potassium, magnesium and copper (George Mateljan Foundation, 2015). *Beta vulgaris* L. also contains beneficial sources of phosphorous, iron, and vitamins C and B6 (George Mateljan Foundation, 2015), soluble fiber, nitrate and calcium (Csiki, 2011). There is a global need for increased production of powerhouse, nutrient rich foods, especially for those suffering from hunger and malnutrition. Such factors prompted the need to examine a novel, economically efficient, and sustainable food production method, such as the A-frame vertical structure used in this work. The purpose of this work was to evaluate the effectiveness of producing *Beta vulgaris* L. ‘Detroit Dark Red’ in containers on an A-frame vertical growing structure compared to a traditional, horizontal greenhouse bench-top production method. A specific goal of this work was to create a more economical and sustainable method for producing edible plants within a limited amount of space.

Materials and Methods

Two experiments were conducted, one during May 2014, and a second during February 2015, to evaluate plant performance and production of *Beta vulgaris* L. ‘Detroit Dark Red’ grown in containers and placed in an expensive A-frame vertical growing structure compared to traditional, horizontal bench-top methods. Both Experiments were conducted in a double-wall poly greenhouse in the Paterson Greenhouse Complex on the Auburn University campus in Auburn, AL 36849. *Beta vulgaris* L. ‘Detroit Dark Red’ seed was ordered from Park Seed Company located at 3507 Cokesbury Road Hodges, SC. Plants were specifically selected to fulfill certain requirements in order to enhance the study by achieving marketable and beneficial results for the green industry and potential consumers around the globe. This crop was selected because it met the following requirements: high nutritional values and numerous health benefits for consumers, easy to grow, rapid production time (minimal number of days to harvest, i.e. 50-65 days from seed to maturity/harvest), shallow root systems, and appropriate growth habits (i.e. small herbaceous plants).

Experiment 1: Prior to sowing, seeds were soaked in water at room (approximately 23.33°C/ 74°F) for 24 hours. The seeds were then dried with a paper towel. All seeds were sown in Fafard 3B substrate and placed in 806 black plastic cell packs in the greenhouse. Greenhouse temperature settings for the stage 1 cooling fans were set to 26.7°C/ 80°F, stage 2 (cooling pads) was set to 30.6°C/ 87°F, and the heat was set to 18.3°C/65°F. Each seed tray was covered with a clear plastic Bio Dome humidity cover to aid in germination (Park Seed, 2014). The Bio Dome was removed once seedlings germinated and had two sets of true leaves. A total of 84 seedlings were transplanted into 15.24 cm x 16.51 cm (6 inch x 6.5 inch) black, Belden Magnum Square pots, and placed into the experimental set up. Experiment 1 was initiated May 2, 2014. The experiment took place over 5 weeks. Containers were filled with Fafard 3B substrate and top-dressed with 8 grams/0.3 ounces of Harrell's 14-14-14, 2-3 months control release fertilizer (manufactured for Harrell's LLC). Harrell's fertilizer consists of 6.94% nitrate nitrogen and 7.06%, ammoniacal nitrogen, 14.00% available phosphate (P_2O_5), and 14.00% soluble potash (K_2O). Plants were irrigated with a drip-irrigation system. See Chapter 4 for a full description of drip-irrigation system used. Containers were watered 4 times a day for 3 minutes at each watering. Irrigation times were set for 8:00 AM, 11:30 AM, 2:00 PM and 5:00 PM. To ensure all containers received adequate water, holes were drilled into containers about one inch below the pot rim using a 15/64" drill bit, which allowed for irrigation tubing to be inserted into the containers.

The experimental design for both experiments was a randomized complete block design with 4 blocks. Each block had one vertical structure that occupied a $16ft^2$ area, and one greenhouse bench that occupied the same square footage. Each vertical structure consisted of a north and south facing metal cattle-fencing wall panel, each of which were 4 ft. x 4 ft. Experiment 1 had 7 plants (sub-samples), per species, per treatment, per block. Each block had 3 treatments: 1) plants grown traditionally on raised greenhouse benches, 2) plants grown on an A-frame vertical structure with wall panels facing north, and 3) plants grown on an A-frame vertical structure with wall panels facing south. Plant species were grouped into sub-samples of 7 and randomly placed within each treatment in each block (e.g. 7 beets were placed on the top row of the vertical structure in block A, Treatment 2, and in the bottom row of the structure in block A, Treatment 3). Once Experiment 1 was initiated, growth indices (GI) were collected13, 20, 27, 34 and DAI (days after experiment initiation). GI was calculated as follows: [(height + width 1 + width 2)÷ 3].

Container leachates were collected during the experiment using the Virginia Tech Pour-Through Method (Wright, 1986) to measure soluble solution electrical conductivity (EC), and pH of the substrate solution. EC and pH readings were determined with an Agri-meter™, model HG6/PH (Myron L® Company, 2013) 14, 21, and 28 DAI.

Plants were harvested June 10, 2014. The following post-harvest data were collected: leaf number per plant, leaf area indices (LAI) per plant, leaf area indices per leaf (leaf surface area), fresh and dry weights for foliage and beetroots, and beetroot measurements (root length, width, and circumference). Beetroot width, length, and circumference measurements were collected using a 25-foot tape measure. Measurements for root circumference involved wrapping the tape measure around the central, widest portion of the root. In order to assess LAI, a direct method was used which involved manually sampling leaves for each sub-sample, per treatment, per block, per species. Leaf area index (LAI) is the amount of one-sided leaf area per unit of ground surface area (Baldocchi, 2012). LAI was measured using a LI-3100C leaf area meter (LI-COR, 2015). Average leaf size per sub-sample, per treatment, per block was calculated as follows: (total LAI cm^2 per plant ÷ total leaf number per plant). Once fresh harvest data was collected, foliage and beetroots were placed in a labeled, brown paper bag and dried for 48 hours at 82.22°C/ 180°F in a Grieve Laboratory Oven.

Experiment 2: The experiment was initiated on February 13, 2015 and took place for 6 weeks. Materials used for Experiment 2 were the same as in Experiment 1, with exceptions for the following: approximately 1,415.2 grams/49.92 ounces of Harrell's 14-14-14 fertilizer was incorporated into 10.5 cubic feet/0.297 cubic meters of Fafard 3B commercial substrate. Irrigation times were modified to run 4 times a day for 2 minutes at each watering. Since Experiment 2 was conducted in early spring, the greenhouse was cooler, which resulted in the substrate drying out less, requiring less water. Data collection methods were the same as in Experiment 1, except GI was collected 7, 14, 21, 28, 35 and 42 DAI. Leachates were collected 27, 34, and 41 DAI, and EC and pH values were determined using a Fisher Scientific™ Accumet™ Excel XL50 Dual Channel pH/mV/Temperature/ISE Conductivity Meter (2015). Plants were harvested the week of April 1, 2015.

Data Analyses: Data for Experiments 1 and 2 were subjected to analyses of variance for all responses using PROC GLIMMIX in SAS version 9.3 (SAS® Institute, Cary, NC). Post-harvest data from Experiments 1 and 2 were the only data sets combined and collectively analyzed for *Beta vulgaris* L. because time was not a factor for the post-harvest data. Data were analyzed as randomized complete block designs, and data recorded over time was analyzed as a factorial design with repeated measures. Experiment replications, Experiment 1 and 2, were treated as a random variable in the model in some cases. Where residual plots and a significant COVTEST statement using the HOMOGENEITY option indicated heterogeneous variance, a random statement with the GROUP option was used to correct heterogeneity. Differences among treatment least squares means were determined using the Shaffer Simulated Method. Linear and quadratic trends over weeks were tested using orthogonal polynomials in CONTRAST statements. All significances were at $\alpha = 0.05$.

Results and Discussion

Experiment 1: Results for plant height indicated there was an interaction between weeks and treatments for plant height (Table 3.1). However, there was a quadratic trend with plant height increasing over time exponentially for all treatments. Plant heights recorded seven DAI were similar among treatments. In weeks 2-5, the north wall panel (Treatment 2) had shorter plants compared to plants on raised greenhouse benches (Treatments 1) and plants on the south wall panel (Treatment 3). Plants in Treatments 1 and 3 were similar in plant height. Plant height appeared to be effected most by sun exposure, which was caused by the orientation and placement of the vertical structures and greenhouse benches. Treatment 2 faced north on the vertical structure, and received less sunlight than Treatment 3, which faced south. This may have caused the south side of the greenhouse bench to receive enough sunlight to result in similar plant heights for Treatment 3.

There was no interaction between treatment and time involving GI for *Beta vulgaris* L. (Table 3.2). Plant GI increased exponentially over time for in both experiments, regardless of treatment. In Experiment 1, Treatments 1 and 3 had similar GI's, and both treatments had greater GI's than plants in Treatment 2. In Experiment 2, GI for Treatments 1 and 3 was larger than Treatment 2.

There was no interaction between treatment and time for substrate solution electrical conductivity (EC) or pH; therefore, only main effects will be discussed (Table 3.3). Substrate solution pH in Treatment 1 was greater than Treatment 2 and 3. Substrate solution EC values for Treatments 2 and 3 were greater than Treatment 1 in Experiment 1. According to the *Milwaukee Precision Agriculture Testing Manual for pH and Electrical Conductivity (EC) in Soil-Fertilizer-Water* (2014), all EC values were within an optimal range for most agriculture plant production.

Across all treatments, there was a quadratic response with EC levels beginning to decline by week 4. As with other work (see Chapter 2), higher substrate EC readings were seen with Treatments 2 and 3 compared to Treatment 1.

Experiment 2: As in Experiment 1, there was an interaction between weeks and treatments for plant height (Table 3.1). There was a quadratic trend of exponentially increasing plant height over time, regardless of treatment. In weeks 1 and 2, plant height was similar in all 3 treatments. By week 3, plants in Treatment 1 were shortest, while plants in Treatment 3 were tallest. Plants in Treatment 2 had similar heights to those in Treatments 1 and 3. Plant heights for Treatment 3 were taller than plants in Treatments 1 and 2 by week 4. Plants in Treatments 1 and 2 were similar in height. Plants in Treatment 3 were taller than those in Treatment 2 by week 5, with plants in Treatment 1 being similar to the plant heights of Treatments 2 and 3. At the termination of Experiment 2, plant heights were greatest in Treatment 3. Once again, the results for plant height may be attributed to the orientation of the vertical structures. Treatment 3 produced the greatest plant heights in both experiments. The orientation of the wall panel allowed plants in Treatment 3 to receive more sunlight for a longer duration throughout the day, unlike the north wall panel or the greenhouse bench.

There was no interaction between treatment and time for GI in Experiment 2; therefore, only main effects of treatment and time will be discussed (Table 3.2). Regardless of treatment, GI increased exponentially over time. Plants in Treatment 3 had greater GI than plants in Treatment 1 or 2.

An interaction between treatment and weeks occurred for substrate pH and EC in Experiment 2 (Table 3.4). Substrate pH's for Treatments 2 and 3 had linear responses, while Treatment 1 data had no significant model over weeks. Substrate solution pH's ranged from 5.1

to 6.1; all values were acceptable for container production. Substrate solution EC values for Treatment 1 were lower than those in Treatments 2 or 3 throughout the experiment, with the exception of week 6. By week 6, Treatment 2 had the highest substrate solution EC when compared to EC's for the other two treatments. Different statistical models for each of the 3 treatments over weeks were found in Experiment 2. Treatment 1 had a quadratic model, while Treatment 2 had no significant model, and Treatment 3 had a linear model. Because of the different models for the treatments, the substrate solution EC's responded differently over weeks in the experiment.

Combined Results from Experiments 1 and 2: There were no differences in leaf number due to all treatment (Table 3.5). Plants in Treatment 3 had the highest LAI and LAI per leaf, while plants in Treatment 1 had the least. Differences for average LAI per plant, per treatment may be attributed to orientation of the vertical structure.

Plants in Treatment 3 had a greater foliage fresh and dry weight than plants in Treatments 1 and 2 (Table 3.5). Treatments 1 and 2 had similar foliage dry weights. Fresh weight for plants in Treatment 1 had the lowest mass.

As for root dry and fresh weights, Treatment 1 plants had the greatest root mass compared to Treatment 2, while Treatment 3 was similar to Treatments 1 and 2. *Beta vulgaris* L. root widths were greater in Treatments 1 and 3 than those in Treatment 2. There was no treatment effect on root length. Root circumferences were similar to root widths for all treatments. Root circumferences for Treatments 1 and 3 were similar and greater than those in Treatment 2.

Comparison Results and Discussion for Experiments 1 and 2: For both experiments, week 1 had differences in plant height due to treatment (Table 3.1). In week 2 of Experiment 1, plants in Treatments 1 and 3 were similar and taller than plants in Treatment 2. In week 2 of Experiment 2, there were no treatment differences for plant height. However, for weeks 2 through 5 of Experiment 1, plant height treatment trends were similar for the duration of the experiment, with Treatments 1 and 3 having the tallest plants and Treatment 2 the shortest. For Experiment 2, plant height differences varied for Treatments 1 and 2 in weeks 3 through 6. By week 5, plants in all treatments in Experiment 2 were much larger than plants in Experiment 1 by about 30% regardless of treatment. Week 5 showed the biggest increase in height for both experiments. Faster growth could be contributed to the cooler weather in Experiment 2 versus Experiment 1, which was conducted from early to mid-summer. Furthermore, faster plant height rates in Experiment 2 correlate with Burton's (2005) article stating that *Beta vulgaris* L. performs best in cool weather conditions.

Both experiments exhibited similar trends. However, Experiment 2 had bigger differences. Trends show a larger GI for plants in Experiment 2 when compared to Experiment 1. Plants in Experiment 2 were on average about 17% larger than plants in Experiment 1 with respect to GI, regardless of treatment. When comparing the average GI between treatments in Experiment 1, Treatments 1 and 3 were similar, but both differed from Treatment 2. In Experiment 2, GI for Treatments 1 and 2 were similar, but both were different from Treatment 3, which had the largest GI.

In Experiment 1, all pH's were within an acceptable range for container production (Table 3.3). There was no interaction between treatment and week for pH or EC in Experiment 1, but in Experiment 2 there was an interaction for both pH and EC (Table 3.4). Both experiments showed that Treatments 2 and 3 had higher substrate solution EC readings than Treatment 1 throughout. Higher EC readings for Treatments 2 and 3 were more probably a result of the angle at which containers were placed into the wall panels of the vertical structure. Experiment 2 differed greatly from Experiment 1 with respect to EC across all treatments. Experiment 2 treatments also had different statistical models over time (Table 3.4).

Different EC models in Experiment 2 may be attributed to the treatment by week interaction. Dissimilar models for EC in both experiments could be due to whether fertilizer was top-dressed (Experiment 1) or incorporated into the substrate (Experiment 2). According to the Southern Nursery Association's (SNA) Guide for Producing Nursery Crops (2013), controlled-release fertilizers (CRF) should be uniformly incorporated into substrate instead of broadcasting CRF's on spaced containers. Common disadvantages found in top-dressing with CRF's include fertilizer spillage if containers are turned over, fertilizer may be spilled onto greenhouse floors during top-dress application, or may be blown away from the surface of the substrate by greenhouse fans or wind, all of which can result in nutrient loss (Warren et al. 2001). Temperature and time of year could have also affected the EC results for both experiments, especially since Experiment 2 took place in late winter and continued into early spring, while Experiment 1 took place in early summer and ended in mid-summer. Cooler temperatures could have inhibited the release of fertilizer nutrients into the substrate, followed by the fact that fertilizer nutrients usually release more slowly when incorporated into the soil, as opposed to fertilizer that is top-dressed. Additionally, as Experiment 2 progressed, temperatures increased as spring approached, which may have also affected the release and absorption of fertilizer nutrients. Therefore, temperature and time may have caused different reactions among the treatments, resulting in different statistical models for Experiment 2.

Conclusion

This study confirmed that the A-frame vertical growing structure is an effective, resourceful, and economically sustainable method for producing *Beta vulgaris* L. 'Detroit Dark Red'. The study also showed that the vertical structure is capable of producing *Beta vulgaris* L. plants equivalent to those grown using traditional, horizontal greenhouse bench-top production methods. Furthermore, the structure efficiently maximized greenhouse production space and was able to produce over two times the amount of *Beta vulgaris* L. foliage and almost two times the amount of root when compared to horizontal bench production. Both *Beta vulgaris* L. experiments confirm that orientation and placement of the vertical structure does affect plant growth. Collectively, Treatment 3 yielded the best plants, regardless of experiment and time of year; this was likely to have been caused by the orientation of the vertical structure. Plants in Treatments 2 and 3, regardless of experiment, had significantly higher substrate solution EC readings than Treatment 1. Therefore, plants in Treatments 2 and 3 may have had more essential nutrients available in the substrate solution, leading to increased yield. Higher EC readings for plants in Treatments 2 and 3 were probably affected by the container angle, or placement, of containers in the vertical structure, along with temperature and time of year.

Overall, this study illustrates that the A-frame vertical growing structure can produce healthy, edible crops in a sustainable and space efficient manner. Furthermore, this study demonstrated that vertical gardening can be a sustainable alternative growing method capable of increasing crop yields in limited areas and producing quality plants equal to, or better, than those produced using horizontal, greenhouse bench production methods

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Table 3.1. Plant height for *Beta vulgaris L.* 'Detroit Dark Red' Experiments 1 and 2.

	Height (cm): Experiment 1				**Height (cm): Experiment 2**		
	Treatment				Treatment		
Week	1^{w}	2^{v}	3^{u}	Week	1	2	3
1	$5.4^{y,NS}$	4.3	5.4	1	8.8^{NS}	8.1	9.4
2	10.1A	7.4B	9.9A	2	13.8^{NS}	13.5	14.8
3	17.2A	13.5B	18.2A	3	22.2B	24.5AB	25.3A
4	29.1A	23.7B	29.3A	4	33.7B	33.5B	38.2A
5	36.4A	31.0B	37.7A	5	51.4AB	47.6B	54.6A
				6	61.2B	59.8B	71.9A
Significance	Q***^{x}	Q***	Q***	Significance	Q***	Q***	Q***

[y] Least square means comparisons within rows using the Shaffer Simulated Method at $\alpha = 0.05$.

[x] Significant and Quadratic (Q) trends over weeks using orthogonal contrasts at $\alpha = 0.001$ (***).

[NS] Means are not significantly different.

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of the vertical structure.

[u] Treatment 3, south wall panel of the vertical structure.

Table 3.2. Growth indices of *Beta vulgaris* L. 'Detroit Dark Red', Experiments 1 and 2.

Growth indices (cm): Experiment 1				**Growth indices (cm): Experiment 2**			
Treatment		Week		Treatment		Week	
1^w	15.2a[y]	1	6.6	1	15.1b	1	3.4
2^v	12.6b	2	10.7	2	14.4b	2	5.2
3^u	14.9a	3	15.2	3	16.2a	3	10.4
		4	18.5			4	16.8
		5	20.1			5	24.2
						6	31.4
		Significance	Q***[x]			Significance	Q***

[z] Only the treatment and week main effects were not significant at $\alpha = 0.05$

[y] Least square means comparisons within column using the Shaffer Simulated Method at $\alpha = 0.05$.

[x] Significance and Quadratic (Q) trend over weeks using orthogonal contrasts at $\alpha = 0.001$ (***).

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of the vertical structure.

[u] Treatment 3, south wall panel of the vertical structure.

Table 3.3. Substrate solution pH and electrical conductivity (EC) for *Beta vulgaris* L. 'Detroit Dark Red', Experiment 1.

Treatment	**pH**	Week	**pH**	Treatment	**EC (millimhos/cm)**	Week	**EC (millimhos/cm)**
1[w]	6.7a[y]	2	6.5	1	0.15b	2	0.71
2[v]	6.3b	3	6.3	2	1.02a	3	0.95
3[u]	6.2b	4	6.5	3	1.03a	4	0.53
		Significance	Q***[x]			Significance	Q***

[z] Only the treatment and week main effects were not significant at α = 0.05.

[y] Least square means comparisons within column using the Shaffer Simulated Method at α = 0.05.

[x] Significance and Quadratic (Q) trends over weeks using orthogonal contrasts at α = 0.001 (***).

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of the vertical structure.

[u] Treatment 3, south wall panel of the vertical structure.

Table 3.4. Substrate solution pH and electrical conductivity (EC) for *Beta vulgaris* L. ‘Detroit Dark Red’, Experiment 2.

pH	Treatment			**EC (millimhos/cm)**	Treatment		
Week	1[w]	2[v]	3[u]	Week	1	2	3
3	5.9B[y]	6.0AB	6.1A	3	0.63B	1.69A	1.93A
4	5.9B	5.9B	6.1A	4	0.78B	1.99A	1.56A
5	6.0A	5.8B	5.8B	5	0.40B	1.52A	1.67A
6	6.0A	5.7B	5.9AB	6	0.21C	1.66A	1.01B
Significance	NS	L***[x]	L***	Significance	Q***[x]	NS	L***

[z] The treatment by week interaction was significant at $\alpha = 0.05$.

[y] Least square means comparisons within rows using the Shaffer Simulated Method at $\alpha = 0.05$.

[x] Significance and Linear (L) or Quadratic (Q) trends over weeks using orthogonal contrasts at $\alpha = 0.001$ (***).

[NS] Means no statistical model could analyze pH for Treatment 1 or EC for Treatment 2.

[w] Treatment 1, (control) plants grown on a greenhouse bench.

[v] Treatment 2, north wall panel of the vertical structure.

[u] Treatment 3, south wall panel of the vertical structure.

Table 3.5. Combined means for leaf number, leaf area indices, leaf area indices per leaf, foliar dry and fresh weight, root dry and fresh weight, root width, root length and root circumference for *Beta vulgaris* L. 'Detroit Dark Red', Experiments 1 and 2.

Treatment	Leaf number	Leaf area index (cm^2)	Leaf area index per leaf (cm^2)	Foliage dry weight (g)	Foliage fresh weight (g)	Root dry weight (g)	Root fresh weight (g)	Root width (cm)	Root length (cm)	Root circum. (cm)
1[y]	14[z, NS]	916.3c	66.6c	6.2b	70.6c	7.3a	59.5a	7.0a	7.7[NS]	21.4a
2[x]	13	1065.3b	81.4b	6.2b	81.2b	5.2b	45.4b	5.9b	7.4	18.5b
3[w]	14	1244.1a	90.4a	8.1a	97.6a	6.5ab	54.9ab	7.0a	8.1	22.2a

[z] Least square means comparisons within columns using the Shaffer Simulated Method at $\alpha = 0.05$.

[NS] Means are not significantly different.

[y] Treatment 1, (control) plants grown on a greenhouse bench.

[x] Treatment 2, north wall panel of the vertical structure.

[w] Treatment 3, south wall panel of the vertical structure.

CHAPTER IV

Evaluation and Cost Analyses Comparison of Three Vertical Gardening Systems

Abstract

Vertical gardening systems can be a sustainable method for growing fresh produce. Systems can be divided into two categories: green facades and living wall systems (LWS). LWS utilize newer growing methods in which plant roots are suspended above ground and are established and grown in pre-vegetated wall panels, planter boxes, planted blankets, or vertical modules. LWS require smaller production areas, are able to provide fresh and localized produce on a larger scale, and can be quite versatile when compared to traditional gardening methods. This work compares the design, construction, and costs of three different LWS. Each LWS design offers various key characteristics that either attract or deter consumers from purchasing and implementing vertical garden systems into businesses and residential areas. The comparison of three different LWS designs helps to facilitate a better understanding of the diverse and versatile design systems commercially available to consumers. The comparison also aims to inform consumers about benefits and advancements of LWS, while also demonstrating that vertical gardening does not have to be expensive, elaborate, or labor intensive.

Introduction

Interest in vertical plant production has increased over the past 20 years due to the evolution of realistic design techniques making vertical gardening a more practical and economical growing method than vertical gardening once was (Fletcher, 2012). One chief principle for modern vertical growing systems tends to focus on creating sustainable and resourceful approaches to provide fresh, accessible food, healthy environments, and to connect people to nature. Vertical gardening systems (VGS) can provide revolutionary alternatives for food production, increasing food availability in urban areas (Specht et al., 2013). These systems possess a considerable amount of innovative potential, particularly in spaces with limited or non-existent arable land, or in areas where arable land or horizontal growing space is at a premium (Dunnett and Kingsbury, 2008). VGS can be constructed with a variety of readily available materials that are cost efficient, recyclable, and durable.

VGS or concepts are typically divided into two categories: green facades and living wall systems (LWS) (Feng and Hewage, 2014). The key difference between green facades and LWS is determined by the manner in which the plants are grown (Perini and Rosasco, 2013). Green façades provide stability and support for climbing plants or hanging shrubs to cling to and grow upward. Plants grown on green facades are either established directly in the ground or in containers placed at the base of the structure, or in containers (Feng and Hewage, 2014). LWS, or green walls, grow and establish plant material using various techniques. LWS can be comprised of planter boxes or modular panels, where each planter box contains its own root substrate, or each modular panel is pre-vegetated in its own substrate (Ottéle et al., 2011). These systems are typically attached vertically to a structure or wall frame (Feng and Hewage, 2014). Green facades represent the traditional method of vertical gardening, while LWS utilize various contemporary growing methods differing in appearance and design techniques.

An innovative alternative for a LWS is a wooden A-frame vertical structure designed at Auburn University. The purpose of the vertical structure was to create a sustainable growing method capable of producing higher crop yields than traditional horizontal growing methods. The concept and development of a resourceful, sustainable, and inexpensive A-frame VGS emerged from the escalating movement involving innovative and sustainable forms of urban agriculture. The design concept for the A-frame vertical structure was derived from modern

LWS and structures designed and built onto building facades and self-supportive walls. Unlike other LWS and structures, the A-frame vertical structure is a scalable, portable structure that can accommodate virtually any horizontal area. The structural components are durable, readily available, inexpensive, and re-usable. The useful life span of the structure should be able to last for as many as 9 years, or more, due to the durability of structural components. Irrigation is flexible since the system's users can add irrigation or hand-water plants in the vertical structure. Moreover, the cost analysis of one vertical structure supports the assertion that the system is an economically efficient and sustainable method for growing plants. Unlike most LWS, which are designed with only one wall panel, the A-frame vertical garden structure has two wall panels; thus, it is able to produce greater yields using more plants and less horizontal space. In a study comparing production yields of amaranth, beets, and basil on a wood, A-frame vertical structure versus crops grown on traditional horizontal greenhouse bench tops, the vertical structure produced 1.8 to 2.0 times more plants than the greenhouse bench tops (Chapters 2 and 3).

Materials and Methods

Design Plan and Construction of an A-frame Vertical Growing Structure

The wood A-frame vertical structure is a relatively simple, inexpensive living wall system that can be easily assembled in a step-by-step manner. The information that follows demonstrates how to build the wooden A-frame vertical structure that is 7' tall, 4' wide, and occupies 16 ft^2 of horizontal ground space, but provides almost 52 ft^2 of vertical growing space.

The required structural components needed for building this A-frame vertical structure are listed in Table 4.1. See Figure 1 for structural component images. Tools needed for construction include: hammer (or nail gun), handsaw (or electric power saw), a tape measure, and crescent wrench. Components needed for assembling the vertical structure are listed in Table 4.1.

The A-frame vertical structure is comprised of 2” x 4” x 8’ boards that are pressure treated with copper azole (CA), a water borne wood preservative approved by the American Wood Protection Association (Lowe’s, 2015). Treated wood boards were selected for the framing material to allow for the structure to tolerate various environmental conditions, either in a greenhouse or outdoors. A total of five treated 2” x 4” wood boards serve as the base and support for the two cattle fence wall panels. Of the five boards, four of them were cut to a length of 7’. The ends of the 7’ boards were cut at to 40°-50° angle, which allows the structure to stand firmly on the ground. In order to create and stabilize the “legs”, or wood frame, one of the five boards was cut to measure 2”x 4” x 3’. The two, 3’ long boards connect the 7’ boards, allowing the structure to stand upright.

Support for the cattle fence wall panels were assembled first by using five boards that measured 2” x 4” x 7’. The four, 7’ boards were connected with a total of two, 3/8” x 3” galvanized steel carriage bolts, 5/16” nuts, and 5/16” washers (Figures 2 and 3). After both wall panels were connected, the 2” x 4” x 3’ boards were attached horizontally across each leg of the two wall panels of the structure with four, 3/8” x 3 “ bolt, nut, and washer. Both of the 2” x 4” x 3’ boards stabilize the two legs of the A-frame structure by allowing the legs to stand up right (Figures 4 and 5). The legs of the structure look similar to an isosceles triangle. The 2” x 4” x 7’ boards, or legs, are the two longer sides the isosceles triangle, and the base of the triangle is formed by the 2” x 4” x 3’ board.

Two cattle-fencing panels were used to support the potting containers on the A-frame vertical structure. Cattle fencing, or livestock panels, are a fencing material made of heavy gauge galvanized welded wire (Wiskerchen, 2012). The cattle-fencing panel material was chosen to support the living wall since the panel is flexible, relatively lightweight, durable, strong, fairly inexpensive, and readily available. The dimensions of the cattle-fencing's rectangular cells are important because the growing containers must be able to properly fit into the cells of the fencing. Each cell in the cattle-fencing panel is 6 ¼" wide by 8 ¼" in length, which accommodates 6" x 6 ½" black, a squared Belden growing container (Belden Plastics Inc. 2582 Long Lake Road, St. Paul, MN 55113). The cattle-fencing panel was cut into two equal panels to create the two walls for the vertical structure. The two newly cut panels measure approximately 56" in length by 48 ¼" wide.

After the wood A-frame support structure was assembled, the two cattle-fence panels were attached to the two legs of the structure with a total of 16, 1½" galvanized steel fencing staples (Figure 6). Before the panels were attached, the structure was laid on the ground. The two panels were attached one at a time. The first wall panel was laid on top of the wood legs, and then attached to the structure with eight fencing staples. The fencing staples were placed approximately 14" apart onto the structures' legs. The structure was then turned over onto its other side, and the second panel was attached in the same manner as the first panel. Once both fencing panels were attached with the fencing staples, the vertical structure was placed upright. The structure occupied 16 ft^2 of ground space (Figure 7).

The last component that was attached to the vertical structure was treated wood slats (Figure 8). A total of 24, 1" x 2" x 4' slats were attached to the structure using 2 ½" galvanized nails. On each of the two wall panels, 12 slats were nailed behind the cattle fencing and onto the legs of the structure. The purpose of placing the slats onto the structure, and behind the cattle-fencing panel was to securely support the 6" x 6 ½" black, plastic Belden Magnum Square containers. Once the slats were added, the construction of the wood, A-frame vertical growing structure was complete (Figure 9).

For research purposes, drip-irrigation was installed (Figure 10). However, this vertical garden design does not require a drip-irrigation system because the pots can also be hand-watered. The irrigation methods for the simple A-frame design are contingent upon the user's desires.

The drip-irrigation components consisted of Rain Bird® 2-gallon per hour (gph) irrigation emitters, ½" polyethylene tubing and ¼" vinyl drip irrigation tubing from Landscape Products™ (610 S. 80th Avenue Tolleson, AZ 85353), ½" and ¾" PVC pipe, PVC glue cleaner to connect the PVC pipe, ½", 90° compression ell connectors, compression end valve, ¾" solenoid valve, ½" C x ¾" S socket adapter, ¾" 30 PSI regulator, ½" threaded end cap from EWING Irrigation, Golf and Industrial (3441 E. Harbor Dr. Phoeniz, AZ 85034), and a Rain Bird® ESP series modular controller (970 W. Sierra Madre Ave. Azusa, CA 91702). Table 4.1 includes the cost of the irrigation system components. See Figure 11 for irrigation system parts.

The drip-irrigation system was set up in a double-poly greenhouse on the Auburn University campus. The water source was a one-inch water line located inside the greenhouse using municipal water. A ¾" PVC pipe was attached to the water source. The ¾" PVC pipe was then connected to the ¾"-solenoid valve, which was placed below the vertical structure on the greenhouse floor. The PVC pipe ran up along one side of the vertical structure and was connected to the ½" poly drip tubing, or zone lines, with a socket adapter (½" C x ¾" S). Rain Bird® 2-gph emitters were attached to the ½" poly drip tubing. The ¼" vinyl drip lines were then attached to the emitters located on the ½" poly tube. After the ¼" vinyl lines were inserted through the pre-drilled holes in each 6" x 6 ½ " black, plastic Belden Magnum Square container, a 2-gph emitter was connected to the end of the tubing (Figure 12). The ¼" drip tubing was inserted through a pre-drilled hole in the pot rim to ensure each pot received sufficient watering. A 15/64" Turbomax drill bit was used to create the holes in the 6" x 6 ½" square pots. The holes were drilled in the center, and 1" below the pot rim.

Cost Estimate Analysis

Budget development and cost estimations are a disadvantage for many forms of VGS (Carpenter, 2008). Conversely, the cost to build the wood, A-frame vertical structure previously described is considerably low when compared to other living wall systems and structures that are on the market. This section contains a cost estimate analysis and evaluation of the structural components used to build the 7', wood A-frame vertical structure that occupies a total of 16 ft^2 of horizontal production space. Additionally, the retail cost estimate and analyses of two different, reportedly low cost, commercially available LWS designs is included. Only one design type from each of the two companies is evaluated in this comparison. Both companies offer various vertical garden design systems sold at different retail costs. The designs selected from each company represents their simplest and most inexpensive design available to consumers. The LiveWall® Planted Wall Sprout DIY kit system (LiveWall, 2015) and Woolly Pocket Living Wall Planter (Woolly Pocket, 2015) were selected because both systems are similar to the wood A-frame vertical structure, especially since each system uses a type of container that holds plant material and substrate. Containers or planters are either attached to a vertical structure that is fitted onto a building façade, or attached directly onto a wall. The LiveWall system is shown in Figures 13 and 14, the Woolly Pocket design is shown in Figures 15, 16, and 17, and the A-frame system can be seen in Figures 1 through 10. Table 4.1 contains a cost analysis and list of components for the wood, A-frame vertical structure.

The wood A-frame vertical structure is a simple vertical garden system designed and constructed with basic building materials. The vertical structure was designed and built by faculty, staff, and graduate students in the Department of Horticulture at Auburn University in Auburn, AL 36849. The purpose of designing and building the inexpensive wood, A-frame vertical structure was to create a more economical and sustainable method for producing edible plants within a limited amount of ground space.

The A-frame vertical growing structure contains numerous benefits and advantages. The structural components used to build and assemble the structure consist of basic and traditional building materials such as treated wood boards, nails, bolts, nuts, and washers that were readily available. According to Paul Fisette, from the University of Massachusetts, Amherst (2005), treated wood lasts about 9 years. Research results found in Chapters 2 and 3 exhibit sustainable and efficient plant yields. The structure can produce 6 plants per ft^2 using 6" x 6.5" black, plastic Belden Magnum Square pots spaced 6.5" apart. If a seventh slat is added to the bottom row of each cattle-fencing frame, 3 plants per ft^2. Additionally, the structure has two living wall panels instead of one wall panel, which allows for a total of 42 plants produced in 16 ft^2 of horizontal production space, or 3 plants per ft^2 of horizontal ground space. The cost of one vertical structure, without a drip-irrigation system, is about $60.00, not including tax. The cost of one vertical structure equipped with a drip-irrigation system amounts to approximately $293.00. The cost of the vertical structure that occupies 16 ft^2 of ground space is 10.4% of the cost of the LiveWall® Sprout design, and 14.9 % of the cost of the Woolly Pocket Living Wall Planters. The vertical structure is also portable and weighs approximately 95 pounds; this weight is for the vertical structure only and does not include the weight of pots filled with saturated substrate and plants. The structure itself is light enough to be placed in various locations, such as consumers' balconies or porches, or inside a business. The structure can also be oriented and placed in various directions, thus allowing the structure to take advantage of available light wherever it is placed. Moreover, the structure can be scaled to various sizes to accommodate the desires of product users. The irrigation techniques are versatile since plants can be hand-watered on the structure, or an automated irrigation system can be installed.

Despite the many advantages of the A-frame vertical garden structure, there are a few disadvantages. Since the vertical structure is a new design, it is still being evaluated. Furthermore, the structure is not commercially manufactured, and the design plans are not commercially available. Compared to the other two systems, the A-frame structure produces the least amount of plants per square foot of horizontal ground space. However, this structure is the most economical of the three systems. Like almost all living wall systems, the weight of the structure combined with the weight of plant containers and saturated substrate could be a disadvantage. The weight of one 6” x 6 ½ ” black, plastic Belden Magnum Square pot containing the commercial substrate when saturated weighs a little over 3 pounds. The weight of one structure combined with the weight of 48, 6” x 6½ ” square, plastic pots filled with saturated Fafard 3B(Sun Gro Horticulture, 770 Silver Street Agawam, MA 01001) substrate would weigh about 250 pounds. However, the wood, A-frame vertical structure is already equipped to support the additional weight of containers, substrate, and plant material, unlike the Woolly Pocket’s design, which requires a supportive framework, as seen in Figure 16. Compared to the other two systems, the A-frame structure occupies a total of 16 ft^2 of horizontal ground space, which is more than the other two systems. Additionally, soil erosion poses a potential issue since the pots sit at an angle when placed in the cattle fencing. Over-watering can cause the substrate to become unequally distributed among the pots, inhibiting uniform plant growth and exposing plant roots to pests and diseases. However, a lighter substrate could be used, and additional research involving the A-frame system could eliminate current drawbacks associated with the structure.

LiveWall®, LLC is a vertical garden venture founded in 2008 by Dave McKenzie (P.O. Box 533 Spring Lake, MI 49456). The intent of the LiveWall® company was to create beautiful and sustainable planted living walls for residential and business consumers. Only one LiveWall® LWS was evaluated for our comparison study, which is the LiveWall® Planted Wall Sprout design.

The LiveWall® Planted Wall Sprout is one of the company's DIY kit designs (Figures 13 and 14). According to the LiveWall® website, this particular design comes with many advantages. Since the Sprout system is a DIY green wall kit, consumers receive step-by-step installation instructions, as well as planting and maintenance guides. The DIY kit contains all structural and irrigation components required for installation and operation. The purchaser can install the system or have a company representative install the system. The Sprout design comes with a 10-year warranty. The company states that the design possesses a unique and patented RainRail® mounting irrigation system, along with WallTer® planting modules that are made from 100% recycled post-industrial materials. The WallTer Inserts for Topside® allows for natural soil orientation and vertical growth of plants. LiveWall® also states that the Sprout green wall is comprised of durable components, and that the planting module tiers are "high impact ultra-violet resistant." The green wall is also relatively easy to maintain, provides aesthetic displays, and is optimal for interior and exterior areas. The company also declares that annuals, perennials, succulents, herbs, and vegetables can be grown in the Sprout green wall. Furthermore, LiveWall® provides consumers with general advantages to using their products.

The company states that their designs eliminate soil erosion, and that their green walls are versatile, sustainable, and functional designs that come in various sizes and colors. Furthermore, consumers can purchase custom or pre-fabricated green wall designs, such as the Sprout design. As for the cost of the systems, the company claims that it depends upon the complexity and scale of the design, as well as ease of access to the area of installation.

The disadvantages of purchasing and utilizing the Sprout green wall include the retail cost of the design, limited growing space, and the amount of time involved during installation. The retail cost of this DIY system is $575.00, which can be a deterrent to some consumers. Dimensions of the Sprout green wall are approximately 4’ tall, 2’ 8” wide, 5’ 3/8” deep and consist of 3 tiers of planters. As seen in Figure 12, this is a relatively small green wall with limited space for plant material. The Sprout design is capable of producing about 3.5 plants per ft^2 of horizontal ground space and costs approximately $69.00 per ft^2. The plant production calculation per ft^2 was based on the dimensions of the Sprout design wall planters, and the number of plants each wall planter holds. Furthermore, the company declares that smaller projects require longer installation time than larger projects; thus, the Sprout design may be time consuming to install. Moreover, LiveWall® states that the weight of the planting tiers ranges between 10-15 pounds per ft^2 when tiers contain saturated substrate and plants (LiveWall, 2015). Based on the weight of 15 pounds per tier, and the dimensions of the Sprout design cited by the LiveWall® company, the weight for the Sprout design, including saturated substrate and plants, ranges from a total of 50-60 pounds.

Woolly Pocket Inc. is a modular green wall company founded in 2008 by Miguel and Rodney Nelson (5900 Wilshire Blvd. Los Angeles, CA 90036). The company produces two types of versatile, modular, green wall, and vertical gardening containers. Woolly Pocket’s purpose for living wall planters and pockets is to create a variety of modular, “lush green walls and magnificent vertical gardens” for the indoors and outdoors (Woolly Pocket, 2015). For the comparison study, the living wall planter was the only design type evaluated.

The Woolly Pocket Company states that the Living Wall Planter is easy to install and contains unique, built-in breathable moisture barriers for both indoor and outdoor containers. The wall planters possess an integrated watering well that holds one liter of water and can hydrate plants for approximately two weeks. The company states that the hydration time frame depends upon the climate and plant species. Figure 15 shows this particular living wall utilizes a drip-irrigation system, which contains a Woolly Pocket's Living Wall Planter Drip Kit, Drip Supply Line Kit, and a Digital Drip Timer Valve. In Figures 13 and 15, all irrigation components are hidden from view and are installed inside each watering tank. For this design, the company points out that the Drip Supply Line Kit was installed inside the wall during construction to create the effect that the green wall is floating. The green wall in Figure 15 can also be hand-watered, but the company offers buyers the option to integrate drip-irrigation kits into green walls if desired. Since the planters are modular, they can stand-alone without support. The planters are easily attachable to walls, rails, and fences, and containers come in different colors. As stated by the company, containers are constructed from 100%-recycled materials domestically produced, and provide aesthetically pleasing displays. A variety of plants can be grown in the planters, such as annuals, perennials, succulents, indoor tropical, herbs, and vegetables. The company website also lists substrate types compatible for plant types listed in the previous sentence. The Woolly Pocket design shown in Figure 17 is capable of producing about 6 plants per ft^2, which is similar to the LiveWall® Sprout plant production yield per ft^2. The planter is a versatile and space efficient method for growing plants in non-traditional spaces, and is commercially available for businesses and residential consumers around the globe (Wooly Pocket, 2015). The LWS is shown in Figures 15 through 17.

The disadvantages associated with the Woolly Pocket Living Wall Planter include the retail cost, limited growing space within a planter, no substrates are suggested, and multiple planters must be purchased in order to create a living wall. The Woolly Pocket Company provides two sizes of living wall planters. The price for the small planter is \$18.99, and the large planter costs \$26.99. Since multiple planters are needed to create a green wall, several planters must be purchased, which can become costly. Moreover, one planter can only hold three plants, which indicates limited space for plant material. The Woolly costs about \$50.00 per ft^2 of production. As for substrate holding capacity, the company states that the large planter is 13" in height x 18" wide x 8" deep, and can hold 0.50 ft^3 of substrate. The small planter is 8" in height x 11.75" wide, and holds 0.25 ft^3. Lastly, the company claims that one planter holds up to 50 pounds of weight. If multiple planters are required to create a modular green wall, buyers must keep in mind that the weight of multiple planters may require a structural support system or frame if building facades or walls cannot support the additional weight of the planters (Woolly Pocket, 2015). Figures 15 through 17 illustrate a residential case study that involves the installation of 15 living wall planters onto a concrete wall. If each planter within this wall weighed 50 pounds, and the design in Figure 17 contained 15 planters, then the entire LWS maximum weight would amount to 750 pounds.

Results and Discussion

Overall, the design of the wood, A-frame vertical structure is simple, economical and environmentally sustainable method for increasing plant production yields in a limited amount of space. According to Wong et al. (2010), the expenses most associated with LWS are attributed to installation costs, which include methods, project, scale, and watering systems. The construction and installation process for the A-frame structure requires minimal input, irrigation methods are flexible, and the cost to build and operate the structure can easily pay for itself by doubling, and almost tripling plant yields since the design has two living wall panels (Chapters 2 and 3). Comparing production yield per ft^2, the LiveWall® and Woolly Pocket systems produce about 8 plants per ft^2, while the vertical structure produces less than 1 plant per ft^2 (this includes both wall panels). The vertical structure can produce about 50% more plants per ft^2 than the LiveWall® or Woolly Pocket designs. Moreover, the design can also be scaled to suit business or residential users needs, and the total cost of the structure is much less than the cost of other LWS.

Between the three LWS, the A-frame vertical structure is the most affordable vertical system, and is the only system designed with two living wall panels. The A-frame structure is also the only portable system. The structure exhibits a simple design that consists of sustainable and durable components that are affordable and found at various hardware stores. Irrigation methods are versatile since consumers can hand-water or attach an irrigation system to the vertical structure. Drawbacks of the vertical structure include the combined weight of the structure with saturated substrate, containers, and plant material. Even though the structure produces fewer plants per ft^2, the structure is a more economical model compared to the other two vertical systems. Lastly, the structure is not commercially available and is still in the research phase.

The LiveWall® Sprout design is the most lightweight. It is also space efficient, sustainable and durable (according to the company), and produces the highest production yield per ft^2. The most significant drawback to the Sprout design is the cost, which is the highest of all three designs, followed by the installation process, and irrigation method, both of which seem to be somewhat labor intensive and time-consuming. LiveWall® states that smaller projects, like the Sprout design, require more installation time than large LiveWall® designs. Time-consuming installation processes may discourage residential consumers from purchasing the Sprout design, especially since most homeowners are more likely to purchase more practical, smaller LWS. Despite the cost and installation time, the system is designed with built in irrigation, which can be a more sustainable watering method than hand watering. Although, the built in irrigation system may contribute to the high cost of the Sprout design. Moreover, this particular design forces the consumer to purchase a system that only has one irrigation method.

Out of all three living wall system examples, Woolly Pocket's Living Wall Planter is the second most expensive and heaviest LWS. However, the Woolly Pocket's plant yield per ft^2 was comparable to the other commercial LWS. Since the Woolly Pocket Living Wall Planter is a modular LWS comprised of multiple planters, consumers must purchase more than one planter to create a living wall, which can become expensive. Furthermore, the company states that the weight of one planter can amount to 30 pounds. Another disadvantage of the Woolly Pocket Living Wall Planter is that one container only holds three plants. However, based on the installation information provided by the Woolly Pocket website, the living wall planter seems very easy to install and does not require an integrated irrigation system, although, an integrated irrigation system option is available. The company also indicates that the planters are a sustainable design method and effectively maximize space.

Conclusion

LWS represent one form of vertical gardening that continues to grow and advance as more research and interest is shown from agriculture and horticulture sciences, urban planning, ecology disciplines and landscape design, architects, and economics and social sciences (Specht et al., 2013). This manuscript demonstrates the diverse design methods that are currently available to professionals, businesses, and residential consumers. Three different LWS were evaluated in order to compare each system's design elements and parameters regarding cost, installation, and operation. Of the three LWS, one living wall design was chosen from LiveWall® and Woolly Pocket, LLC; both are successful vertical greenery ventures that promote aesthetic, environmental, and social benefits of growing plants vertically in unconventional, futuristic spaces in a sustainable manner. The third LWS is a wood, A-frame vertical structure, which is still in the research phase. Of the three LWS, the A-frame structure exhibits desirable operational and design qualities that are central to creating a sustainable and economically efficient VGS. The LiveWall® Sprout design also exhibits desirable characteristics, but it is the most expensive. Compared to the other two LWS, the Woolly Pocket Living Wall Planter requires consumers to purchase multiple planters to create an actual living wall, and both cost and weight of multiple planters can accrue quickly depending upon how many planters are purchased and used. However, the Woolly Pocket planter is more affordable than the LiveWall® Sprout design, and also quite versatile. Collectively, the Woolly Pocket planter is the easiest of all systems to install because it is modular and can be hooked, hung, or zip-tied onto a supportive edifice.

This comparison indicates that each of the three LWS possess desirable and undesirable design qualities and characteristics. The comparison also facilitates public awareness of LWS, helps to inform and educate the public about the innovative and diverse design styles, and illustrates important characteristics and qualities that should be considered when purchasing or designing a LWS. Some LWS are "very expensive and difficult to maintain" (Perini and

Rosasco, 2013). Minimizing the economical impact of vertical greenery systems is a must in order to promote and implement the use of such systems. Therefore, living wall and vertical garden companies and designers need to create more affordable and modest designs in order to entice and encourage consumers to garden vertically and implement LWS into urban areas, homes, and businesses.

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Table 4.1. Itemized list of materials and cost estimate for constructing of a wood, A-frame vertical structure.

Item Description	Quantity	Cost	Total Cost
Vertical Structure (VS) Components			
Nails- 2 ½ inch galvanized steel	1 lb. box	$2.97	$2.97
Fencing staples - 1 ½ inch Galvanized steel-	1-9gal. box	$1.19	$1.19
Carriage bolt- 3/8 inch x 3 inch Galvanized steel	6	$0.45	$2.70
Washers- 5/16” Galvanized steel	6	$0.12	0.72
Nuts- 5/16” Galvanized steel	6	S0.17	$1.02
Cattle fencing panel- 9.25 ft. x 8 ft.	1	$12.99	$12.99
2 inch x 4 inch x 8ft. treated wood board	5	$3.57	$17.85
1 inch x 4 inch x 8ft. treated wood board	6	$3.37	$20.22
Magnum square plastic pots- 6” x 6.5” ($0.40/pot)	150/box	$60.00	$60.00
Total Cost			$119.66
Item Description	**Quantity**	**Cost**	**Total Cost**
Irrigation Components			
2 GPH XB20PC Xeri-bug Rain Bird emitters	2 bags	$10.50/bag	$21.00
¼” vinyl drip tubing 10.50ft^2	$\$7.49/100\text{ft}^2$	$1.47	$1.47
½” polyethylene drip tubing 10.67ft^2	$\$13.77/100\text{ft}^2$	$0.85	$0.85
90°, ½” compression Ell connector	1	$0.65	$0.65
Compression end valve	1	$1.39	$1.39
Rain Bird modular controller	1	$117.00	$117.00
Solenoid valve	1	$15.67	$15.67
Socket adapter- ½” C x ¾” S	1	$0.51	$0.51
Pressure regulator (30 PSI)-3/4”	1	$10.17	$10.17
½” thread end cap	1	$0.51	$0.51
Polyvinylchloride pipe (PVC)- ½” and ¾” 30ft^2	$\$13.00/100\text{ft}^2$	$3.90	$3.90
Total Cost			$173.12[x]

TOTAL COST of VS components with irrigation components **$292.78**[x]

[z] Cost of components were provided by Lowe’s and local hardware stores in Auburn, AL 36849. Cost of items may vary based on location.

[y] Prices calculated in April 2014.

[x] Tax is not included for the total coast or cost of each component. The cost estimate does not include the cost of substrate and plants.

Figure 4.1. The A-frame vertical structure components shown in Figure 1 are listed below in the order as shown moving from left to right: cattle fencing panel- 9.25 feet x 8 feet, 5/16 inch galvanized steel washer, 5/16 inch galvanized steel hex nut, 2” x 4” x 8’ treated wood boards, 1-½ inch galvanized steel fencing staple, 3/8 inch x 3 inch galvanized steel carriage bolt, and 2-½ inch galvanized steel nails. See Table 1 for the quantity and cost of each component needed to construct one A-frame vertical structure.

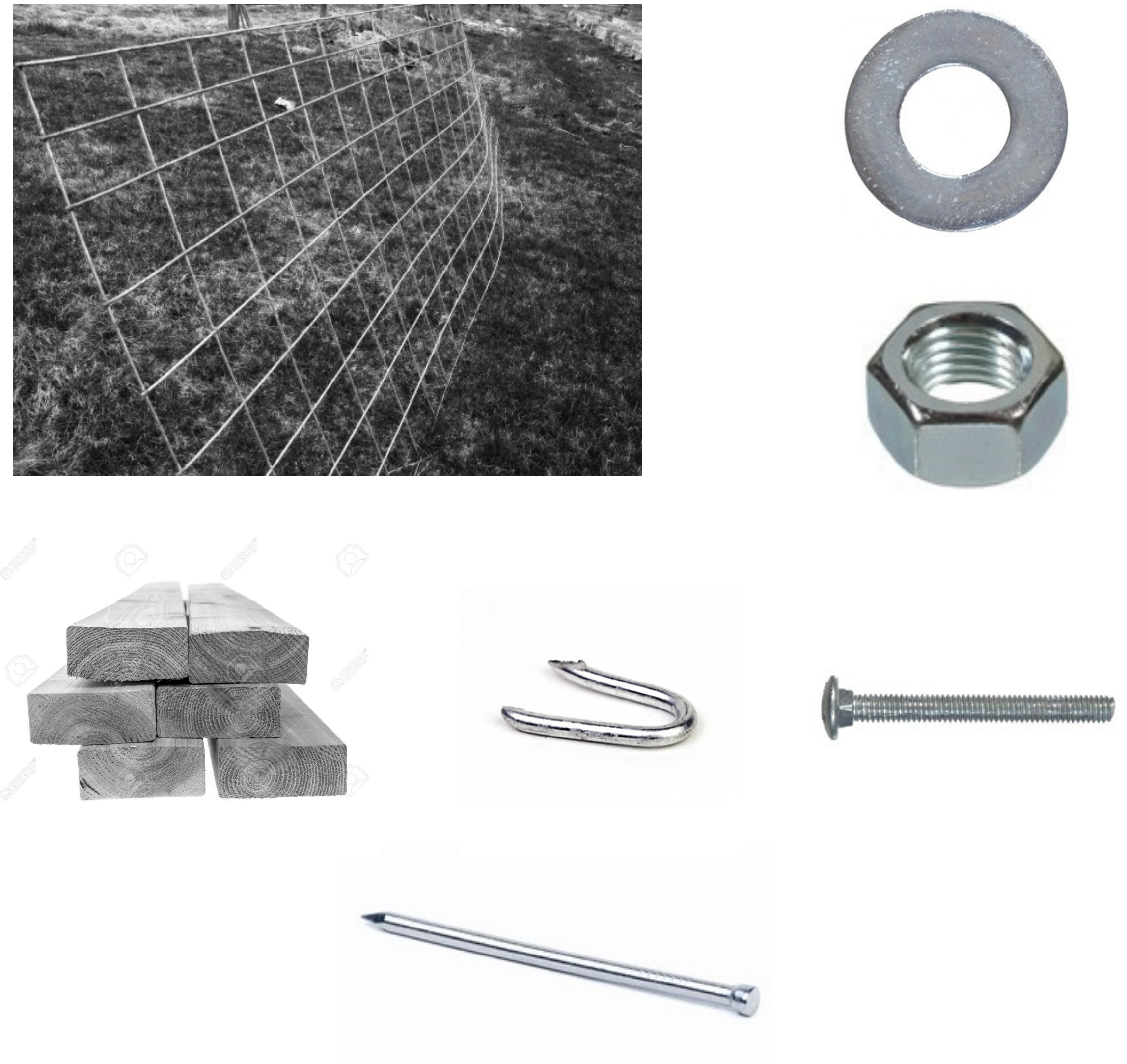

Figure 4.2. The A-frame vertical structure consists of two cattle-fencing panels that represent the living wall panels. The two wall panels are attached to each other by connecting the two, 2” x 4” x 7’ boards with two, 3/8 inch x 3-inch bolts, 5/16-inch nuts, and 5/16 inch washers. The legs, or 7-foot boards, are stabilized once the two, 3-foot boards are attached to the legs. The 3-foot boards are attached to each leg of the structure using four, 3/8-inch bolts, 5/16-inch nuts, and 5/16-inch washers. The 3-foot boards are shown at the bottom of Figure 1. See Figures 2-4 for further information on stabilizing the wood frame of the structure.

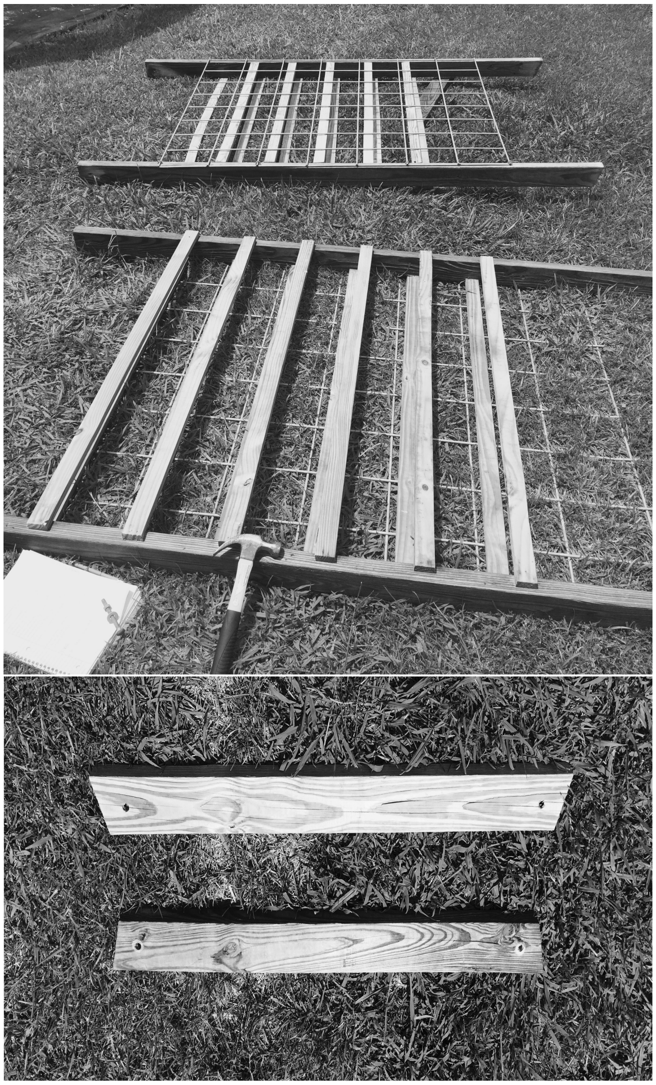

Figure 4.3. Two treated wood boards measuring 2” x 4” x 7’ are connected with two, 3/8 inch x 3 inch galvanized steel carriage bolts, 5/16 inch galvanized steel hex nuts, and 5/16 inch galvanized steel washers. This image shows the top of one leg of the A-frame vertical structure connected with one bolt, nut, and washer. Each leg of the structure requires two bolts, nuts, and washers.

Figure 4.4. The 3-foot board is connected to the two legs, or 2” x 4” boards. The smaller board was connected to the legs of the structure with a total of four 3/8 inch x 3 inch galvanized steel carriage bolts, 5/16 inch galvanized steel hex nuts, and 5/16 inch galvanized steel washers. Once the 3’ boards are attached to both legs, the structure occupies 16 ft^2 of production space.

Figure 4.5. A 3-foot board joins the legs, or, 2” x 4” boards, to each other with a 3/8-inch x 3 inch galvanized steel carriage bolt, 5/16 inch galvanized steel hex nut, and 5/16 inch galvanized steel washer. The 3’ boards stabilize the legs of the A-frame structure. Each three-foot board requires a total of four bolts, nuts, and washers.

Figure 4.6. Fencing staples that are 1 ½ inch galvanized steel were used to securely attach the cattle fencing panels onto the edge of the 2” x 4” x 7’ treated wood boards, or legs, of the A-frame vertical structure. Fencing staples were placed approximately 14 inches apart from each other on the 2-inch edges of the 7-foot boards, as shown below.

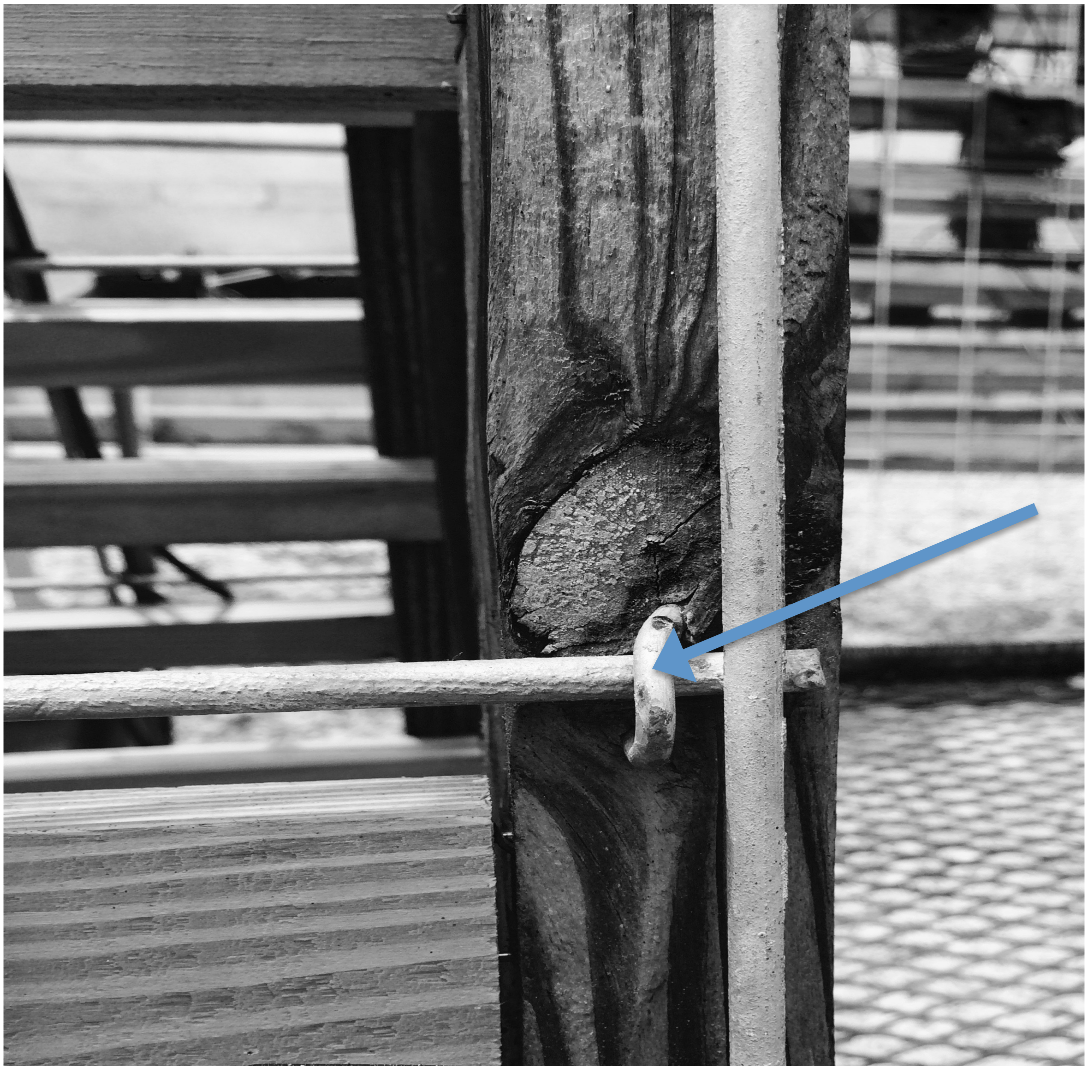

Figure 4.7. Illustrates one half of the A-frame vertical structure with wood slats in place behind one wall panel. The slats are nailed to the vertical structure with 2 ½ inch galvanized steel nails. The slats are attached to the structure to support the 6-inch pots placed in the square cells of the wall panel.

Figure 4.8. Displays where and how slats were placed behind the cattle-fencing panels. The slats are placed between and on the inside of the structure to prevent the 6-inch pots from falling through the square wall panel cells. One slat stabilizes the top of the pot, while the other slat stabilizes the bottom of the pot. Slats were nailed into place with 2 ½ inch galvanized steel nails. The slats are nailed into place in two different areas behind the wall panels. The first image shows the slats nailed into place on the edge of the legs; these slats are spaced 6 ½ inches apart and are the back slats. In the second image, the front slats are wedged and nailed in between the two legs and placed directly behind the cattle fencing. The front slats are spaced 6 ¼ inches apart. The image on the right shows how the front and back slats secure the pots when placed in the structure.

Figure 4.9. A fully assembled, 7-feet tall by 4 feet wide, wooden A-frame vertical structure without irrigation installed is shown.

Figure 4.10. A full view of one side of the vertical structure shows how the irrigation system is installed. The main irrigation line is placed on the upper edge of each cattle-fencing panel. Spaghetti tubing is connected to the main irrigation line by two gallon per hour irrigation emitters. Each line of spaghetti tubing is inserted through a pre-drilled hole in the rim of each pot. A 15/64-inch Turbomax drill bit was used to create the hole for the spaghetti tubing.

Figure 4.11. The drip irrigation system shown in Figure 11 is composed of the components shown below. Components are listed in the order as shown moving from left to right: 2 gallon-per-hour Rain Bird® emitter, ½ inch polyethylene and ¼ inch vinyl drip tubing from Landscape Products™, Rain Bird® ESP series modular controller, PVC pipe- ¾ inch and pipe fittings, 30 PSI regulator- ¾ inch, solenoid valve, socket adapter (½ inch C x ¾ inch S) and 90° compression ell connectors-½ inch, threaded end cap- ½ inch.

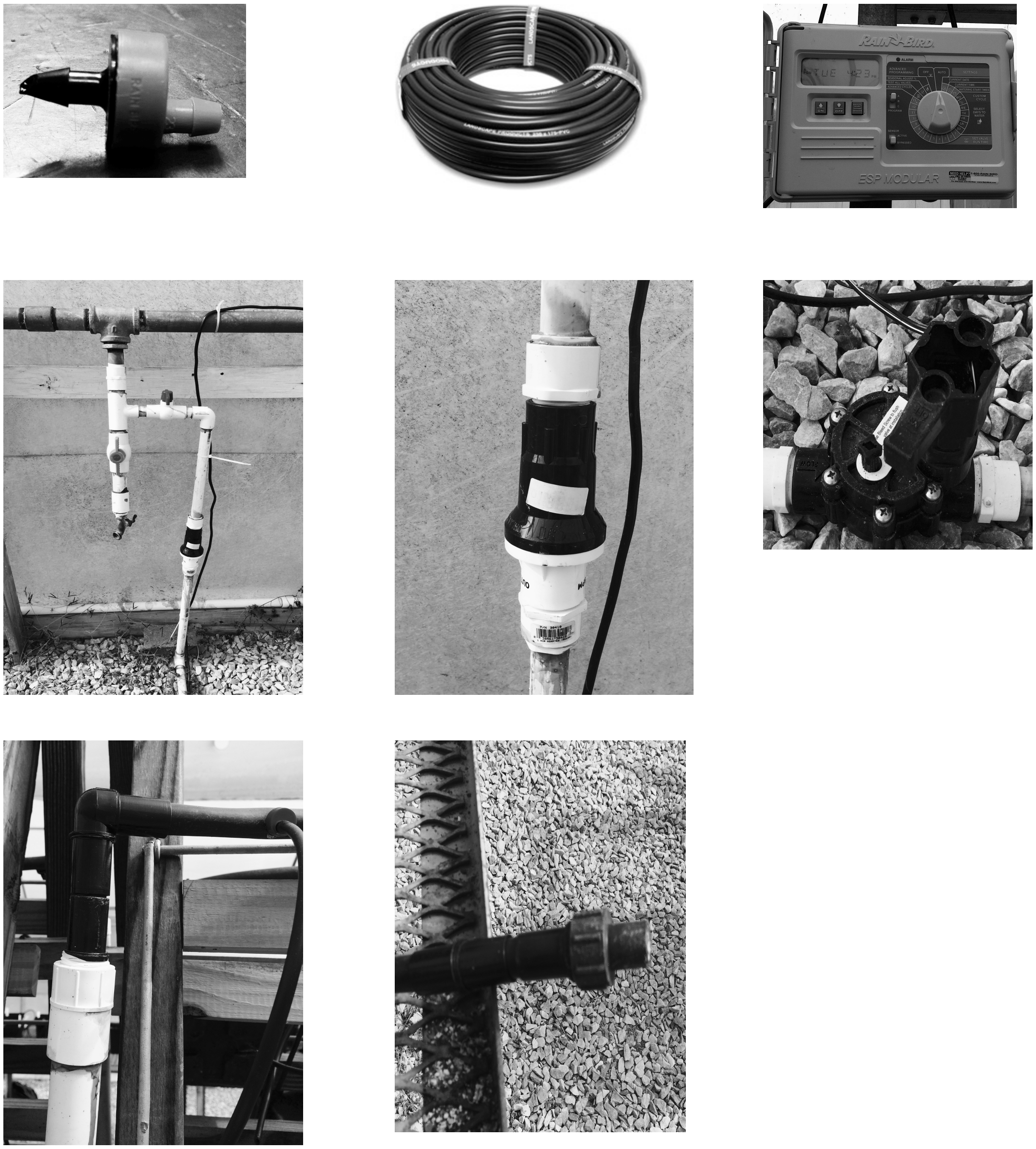

Figure 4.12. The main irrigation line is attached to the top of the cattle-fencing panel with plastic zip ties. The main irrigation line wraps around the top part of the vertical structure and extends to both wall panels. The secondary irrigation lines, or spaghetti tubing lines, are connected to the main irrigation line via two gallon- per-hour emitters. The spaghetti tubing is inserted through a pre-drilled hole located one inch below, and in the center of the pot rim. A 15/64 inch Turbomax drill head was used to create the pre-drilled hole in the rim of the pot. Once the secondary line was inserted through the pot, another two gallon-per-hour emitter was attached to the end of the spaghetti tubing, as shown below.

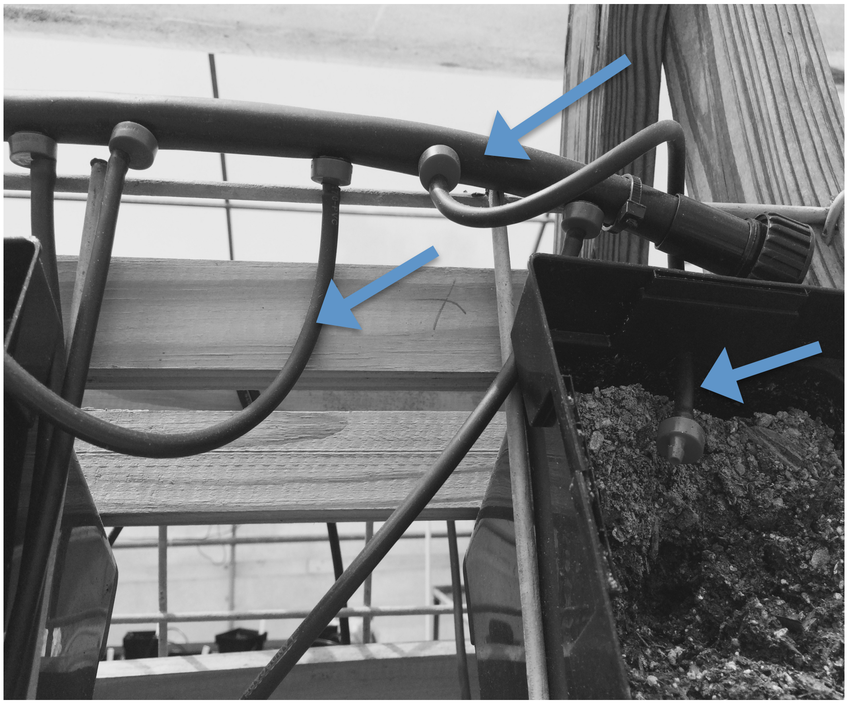

Figure 4.13. Illustrates step 7 of the LiveWall® Sprout DIY kit: Installing WallTer® planters and inserts. The design consists of seven planters, which are divided into three separate tiers. The middle tier consists of three planters, while the top and bottom tiers consist of two larger planters. The large containers are 16 inches wide, and the small containers are 8 inches wide. The living wall system is 4 feet tall and 2 feet, 8 inches wide. The figure on the right shows the design with plants placed in the containers. See LiveWall® Sprout (Automatically Irrigated) Assembly Instructions PDF for additional information. <http://www.livewall.com/docs/Kit-Assembly-Instructions-Sprout.pdf>

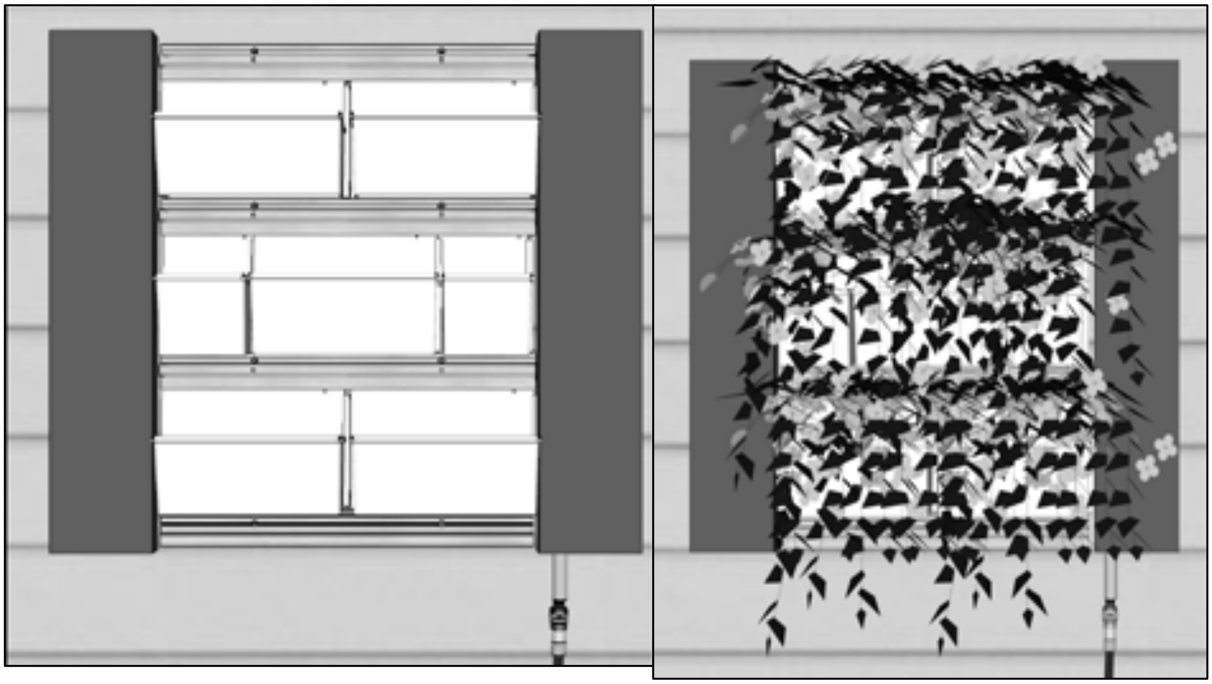

Figure 4.14. LiveWall® Sprout DIY living wall system is a three tiered living wall design that is 2 feet and 8 inches wide, approximately 4 feet tall, and 5 feet and 3/8 inches in depth. The figure illustrates a fully installed Sprout living wall system. This particular living wall system is a pre-fabricated living wall system.

Figure 4.15. The Woolly Pocket, Inc. living wall planter contains an integrated irrigation system. The figure illustrates how plants are watered via irrigation lines that are built into the Woolly Pocket living wall planter design. Irrigation components are as designed, hidden from view, and installed inside each watering tank. For the design in Figure15, the irrigation system was built inside a concrete wall to create a floating effect for the living wall.

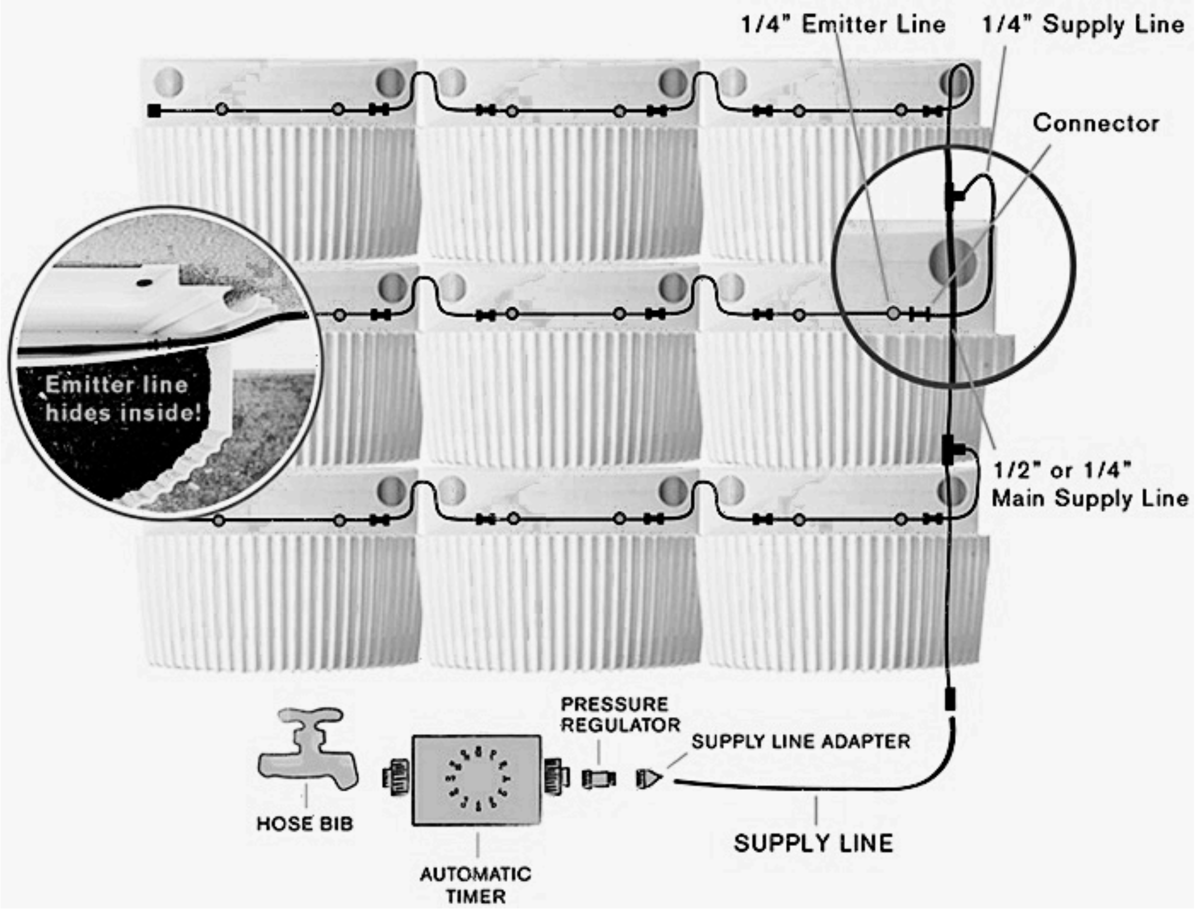

Figure 4.16. Prior to attaching the living wall planters for the Woolly Pocket living wall design shown in Figure 15, a wooden structural support system was installed onto a concrete wall.

Figure 4.17. This particular design was installed for a residential consumer from Aptos, California in July 2013. The Woolly Pocket living wall planters are attached to the wood support structure, which is shown in Figure 14. There are fifteen living wall planters used in the design. The dimensions of one planter are 13 inches in height x 18 inches wide. Based on the dimensions of the planters given by the company, the living wall is approximately 5 feet, 6 inches in height and 4 feet, 6 inches wide. The living wall in the figure on the right illustrates the fully installed Woolly Pocket living wall planter design.

CHAPTER V

CONCLUSION

The purpose of this study was to compare and evaluate three edible container-grown crops on an inexpensive A-frame vertical growing structure to crops grown traditionally on greenhouse benches. In addition to researching the efficacy of growing plants vertically on a novel, inexpensive vertical growing structure, the goal of the study was to assess the economical and sustainability aspects of constructing and employing the vertical structure for edible plant production within 16 ft^2 of horizontal production space. In order to facilitate many of the findings for the study, the following three treatments were examined:

1. Plants grown traditionally on raised greenhouse benches.
2. Plants grown on an A-frame vertical structure with wall panels facing north.
3. Plants grown on an A-frame vertical structure with wall panels facing south.

Vertical Plant Production vs. Traditional Greenhouse Bench Production

Findings in this work revealed the A-frame vertical structure to be a proficient method for producing *Amaranthus tricolor*, *Beta vulgaris* 'Detroit Dark Red', and *Ocimum basilicum* 'Cardinal Red'. Each species that was grown on the vertical structure showed comparable, or better, production yields then the crops grown traditionally on greenhouse benches. Research results in both experiments showed that plants on the south wall panel of the vertical structure performed the best, regardless of species. Despite the fact that the experiments were conducted in early-mid spring and early-late summer, time of year did not affect overall plant performance on the south-facing wall panels of the vertical structure. This is most likely due to the angle of mid-day sun, day length, and geographic location. According Schaetzl and Anderson (2005), when one is north of the Tropic of Cancer (23° N latitude) the sun is always in the southern part of the sky. When the sun is in the southern part of the sky, south facing slopes, or in this case wall panels, receive more direct sunlight than the northern slopes. As each experiment progressed throughout the year, day length increased and the angle of the sun rose higher, which resulted in the sun's rays becoming more concentrated. North-facing wall panels most likely became more shaded than south-facing panels as the sun started to set. Additionally, summer sunrays are more intense, and warmer than winter sunrays. Winter sunrays cover less ground area and strike the ground at an indirect angle causing sunrays to scatter across a larger area, creating less heat (Schroeder, 2011). Overall, the data demonstrates that (when the structure's wall panels face north and south) the plants grown vertically on the structure grew just as well, or better, than the plants grown traditionally on greenhouse benches.

Economic and Sustainable Feasibility

The evaluation and cost analysis discussed in Chapter 4 illustrates the economical and sustainable feasibility of constructing and employing the wood, A-frame structure. The cost analysis revealed that one vertical structure (without drip-irrigation) costs approximately $60.00. Both commercially available retail living wall systems (LWS) evaluated in Chapter 4 cost an average of 715% more than the A-frame structure.

Production yield calculations discussed in Chapter 4 revealed that the vertical structure doubled production yield without requiring the use of additional ground or greenhouse space. Data from both experiments indicate that the vertical structure is able to produce twice the amount of fresh or dried basil (Table 3), nearly double the amount of fresh or dried amaranth foliage when compared to the production yield of a 16 ft^2 horizontal greenhouse bench (Table 2), and over one and a half times the amount of fresh beetroots (Table 3). Research results also show that the vertical structure is an economically efficient and sustainable growing method capable of increasing production yield in the same amount of production space versus traditional, horizontal greenhouse bench methods. If employed by growers and local markets in urban and rural areas, the structure could help to generate more profits by facilitating higher crop production turnover rates and increased production yields without having to purchase more growing space.

Future Research

This work assessed the overall efficacy of constructing and employing a novel, inexpensive wood A-frame vertical growing structure with a holistic goal of developing an economical and sustainable method for edible crop production in a limited amount of space. By utilizing this structure in various climates and locations around the world, limited and confined spaces could be maximized, more edible crops could be produced, and people all over the world could gain easier access to fresh, nutritious, and inexpensive food sources. Moreover, the A-frame vertical structure possesses significant potential in regards to serving as an economically sustainable alternative to traditional greenhouse bench top and ground plot growing methods, both of which require large amounts of irreplaceable space and vital, natural resources such as arable cropland.

Future research for the vertical structure should include the continuous testing of other nutritious, edible crops, as well as ornamental crops, in order to determine which plant species are best for being used on the vertical structure. A continuation using *Amaranthus tricolor* and *Ocimum basilicum* 'Cardinal' basil could be done on the vertical structure in order to assess how each species responds to foliar harvesting at different stages of plant maturation. Varying the orientation of the vertical structure in order to determine plant performance and production yield with wall panels facing east and west could yield helpful information as well, especially since many previous studies involving LWS tend to focus on southern-facing facades. The wood A-frame structure should also be tested outside of a greenhouse setting in order to further assess the economic sustainability, durability, and potential life span of the structure when exposed to various outdoor environmental conditions. Substrate nutrient studies would provide beneficial insights as well due to the fact that the substrate solution electrical conductivity (EC) results in this study showed that pots on both wall panels of the vertical structure had higher EC readings than the pots on the greenhouse benches in all experiments. Higher EC readings likely indicated that the pots on the vertical structure leached less fertilizer than the pots on the greenhouse benches. Additional research that focuses on examining a potential correlation between pot placement and pot orientation (on the vertical structure), and how it affects leaching of supplemental nutrients and amendments commonly incorporated into substrates could help researchers and growers conserve or reduce recommended rates of supplemental nutrients for substrates.

Vertical greening systems (VGS) possess the potential to become an economically efficient and sustainable method for plant production. Ultimately, the hope of this work is to demonstrate that VGS can contribute to the overall well being of humans by producing highly nutritious plants with minimal impact on the environment and the economy. The insights gained in this work will hopefully provide beneficial information that encourages researchers within agricultural sciences, urban planners, ecologists, and landscape designers to develop and implement simple and economically sustainable vertical systems suitable for urban and rural areas.

LITERATURE CITED

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