COMPARATIVE EVALUATION OF SMALL-SCALE VERTICAL HYDROPONIC STRUCTURES AGAINST GROWING PLANTS IN SOIL WITH RESPECT TO GROWTH PARAMETERS AND RESOURCE USE EFFICIENCIES

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DECLARATION 1 - PLAGIARISM

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DECLARATION 2 – PUBLICATIONS

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ABSTRACT

The effects of climate change threaten the capacity of conventional agriculture to adequately meet future food requirements. Modern farming methods, such as vertical farming, may provide a solution for future food production as they are not as affected by climate change. However, large-scale vertical farming is associated with high capital costs and high energy requirements. Currently, there is limited quantitative research on the applicability of small-scale vertical farming systems in replacing conventional farming for future food production. Therefore, the aim of this research was to investigate the use of small-scale vertical farming structures as an alternative method of farming to replace the conventional growth of plants that can be grown hydroponically. To achieve this, Fordhook Giant Swiss Chard (*Spinacea oleracea*) was grown between February and November 2019, in the Engineering Practicals Laboratory at the Ukulinga Research Farm in Mkondeni, Pietermaritzburg. The study was a complete randomised block design and consisted of three factors, each comprising two levels. The main factor of the experiment was the growing method (soil growth in plant pots vs vertical hydroponics). The sub-factors were light provision (sunlight vs light emitting diode grow lights), and nutrient solution concentration (1.4 $g.l^{-1}$ vs 1.9 $g.l^{-1}$). The null hypothesis was that the biometric attributes and resource use efficiencies of small-scale vertical hydroponic structures would not differ from those of growing plants in soil. An ANOVA was conducted, with a 95% confidence interval, to assess whether the plant biometric attributes and the resource use efficiencies of the treatments were significantly different from each other.

Plants grown in vertical hydroponic structures had a significantly higher relative growth rate than plants grown in soil (0.090 $g.g^{-1}.day^{-1}$ vs 0.080 $g.g^{-1}.day^{-1}$ in cropping season one (CS1) and 0.085 $g.g^{-1}.day^{-1}$ vs 0.079 $g.g^{-1}.day^{-1}$ in CS2), $p = 0.030$ in CS1 and $p = 0.011$ in CS2. There was a statistically significant difference between the leaf area of plants grown in vertical hydroponic structures and those grown in soil in plant pots (1 263.39 m^2 vs 914.32 m^2 in CS1, and 1 286.98 m^2 vs 896.63 m^2 in CS2), $p < 0.0005$ in both cropping seasons. There was a significant difference between the total plant dry weight of plants grown in vertical hydroponic structures and plants grown in soil in plant pots (19.01 g vs 12.53 g, and 19.42 g vs 14.52 g in CS1 and CS2, respectively), $p < 0.0005$ in CS1 and p = 0 .001 in CS2.

The vertical hydroponic structures had a significantly higher land use efficiency than the plant pot setup (3 041.05 $g.m^{-2}$ vs 405.89 $g.m^{-2}$ in CS1, and 3 106.41 $g.m^{-2}$ vs 464.53 $g.m^{-2}$ in CS2), $p < 0.0005$. The crop water productivity of the vertical hydroponic structures was significantly higher than that of the plant pot setup (8.45 $g.l^{-1}$ vs 5.72 $g.l^{-1}$ in CS1, and 8.44 $g.l^{-1}$ vs 6.59 $g.l^{-1}$ in CS2), $p < 0.0005$ in CS1 and in CS2, $p = 0.014$.

The energy use efficiency of plants grown in vertical hydroponic structures under sunlight (104.25 $g.kWh^{-1}$ in CS1 and 103.43 $g.kWh^{-1}$ in CS2) was significantly higher than that of plants grown hydroponically under LED grow lights (12.30 $g.kWh^{-1}$ in CS1 and 12.80 $g.kWh^{-1}$ in CS2), and those grown in soil under LED grow lights (8.16 $g.kWh^{-1}$ in CS1 and 9.29 $g.kWh^{-1}$ in CS2), $p < 0.0005$.

The study has shown that vertical hydroponic structures not only produce plants with larger biometric attributes, but also do so more efficiently than the growth of plants in soil under different light treatments. Therefore, the null hypothesis was disproved. The results indicate that small-scale vertical farming structures are a viable replacement for conventional agriculture as they performed better for the attributes that were evaluated.

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1. INTRODUCTION

The productivity and success of conventional agriculture relies heavily on natural resources. Climate change is predicted to result in an overall reduction in the availability of natural resources, thereby threatening long-term dependence on conventional agriculture for food production (Kurukulasuriya and Rosenthal, 2013). Furthermore, the conventional production and distribution of food also contributes negatively to climate change (Godfray and Garnett, 2014). Therefore, there is a need for sustainable food production systems that are not as affected by climate as conventional agriculture and that have a reduced negative impact on the natural environment.

Vertical farming is a relatively new concept that stands to change the way in which food is produced in the future. According to Banerjee and Adenaeuer (2014), vertical farming is a method of farming where fungi, plants, animals and other life forms are cultivated by artificially stacking them vertically. Currently, there are a few operational large-scale vertical farms in different regions around the world, such as USA, Japan, Singapore, and China (Kalantari *et al.*, 2018).

Vertical farming is practised indoors or in closed environments where artificial inputs, such as nutrient solutions, growing media, grow lights, and environmental control are used to provide ideal growing conditions for plants. This level of control means that plant growth is not affected by external weather conditions and crop production can happen all year round, regardless of season (Benke and Tomkins, 2017). Vertical farming can be conducted in repurposed abandoned warehouses and factories, greenhouses, existing buildings and new buildings specifically designed for indoor farming (Howland *et al.*, 2012;Birkby, 2016). The manner in which commercial vertical farming is conducted is very diverse. According to Kalantari *et al.* (2018), some farms grow a variety of plants, whilst others are not diverse. Some farms have made use of retrofitted buildings that have been repurposed for indoor farming. Other farms use new buildings that were specifically designed for indoor farming. The sizes of these farms also differ. Nonetheless, the variations amongst these farms do not negate the advantages of controlled indoor farming.

Conducting vertical farming under controlled conditions offers numerous benefits. The elimination of natural, thus unpredictable, conditions eradicates weather-related plant damage and facilitates season-independent crop production. Another benefit of an enclosed environment is the reduced exposure to pests and diseases, eliminating the need for pesticides (Despommir and Ellington, 2008;Despommier, 2012). The direct provision of nutrients to plants increases the quantity and quality of yield whilst reducing growing time and increasing water use efficiency (Sarkar and Majumder, 2015). Vertical farming also offers social benefits. The growth of the vertical farming industry will create new work and research opportunities (Banerjee and Adenaeuer, 2014).

Urban-area vertical farming will also lead to shortened supply chain lengths as the buildings would be able to facilitate different the stages of food production, from growth to processing and sale. The carbon footprint and energy consumption of the food industry would be greatly reduced as transporting distances would be shortened since the multiple stages of production could be reduced to one location (Gruner *et al.*, 2013).

However, several challenges will be encountered with the establishment of large-scale commercial vertical farms. The initial costs associated with establishing vertical farms will be very high. The highly controlled environments will require precision control and monitoring. Consequently, vertical farms will have high energy- and skilled labour requirements. Jenkins (2018) questioned the sustainability of vertical farms, proposing that the high energy requirements may be counterproductive to emission reduction.

Jenkins (2018) estimated that up to 98% of vertical farm energy use was for artificial light provision and climate control. Furthermore, minor systemic failures could lead to rapid plant damage due to increased plant sensitivity under hydroponic-, aeroponic- or aquaponic growing conditions. In addition, the variety of plants that can be grown under these conditions is limited. Besides technical challenges, social acceptance of the concept of vertical farming may prove difficult to attain as well (Çİçeklİ, 2013;Banerjee and Adenaeuer, 2014;Sarkar and Majumder, 2015).

Current increases in global population numbers coupled with climate change pose a threat to future food security. Although large-scale vertical farms could be a potential solution, the capital costs and energy requirements associated with large-scale vertical farms may deter potential farmers. Furthermore, the associated high energy requirements are counterproductive to the goals of sustainability associated with vertical farms. Therefore, this research was conducted to propose the use of small-scale vertical farming structures as an alternative means of food production. The motivation for investigating small-scale vertical farming structures was that they would be able to produce more yield per unit area than soil growth with lower energy requirements than large-scale vertical farming systems. The overall objective of the study was to compare the performance of small-scale vertical hydroponic structures to soil farming with regards to plant growth parameters and resource use efficiencies.

The specific objectives of the research were:

a) To compare the biometric attributes of plants grown in small-scale vertical hydroponic structures and compare them to plants grown in soil to establish if these attributes were significantly different from each other.
b) To evaluate the productivity of small-scale vertical hydroponic structures compared to soil grown plants based on quantifying the biometric attributes and resource use efficiencies.

It was hypothesised that the difference between the plant biometric attributes and resource use efficiencies of the two growing systems would not be statistically significant.

This document reports on the results of the undertaken study. Chapter 2 is a literature review of vertical farming. In Chapter 3, the plant biometric attributes of the two growing methods are presented. Chapter 4 presents the study of the resource use efficiencies of the two growing methods. In Chapter 5, conclusions are drawn and recommendations for further research in vertical farming are made.

1.1 References

Banerjee, C and Adenaeuer, L. 2014. Up, up and away! The economics of vertical farming. *Journal of Agricultural Studies* 2 (1): 40-60.

Benke, K and Tomkins, B. 2017. Future food-production systems: vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy* 13 (1): 13-26.

Birkby, J. 2016. Vertical Farming. [Internet]. National Center of Appropriate Technology. USA. Available from: https://attra.ncat.org/attra-pub/viewhtml.php?id=512. [Accessed: 04-05-2017].

ÇİçeklÎ, M. 2013. Vertical farming. *Ege Üniversitesi Ziraat Fakültesi Dergisi* (Special Issue Volume 2): 383-388.

Despommier, D. 2012. Advantages of the vertical farm. *Sustainable Environmental Design in Architecture*. (2012):259-275.

Despommir, D and Ellington, E.2008. The vertical farm: the sky-scraper as vehicle for a sustainable urban agriculture. ResearchGate, Dubai, United Arab Emirates *CTBUH 8th World Congress on Tall & Green: Typology for a Sustainable Urban Future.* (2008): 311-318.

Godfray, HCJ and Garnett, T. 2014. Food Security and Sustainable Intensification. *Philosophical Transactions of the Royal Society: Biological Sciences* 369 (1639): 1-10.

Gruner, RL, Orazi, D and Power, D. 2013. Global versus local: an exploration on how vertical farms can lead the way to more sustainable supply chains. *IEEE Engineering Management Review* 41 (2): 23-29.

Howland, A, Kim, N and Marks, A. 2012. ADVANCED FOOD TECHNOLOGIES. [Internet]. Massachusetts Institute of Technology. Available from: https://static1.squarespace.com/static/51352c64e4b00e99bdc21d13/t/513a5cade4b0be1eb03e6b6c/1362779309755/AdvFoodTechFinalPaper.pdf. [Accessed: 01-03-2017].

Jenkins, D. 2017. Rise to the Challenge Vertical Farming within the Urban Environment. Unpublished MSc Dissertation, Architecture, Unitec Institute of Technology, Auckland, New Zealand.

Kalantari, F, Tahir, OM, Joni, RA and Fatemi, E. 2018. Opportunities and challenges in sustainability of vertical farming: A review. *Journal of Landscape Ecology* 11 (1): 35-60.

Kurukulasuriya, P and Rosenthal, S. 2013. *Climate Change and Agriculture: A Review of Impacts and Adaptations*. The World Bank, Washington DC, USA.

Sarkar, A and Majumder, M. 2015. Opportunities and Challenges in Sustainability of Vertical Eco-Farming: A Review. *Journal of Advanced Agricultural Technologies* 2 (2): 98-105.

2. VERTICAL FARMING TECHNOLOGY - A REVIEW

ABSTRACT

Environmental damage, unpredictable climatic conditions, and land resources competition, amongst others, threaten to reduce the quantity and quality of land available for farming. Consequently, field production of crops is unlikely to be able to solely sustain global future food requirements. Use of the vertical plane for food production may provide a solution to future food security concerns. Vertical farming is a method of farming where fungi, plants, animals, and other life forms are cultivated by artificially stacking them vertically. At present, the techniques used to conduct vertical farming are hydroponics, aquaponics and aeroponics. These techniques are used in conjunction with artificial inputs, such as growing structures, growing media, nutrient solutions and grow lights in an effort to optimise growing conditions for plants. The challenges associated with these controlled conditions include high establishment costs and high energy and skilled labour requirements. Minor systemic failures result in rapid plant damage. Furthermore, only a limited range of plants can be grown using hydroponics, aquaponics and aeroponics. Nevertheless, controlled environments eliminate unpredictable natural conditions and reduce exposure to pests and diseases. The direct provision of nutrients to plants increases the quantity and quality of yield whilst reducing growing time and increasing water use efficiency. Vertical farming also offers social benefits. Many new career opportunities can be expected to arise as the industry progresses. Although vertical farming is a relatively new concept, it stands to drastically change the future of food production.

2.1 Introduction

While advances in agriculture have been beneficial to humanity, they have adversely affected the environment. Surges in population numbers have put pressure on natural resources (Graff, 2012). Foley *et al.* (2011) identified modern agriculture as one of the leading causes of degradation to natural resources, resulting in damage to freshwater and land resources, the loss of biodiversity and climate change. Continuing population increases, land resources competition, damage to the environment and changing climatic conditions pose a threat to future food security. Therefore, there is a need to find alternative food production methods that have a reduced reliance on natural systems.

There are several approaches that can be considered for producing food more sustainably. Garnett *et al.* (2013) proposed using strategies that would maximise production on land that is already used for farming. These are also known as intensification strategies. Tester and Langridge (2010) identified areas with low yields as possessing the most potential for increasing agricultural productivity. This is because, globally, there are more low-yield farming areas than those that produce high yields. Strategies that use this approach include genetic modification, plant breeding, conservation and precision agriculture, amongst others. Germer *et al.* (2011) argued that, even though intensification strategies can increase food production, there will come a point where physical and biological limits are reached. This will make achieving higher yield outputs increasingly difficult to accomplish.

In permaculture, on the other hand, the intent is to create sustainability through mimicking the diverse patterns and systems that are found in the natural environment (Hathaway, 2016). Permaculture not only aims for sustainability, but also restoration of natural resources where possible (Suh, 2014). According to Krebs and Bach (2018), the foundation for permaculture-based design is the merger of three ethical norms, which are caring for the earth, caring for people and, setting limits to reproduction and consumption, and redistributing surplus.

Twelve design principles have been developed that act as a framework for permaculture-based design. These principles serve as a guide to provide a course of action for the design of complex systems (Krebs and Bach, 2018; Hathaway, 2016). Permaculture has, however, been criticized for oversimplifying and downplaying the complex and risky nature inherent to its high diversification requirements (Ferguson and Lovell, 2019).

Another approach to sustainable agriculture is using land that was not originally intended for agriculture. Urban agriculture is an example of such an approach. Zezza and Tasciotti (2010) define urban agriculture as “the production of crop and livestock goods within cities and towns”. Producing food within city limits provides several advantages, as it brings the produce closer to the market (Specht *et al.*, 2014). Urban agriculture is also not without challenges. The expected growth in population and the resulting increase in urbanisation will lead to fierce competition for urban-area resources such as water and land (Koscica, 2014). Therefore, if urban agriculture is to be considered a solution for increasing food security, it must be implemented to maximise its outputs whilst minimising required inputs.

Use of the vertical plane for food production, i.e. vertical farming, can provide a solution for maximising resource use efficiency, especially in terms of space. Banerjee and Adenaeuer (2014) defined vertical farming as a method of farming where fungi, plants, animals and other life forms are cultivated by artificially stacking them vertically. Graff (2012) further described it as being practised in soilless media under controlled environmental conditions.

Vertical farming can be conducted in repurposed abandoned warehouses and factories, greenhouses, existing buildings and new buildings specifically designed for indoor farming (Howland *et al.*, 2012;Birkby, 2016). The manner in which commercial vertical farming is conducted is very diverse. Some farms grow a variety of plants, whilst others are not diverse. Some farms have made use of retrofitted buildings that have been repurposed for indoor farming. Other farms use new buildings that were specifically designed for indoor farming. The sizes of these farms also differ. Nonetheless, the variations amongst these farms do not negate the advantages of controlled indoor farming.

The use of artificial growing inputs in vertical farming means that growing conditions can be controlled, thus reducing reliance on natural systems according to the level of control used. However, the increased reliance on technological intervention inherent to vertical farming gives rise to complexities and challenges with respect to input requirements, such as energy and highly skilled labour. The aim of this chapter is to provide an overview of vertical farming. The specific objectives are to review:

a) the technologies used to conduct vertical farming,
b) advantages and limitations of vertical farming, and
c) current developments in vertical farming.

The concept of vertical farming is introduced in Section 2.2, highlighting the techniques used, Sections 2.3 and 2.4 present important vertical farming technologies and advantages, limitations, and prospects of vertical farming. The concept of implementing vertical farming is discussed and conclusions are drawn in Section 2.5.

2.2 Vertical Farming

Fundamentally, crop farming methods have not changed since the beginnings of agriculture. The process has comprised of using water, land (the soil), solar radiation, temperature, and nutrient resources to provide ideal growing conditions for plants. Even though technological advances have allowed these inputs to be used more efficiently, the basics of agriculture have remained the same up to modern times (Despommier, 2013). However, several drivers, such as spikes in population numbers, arable land limitations and climate change, amongst others, have impacted and will continue to impact food production. Consequently, increasing focus has been put into developing technologies that move agriculture away from traditional practices (Howland *et al.*, 2012).

An example of a non-conventional farming technique is vertical farming. Banerjee and Adenaeuer (2014) defined vertical farming as a method of farming where fungi, plants, animals and other life forms are cultivated by artificially stacking them vertically. Graff (2012) further described it as being practised in soilless media under controlled environmental conditions.

As previously stated, vertical farming is practised without the use of soil. In soilless culture, nutrients are delivered to plant roots along with irrigation water (Savvas *et al.*, 2013). Currently, there are three different methods that can be used to grow plants vertically, namely hydroponic-, aquaponic- and aeroponic systems (Birkby, 2016). The general terms “hydroponics, aquaponics, and aeroponics” are used to refer to the technologies and techniques that form part of these systems.

2.2.1 Hydroponics

Sardare and Admane (2013c) defined hydroponics as the growth of plants by immersing their roots in a nutrient solution in the absence of soil. According to Birkby (2016), hydroponic systems are currently the most widely used system in vertical farming. Hydroponic systems offer many advantages over traditional farming techniques. Better quality produce is achieved at higher yields whilst using fewer inputs. This can be attributed to several factors. Indoor hydroponic systems allow high levels of input control, resulting in high water and nutrient use efficiencies and reduced reliance on unpredictable natural systems.

Moreover, systems can be designed such that water, and nutrients can be recycled, thus decreasing the need to replenish large volumes of water and nutrients, and eliminating runoff. The absence of soil eliminates the issue of fatigue, which allows repeated cultivation of the same crop in the same place without having to increase inputs. Furthermore, soil-related problems, such as weed infestation, pests and diseases are largely eliminated, reducing reliance on pest control efforts (Howland *et al.*, 2012;Sardare and Admane, 2013c;AlShrouf, 2017). An example of a hydroponic system is illustrated in Figure 2.1.

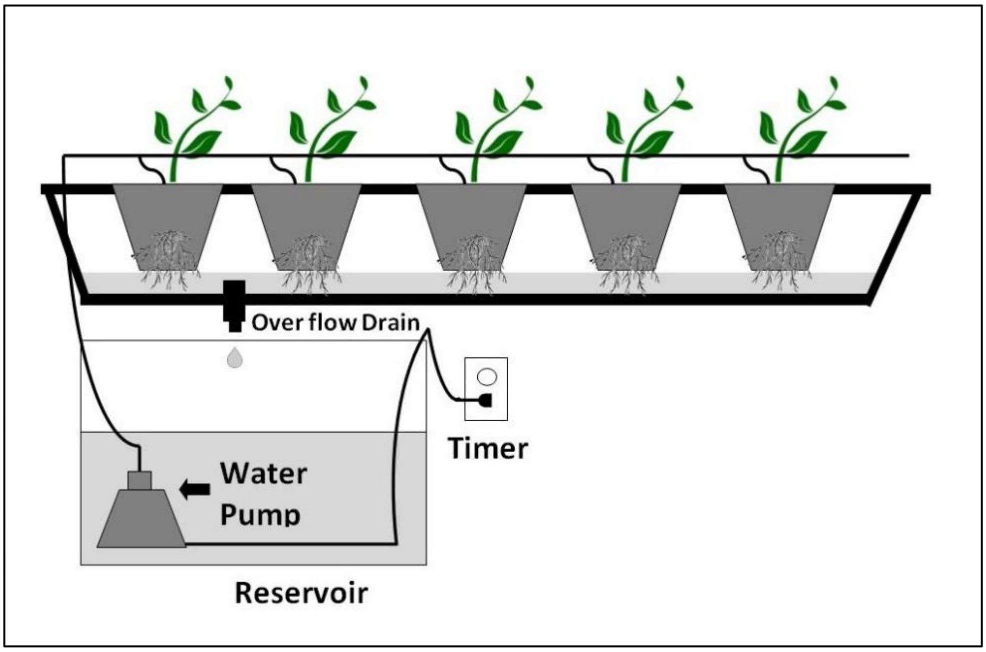

Figure 2.1 A simple hydroponic system (Birkby, 2016)

Growing plants hydroponically is not without limitations. For commercial scale application, hydroponic systems require high capital investment and technical knowledge. At the same time, a limited variety of plants can be grown using hydroponics (Lakkireddy *et al.*, 2012;Sardare and Admane, 2013c). Because the nutrient solution is circulated to all the plants, it is easy for water-borne diseases to spread rapidly among the plants in hydroponic systems (AlShrouf, 2017). Another major drawback of artificial environments is increased sensitivity to growing conditions. Minor changes can negatively affect plants at a faster rate than under natural growing conditions. This creates a need for high levels of control which results in high electricity requirements (Howland *et al.*, 2012;AlShrouf, 2017).

2.2.2 Aquaponics

Essentially, aquaponic systems are hydroponic systems that have been taken a step further. In aquaponic systems, fish rearing is introduced to the hydroponic growing method (Birkby, 2016). Three components are important in aquaponics: fish, plants, and microbes, each with a specific function.

The fish produce waste which provides nutrients for the plants. By consuming the nutrients, the plants act as a purification system for the water which is then recycled to the fish rearing component of the system. Ammonia is released with fish waste. Nitrogen in the form of ammonia is not easy to access for plants. Therefore, the presence of microbes is essential for converting ammonia to nitrate form, which plants are then able to use (Tomlinson, 2015;AlShrouf, 2017). The different components involved in an aquaponic system are illustrated in Figure 2.2.

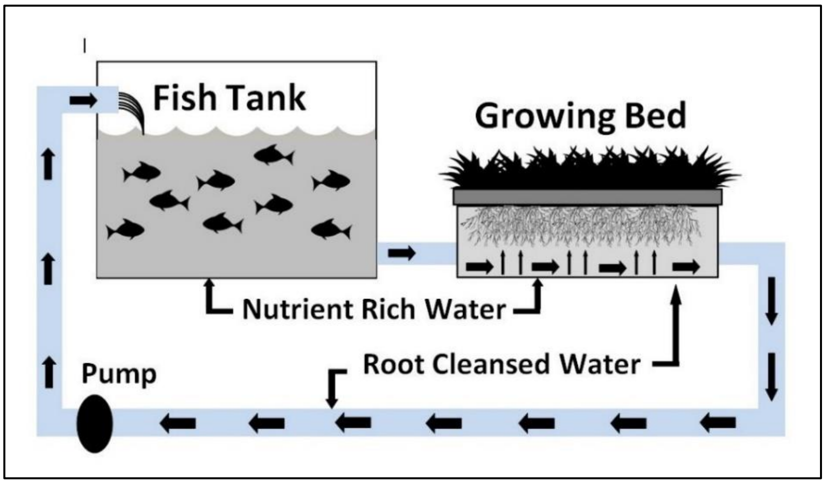

Figure 2.2 A simplified example of an aquaponic system (Birkby, 2016)

In addition to the benefits that hydroponic systems have, aquaponic systems have the added advantage of requiring fewer inputs because fish waste is used to meet the plants' nutritional requirements (Tomlinson, 2015;AlShrouf, 2017). Furthermore, the production of two different commodities makes aquaponics more productive than hydroponics. However, aquaponics is more complex and requires higher capital investment than hydroponics (Rahman and Amin, 2016).

Aquaponic systems also have higher maintenance costs due to the complexities associated with an integrated system (Tomlinson, 2015). Even though the practice of aquaponics is still not common in commercial-scale vertical farming, Birkby (2016) predicted that the development of standardised systems would be a driver for increasing the number of aquaponic systems in commercial vertical farming.

2.2.3 Aeroponics

Distinct from hydroponic and aquaponic systems, aeroponic systems do not supply nutrients in a stream of water but make use of a nutrient laden mist or fog environment for nutrient delivery (Gopinath, 2017). In this system, a nutrient laden mist is sprayed at intervals or continuously onto roots suspended in a dark and enclosed structure (AlShrouf, 2017). Figure 2.3 demonstrates the aeroponic provision of nutrients to roots. Aeroponic systems use a significantly lower amount of water than hydroponic and aquaponic systems and, therefore, have higher water use efficiencies (Gopinath, 2017).

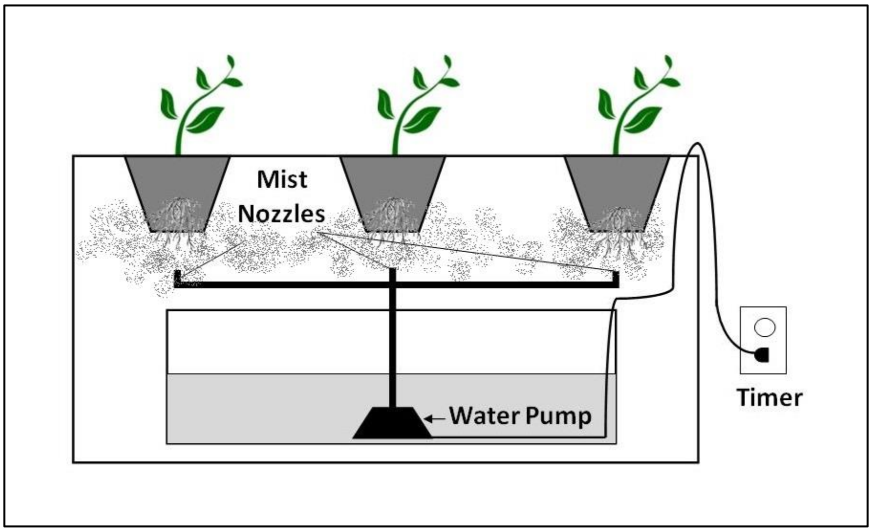

Figure 2.3 Aeroponic provision of nutrients to plant roots (Birkby, 2016)

Lakkireddy *et al.* (2012) attributed the higher metabolism and growth rates in plants grown aeroponically to the increased root exposure to air which allows the plants to access more oxygen. However, aeroponic systems require more attention and control- and monitoring systems (AlShrouf, 2017). The technology used in these systems is more costly and has higher maintenance requirements than that used in hydroponic- and aquaponic systems (Chiipanthenga *et al.*, 2012). Birkby (2016) reported that, even though aeroponic systems are still scarcely used in vertical farming, there exists a considerable interest in developing these systems.

2.3 Important Vertical Farming Technologies

Farming indoors reduces unpredictability in plant growing conditions as the process is highly technical. Traditional farming inputs, such as the soil and fertilisers, are replaced with controlled inputs, such as artificial growing media and nutrient solutions (Howland *et al.*, 2012)

2.3.1 Water and nutrient delivery techniques

In vertical farming, plants are grown under soilless conditions. Nutrients are supplied to the roots with irrigation water. Several methods exist for water and nutrient delivery. Delivery methods must facilitate sufficient aeration of the roots to prevent oxygen deficiency (Savvas *et al.*, 2013).

A water delivery system that is inexpensive and easy to operate is the wick system (Venter, 2017). In a wick system, the nutrient solution is kept in a reservoir that is not directly connected to plants. A wick is then used to draw and deliver the nutrient solution to the growing medium. The wick system does not contain any moving parts and does not require use of electricity (Mugundhan, 2011;Venter, 2017). Coconut fibre, vermiculite and perlite can be used as growing media in wick systems (Sarkar and Majumder, 2015). Venter (2017) described the drawbacks of the wick system as its inability to work for larger plants and the fact it can lead to mineral salt build-up in the root zone. However, Venter (2017) did highlight its ease of operation and non-reliance on electricity as advantages for limited small-scale application.

A system that is more complicated than the wick system is the ebb and flow system, also known as the flood and drain system (Mugundhan, 2011). In a flood and drain system, plants are secured by an aggregated material in a container and are occasionally flooded with the nutrient solution. The nutrient solution is placed in a separate reservoir and drained after the plants are flooded for a certain amount of time (Sheikh, 2006;Patil *et al.*, 2016). Pattillo (2017) provided the reason for draining the system as allowing root aeration to take place. The flooding period is usually 20 to 30 minutes, although this is not a fixed rule (Patil *et al.*, 2016;Pattillo, 2017).

Patil *et al.* (2016) stated that the flooding cycle time is influenced by the aggregate material's water holding capacity and the plant roots' tolerance to submersion. According to Lee and Lee (2015), flood and drain systems are prone to the growth of mould and algae. The plants can get root diseases as well, which is why these systems require the incorporation of sterilization or filtration equipment.

Deepwater culture is also known as floating raft culture because a suspended platform is used to support plants. The platform floats directly on the nutrient solution and contains holes which secure the plants. Generally, the floating platform is made of polystyrene, although the development of food-grade alternatives is underway. The plants are held in place by net plant pots (Pattillo, 2017). According to Savvas *et al.* (2013), the nutrient solution volume compared to the amount of available area for water and air exchange in this system can lead to oxygen deficiency. This issue can be overcome with the use of pumps or aerating the solution with spray nozzles as it is recirculated. Sheikh (2006) identified deep-water culture as an economical option for areas with limited raw materials where hydroponic systems are not manufactured.

In contrast to deep-water culture, the Nutrient Film Technique (NFT) provides the nutrient solution in a thin layer. The solution flows through PVC channels and is in contact with the bottom section of plant roots. The upper part of the roots remains constantly exposed to air to facilitate enough root aeration. Plants are positioned in holes drilled on the top side of the channels (Sheikh, 2006;Savvas *et al.*, 2013;Akil *et al.*, 2016). For horizontal channels, water flow is facilitated by positioning the channels at a slope. The solution is supplied on the elevated end using a pump (Savvas *et al.*, 2013). Pattillo (2017) identified the system's light weight as an advantage because it results in mobility and flexibility. Savvas *et al.* (2013) recommended the use of flat-based channels in horizontal NFT systems. Flat-based channels are more ideal for oxygen uptake and root development because of the increased surface area (Sheikh, 2006).

In drip irrigation systems, timers and driplines are used to deliver the nutrient solution to plants (Mugundhan, 2011). The amount of time for which drippers supply the solution is dependent on light availability and plant development stage. The nutrient solution is flushed to allow root aeration (Sheikh, 2006). Drip irrigation hydroponic systems can be recovery or non-recovery types. In the case of recovery systems, the nutrient solution is recovered and recirculated.

It is more economical because the nutrient solution is reused, however it requires more maintenance because pH levels and nutrient concentration need to be monitored and controlled. In non-recovery systems, the nutrient solution is drained and discarded. It requires less maintenance but is more expensive because larger volumes of the nutrient solution need to be replenished (Mugundhan, 2011).

Although aeroponics qualify as a subdivision of the ways in which vertical farming can be conducted, the aeroponic supply of nutrients qualifies as a nutrient delivery technique. In this system, the nutrients are supplied to the roots in a constant or intermittent mist. Several options, such as polystyrene panels, are available to secure plants (Sheikh, 2006;Savvas *et al.*, 2013). Aeroponics is more high-tech than the other forms of nutrient delivery. Timers are used to ensure that nutrients are delivered in a timely manner by pumps. It is critical that the pump and timers function well at all times because interruptions in nutrient provision can result in plant stress as the roots dry out (Mugundhan, 2011). Furthermore, plants may experience thermal stress in aeroponic systems. Nevertheless, aeroponic systems result in a very high reduction in nutrient and water use, and the roots are sufficiently aerated (Savvas *et al.*, 2013).

2.3.2 Growing structures

The technology used for growing food indoors facilitates the use of vertical structures to support plants. Graff (2012) illustrated four basic structural typologies that can be used to maximise the vertical plane in indoor farming. His descriptions included typical dimensions and land productivity improvement compared to horizontal planting. The land productivity improvement is a factor by which yield produced by a structure is increased compared to horizontal farming. An example of an A-frame trellis is illustrated in Figure 2.4. The triangular configuration results in minimal reduction of sunlight access to plants. The pipes used to form the A-frame can be configured vertically or horizontally.

Figure 2.4 An A-frame trellis design (Graff, 2012)

Stacked tray systems comprise of trays that are stacked above each other in a staggered manner to provide sufficient sunlight to each tray. This system is the most space efficient for systems that depend on sunlight, but a limited variety of plants can be grown. Figure 2.5 shows a stacked tray system.

Figure 2.5 A stacked tray system which makes use of trays to accommodate plants (Graff, 2012)

A stacked drum hydroponic system is shown in Figure 2.6. The use of stacked drums involves mounting plants on a drum equipped with a light source in the centre. This results in maximum use of artificial light and space per drum. The commercial use of this type of design is not yet common.

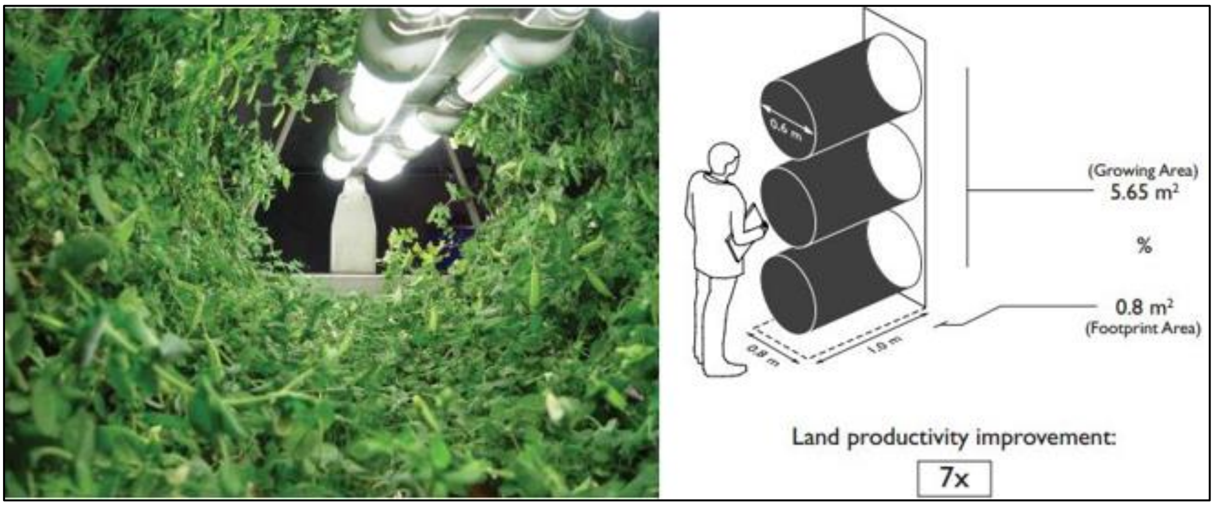

Figure 2.6 Plants grown hydroponically in stacked drums that use a single artificial light source per drum (Graff, 2012)

In the case of stacked beds, hydroponic beds carrying plants are stacked directly above each other. Due to their design, sunlight cannot reach all plants and so artificial lights are used. The lights are attached above each level. Figure 2.7 is an illustration of stacked beds.

Figure 2.7 Plants grown hydroponically in stacked beds (Graff, 2012)

Hydroponic structures that take advantage of the vertical plane in indoor farming are not limited to the above-mentioned structures. More hydroponic design structure can be expected to surface as vertical farming continues to develop.

2.3.3 Growing media

As vertical farming is conducted without the use of soil, there is a need for a substrate to secure plants. Materials used to secure plants in soilless culture are known as growing media. Mugundhan (2011) defined growing media for hydroponic plant growth as inert substrates that are used to provide root support without providing the plant with nutrients. There are two growth medium properties that are critical to its quality for plant growth: its moisture retention and its aeration characteristics. Moisture retention affects the amount of nutrient uptake whilst good aeration is required to ensure that excess moisture is drained. Materials with fine grains can store more water whilst materials that have a loose distribution provide better aeration (Howland *et al.*, 2012).

Organic growing media can be used in hydroponics because they generally cost less and are more widely available than inorganic growing media. They are also easier to dispose of (Barret *et al.*, 2016). Organic growing media that are commonly used for soilless application include coir, composts, peat, bark, and wood residues (Gruda, 2019). Generally, organic growing media can be re-used, although their structure and composition may be compromised after each use (Gruda *et al*., 2013).

The most widely used inorganic growing medium in hydroponics is rockwool. Rockwool is manufactured from basalt rock. In making rockwool, basalt rock is melted and spun into fibres which are bound together by adding additives at high temperatures. The fibres are made into cubes and slabs that are used to anchor plants (Sheikh, 2006;Gruda *et al.*, 2013). Rockwool has a high-water holding capacity and has moderate air porosity, but it cannot be reused in hydroponics and it is not biodegradable (Howland *et al.*, 2012;Dannehl *et al.*, 2015;Patil *et al.*, 2016). However, waste rockwool can be used in the reclamation of degraded soils in mines (Dannehl *et al.*, 2015).

In contrast, perlite has a low water holding capacity and higher air porosity (Pandey *et al.*, 2009;Howland *et al.*, 2012). Perlite is made by heating volcanic rock. It then explodes due to the very high temperatures. The result is a porous medium that can be bagged in plastic sleeves or used in its loose form (Sheikh, 2006). It can be used alone or in combination with other media (Gruda *et al.*, 2013). It can also be mixed with potting soil to decrease its density (George and George, 2016). Perlite can be reused after cleaning and disinfection. Reused perlite has been observed to result in higher yields in tomato growth (Incrocci *et al.*, 2010).

Similar to perlite, vermiculite is also produced by heating a mineral until it expands to pebbles that are lightweight (Pandey *et al.*, 2009;Gruda *et al.*, 2013). However, it has a higher water holding capacity and has wicking characteristics which allow it to draw nutrients to plants (Pandey *et al.*, 2009). Howland *et al.* (2012) recommended combining vermiculite with perlite in a 50/50 ratio because the water holding capacity of vermiculite is very high.

Another type of growing medium that is produced using heat is expanded clay pebbles. Clay pellets are baked at high temperatures. The heat makes the pellets swell. The process results in increased porosity (Pandey *et al.*, 2009;Gruda *et al.*, 2013). Expanded clay pebbles are not suitable for starting seeds, but their main advantage is that they can be washed, sterilised and reused (Patil *et al.*, 2016).

Growth media selection is not always an exact process with one definite answer, it is greatly influenced by financial and technical factors. Several growing medium options exist with various properties. In selecting growing media, certain desirable properties need consideration. Important characteristics include inertness, difficulty to break down and resistance to insects and diseases. Good drainage and moisture retention are also important for adequate plant aeration and nutrition (Sarkar and Majumder, 2015). It is not always possible to obtain all those properties from one type of growing medium. Therefore, substrates can be mixed, disinfected or pH corrections can be undertaken to reach desirable properties (Gruda *et al.*, 2013).

2.3.4 Grow lights

Photosynthetically active radiation (PAR) is required through the various growth stages of plants (Singh *et al.*, 2015). PAR facilitates the occurrence of different plant growth and development processes (Tamulaitis *et al.*, 2005). PAR wavelengths range 400 to 700 nm (Wollaeger, 2013b;Singh *et al.*, 2015). Insufficient solar irradiance can be problematic in vertical farming or other forms of indoor farming. This creates a need for artificial lighting systems (Howland *et al.*, 2012). Several options are available for indoor light provision.

Generally, incandescent lights are used for low-intensity photoperiodic lighting in greenhouses (Craig, 2012;Wollaeger, 2013b). But there is a limited use of incandescent lighting in indoor applications because of life span limitations (750 – 1 000 hours), poor electrical efficiency and low light emission (Girón González, 2012;Pinho *et al.*, 2012;Danila and Lucashe, 2013). Furthermore, incandescent lights release a large amount of heat during operation (Craig, 2012;Girón González, 2012).

Fluorescent light sources have a longer life span (10 000 hours), higher efficiency and higher light emission than incandescent lights (Craig, 2012;Danila and Lucashe, 2013). Because they emit a wider range of wavelengths, fluorescent lamps are frequently used in completely closed growing environments (Wollaeger, 2013b).

Another example of a lighting system that exhibits high electrical efficiencies are high intensity discharge lights. Metal halide and high-pressure sodium lamps are the most commonly used high intensity discharge lights for indoor lighting (Craig, 2012;Pinho *et al.*, 2012). Metal halide lamps can be used in applications where total sunlight replacement is required or for when sunlight needs to be supplemented (Pinho *et al.*, 2012). According to Danila and Lucashe (2013), metal halide lights can have a life span of up to 20 000 hours. However, high intensity discharge lights emit heat energy which may harm plant tissue if they are placed too close to plants (Craig, 2012).

Although conventional indoor lighting systems have certain advantages, they offer limited allowance for light output control. The light they provide cannot be easily manipulated to allow full dimming or pulsed operation. Such limitations, amongst others, have encouraged increasing research on the use of Light Emitting Diodes (LEDs) as alternatives for more energy efficient indoor lighting (Pinho *et al.*, 2012). Sabzalian *et al.* (2014) attributed the increased interest in LEDs as indoor farming light sources to the fact that they:

a) are easy to control,
b) have a long-life span of up to 100 000 hours,
c) do not produce high amounts of heat,
d) have small dimensions, and
e) have high operating efficiencies.

One of the greatest advantages of using LEDs is the fact that changes in natural sunlight can be simulated by manipulating their spectral compositions and altering the intensity of light they emit (Yeh and Chung, 2009). Although LED lighting systems have a high capital cost, Singh *et al.* (2015) predicted a reduction in costs due to a likely increase in demand in the greenhouse and indoor farming industry.

2.4 Advantages and Limitations of Vertical Farming

Conventional farming activities have caused significant environmental damage. Continued reliance on traditional farming techniques poses a threat to the natural environment and future food security. Therefore alternative strategies, such as vertical farming, need to be considered (Despommir and Ellington, 2008). Conducting vertical farming under controlled conditions offers numerous benefits. The elimination of natural, thus unpredictable, conditions eradicates weather-related plant damage and facilitates season-independent crop production. Another benefit of an enclosed environment is the reduced exposure to pests and diseases, eliminating the need for pesticides (Despommir and Ellington, 2008;Despommier, 2012). The direct provision of nutrients to plants increases the quantity and quality of yield whilst reducing growing time and increasing water use efficiency (Sarkar and Majumder, 2015). Vertical farming also offers social benefits. The growth of the vertical farming industry will create new work and research opportunities (Banerjee and Adenaeuer, 2014).

Urban-area vertical farming will also lead to shortened supply chain lengths as the buildings would be able to facilitate different the stages of food production, from growth to processing and sale. The carbon footprint and energy consumption of the food industry would be greatly reduced as transporting distances would be shortened since the multiple stages of production could be reduced to one location (Gruner *et al.*, 2013).

However, several challenges will be encountered with the establishment of large-scale commercial vertical farms. The initial costs associated with establishing vertical farms will be very high. The highly controlled environments will require precision control and monitoring. Consequently, vertical farms will have high energy- and skilled labour requirements. Jenkins (2018) questioned the sustainability of vertical farms, proposing that the high energy requirements may be counterproductive to emission reduction. Furthermore, Jenkins (2018) estimated that up to 98% of vertical farm energy use was for artificial light provision and climate control.

Vertical farming stands to drastically alter the way in which food of the future will be produced. In fact, great research effort has been put into theorising about how vertical farms would be integrated into cities. Therefore, much scientific work on the subject matter remains largely theoretical. There is a lack of quantitative and systematic analysis of the technology and costs involved in existing and operational vertical farms (Kalantari *et al.*, 2017).

Cho (2015) attributed this information deficiency to the short time span that these commercial farms have been in operation. The owners have had no incentive to collect and record operational data. Furthermore, due to competitive reasons, owners are reluctant to reveal too much information. Van der Schans *et al.* (2014) reported that, because urban agriculture is driven by people who may not always have an agricultural background, it is developing as a rather informal sector. The result has been that new developments in urban agriculture, and their associated data, have not always been recognised and recorded by the formal knowledge system. According to Hallock (2013), the first type of vertical farm that was considered commercially viable was the rooftop greenhouse. These types of vertical farms have been popular commercially, but indoor vertical farms are also gaining traction.

2.5 Discussion and Conclusions

As conventional methods of food production continue to face challenges, such as degradation of land and water resources, the effects of climate change and land resources competition, other methods of food production need to be explored. This is especially the case considering future global population estimates. The use of vertical structures for food production offers a potential approach to future food security concerns. Vertical farming makes use of artificial inputs, such as growing structures, growing media, nutrient solutions and grow lights to mimic natural growing conditions. This allows the farmer varying degrees of control over growing conditions.

Of the three options available for conducting vertical farming, hydroponics is currently the most used. This is mainly due to its simplicity and lower capital costs as compared to the other two options. However, aquaponics and aeroponics have potential to overtake hydroponics in terms of popularity with advances in technology and gains in technical skills. It may further be argued that with sufficient technical resources, these technologies would be superior to hydroponics.

Unlike hydroponics, aquaponics facilitates the production of two commodities from one system. The presence of fish also reduces input costs as waste is used to supply plants with nutrients. Aeroponics, on the other hand, uses much lower volumes of the nutrient solution, which further adds to reduced reliance on water resources. The technical complexities inherent to aquaponics and aeroponics can be expected to be simplified as more experience is gained either through research and/or commercial development.

It is further predicted that technological advances will also favour dominance of the aeroponic delivery of the nutrient solution to plants over the other nutrient delivery techniques. Its main advantage being the highly reduced use of water and the nutrient solution. Another contender is the NFT. Both techniques facilitate the simultaneous provision of nutrients and oxygen to the roots. With the other techniques, nutrient solution delivery and aeration are achieved in separate steps or the addition of air pumps is required. Although the wick system is simple to use, its commercial use is highly unlikely. This is mainly because it can only be used with a limited variety of plants, which would be restrictive to farmers.

Because no soil is used in vertical farming, artificial growing media are used to anchor plants. One of the aims of vertical farming is producing food in a sustainable manner. Currently, some commonly used growing media, such as rockwool, cannot be reused in subsequent cycles. Discarding used growing media opposes the concept of minimising the environmental impact of vertical farming. However, these growing media can be repurposed within agriculture, recycled, or reused in non-agricultural applications.

The high establishment costs and energy requirements of large-scale vertical farms are a valid concern in terms of financial feasibility. It is argued that the high energy requirements for environmental control and artificial light provision are counterproductive. Renewable energy could be used to supplement and eventually replace grid electricity. Besides using solar power, the location of vertical farms in urban areas could allow use of electricity generated from waste heat recovered from industrial processes. Alternatively, energy requirements could be reduced by altering existing buildings to allow more sunlight. Perhaps, artificial light could be supplementary as opposed to being the main source of light. Alternately, vertical farming could be initiated on a small scale. This could potentially reduce overall energy use, whilst maximising space-use efficiency.

Use of the vertical plane to grow crops could provide an answer to many issues that are inherent to traditional farming practices. However, one of the biggest challenges of vertical farming are the high initial costs. Additionally, the increased control over growing conditions requires a constant supply of electricity and highly skilled labour. Despite these challenges, vertical farming has great potential for use in food production. Direct provision of nutrients to roots improves yield quality and quantities. Time to grow plants is also decreased. Yield quantities are further increased by the fact that plants are grown on multiple levels.

Current research suggests that vertical farming has potential to eventually replace some conventional farming systems. However, there is a shortage of quantitative data based on experimental work or established vertical farms. Such information is needed to not only allow interested potential farmers to make informed decisions but to also aid in improving current technologies. Furthermore, research from established vertical farms or experimental work could be used to establish standards and regulations to ensure that vertical farming is implemented sustainably.

2.6 References

Akil, K, Sivasakthi, M and Maha, K. 2016. Aquaponics–The Future Farming. *International Journal of Innovative Research in Technology, Science & Engineering* 2 (4): 1-4.

AlShrouf, A. 2017. Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)* 27 (1): 247-255.

Banerjee, C and Adenaeuer, L. 2014. Up, up and away! The economics of vertical farming. *Journal of Agricultural Studies* 2 (1): 40-60.

Barret, GE, Alexander, PD, Robinson, JS, Bragg, NC. 2016. Achieving environmentally sustainable growing media for soilless plant cultivation systems - A review. *Scientia Horticulture* 212 (2016): 220 – 234.

Birkby, J. 2016. Vertical Farming. [Internet]. National Center of Appropriate Technology. Available from: https://attra.ncat.org/attra-pub/viewhtml.php?id=512. [Accessed: 04-05-2017].

Chiipanthenga, M, Maliro, M, Demo, P and Njoloma, J. 2012. Potential of aeroponics system in the production of quality potato (Solanum tuberosum l.) seed in developing countries. *African Journal of Biotechnology* 11 (17): 3993-3999.

Cho, R. 2015. How sustainable is vertical farming? [Internet]. Columbia University. Available from: https://phys.org/print369046891.html. [Accessed: 10 February 2018].

Çİçeklİ, M. 2013. Vertical farming. *Ege Üniversitesi Ziraat Fakültesi Dergisi* (Special Issue Volume 2): 383-388.

Craig, DS. 2012. Determining effective ratios of red and far-red light from light-emitting diodes that control flowering of photoperiodic ornamental crops. Unpublished MSc Dissertation thesis, Horticulture, Michigan State University, East Lansing, USA.

Danila, E and Lucashe, D. 2013. Cost Effectiveness of Growing Plant Lighting System. *Journal of Electrical Engineering* (320): 224-229.

Dannehl, D, Suhl, J, Ulrichs, C and Schmidt, U. 2015. Evaluation of substitutes for rock wool as growing substrate for hydroponic tomato production. *Journal of Applied Botany and Food Quality* 88 (1):68-77.

Despommier, D. 2012. Advantages of the vertical farm. In: *Sustainable Environmental Design in Architecture*. Springer, New York, USA.

Despommier, D. 2013. Farming up the city: the rise of urban vertical farms. *Trends in Biotechnology* 31 (7): 388-89.

Despommir, D and Ellington, E.2008. The vertical farm: the sky-scraper as vehicle for a sustainable urban agriculture. *CTBUH 8th World Congress on Tall & Green: Typology for a Sustainable Urban Future*, 311-318. ResearchGate, Dubai, United Arab Emirates.

Ferguson, R.S. and Lovell, S.T., 2019. Diversification and labor productivity on US permaculture farms. *Renewable Agriculture and Food Systems* 34 (4): 326-337.

Foley, JA, Ramankutty, N, Brauman, KA, Cassidy, ES, Gerber, JS, Johnston, M, Mueller, ND, O'Connell, C, Ray, DK and West, PC. 2011. Solutions for a cultivated planet. *Nature* 478 (7369): 337-342.

Garnett, T, Appleby, M, Balmford, A, Bateman, I, Benton, T, Bloomer, P, Burlingame, B, Dawkins, M, Dolan, L and Fraser, D. 2013. Sustainable intensification in agriculture: premises and policies. *Science* 341 (6141): 33-34.

George, P and George, N. 2016. Hydroponics-(Soilless Cultivation Of Plants) for Biodiversity Conservation. *International Journal of Modern Trends in Engnieering and Science* 3 (6):97-104

Germer, J, Sauerborn, J, Asch, F, de Boer, J, Schreiber, J, Weber, G and Müller, J. 2011. Skyfarming an ecological innovation to enhance global food security. *Journal für Verbraucherschutz und Lebensmittelsicherheit* 6 (2): 237-251.

Girón González, E. 2012. Leds for General and Horticultural Lighting. Unpublished MSc Dissertation thesis, Electronics, Aalto University, Greater Helsinki, Finland.

Gopinath, P. 2017. Aeroponics Soilless Cultivation System for Vegetable Crops. *Chemical Science Review and Letters* 6 (22): 838-849.

Graff, GJ. 2012. Skyfarming. Unpublished MSc thesis, Department of Architecture, University of Waterloo, Ontario, Canada.

Gruda, N, Qaryotui, MM and Leonardi, C. 2013. Growing Media. In: eds. Wilfried, B, Remi, N-W, Nebambi, L, Alison, H, Nicolás, C, Cherubino, L, Stefania, DP, Muien, Q and Duffy, R, *Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate Areas*. Ch. 11, 271 - 302. Food And Agriculture Organization Of The United Nations, Rome, Italy.

Gruda, NS. 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy 9 (6): 298 – 322.

Gruner, RL, Orazi, D and Power, D. 2013. Global versus local: an exploration on how vertical farms can lead the way to more sustainable supply chains. *IEEE Engineering Management Review* 41 (2): 23-29.

Hallock, LS. 2013. Vertical Farms, Urban Restructuring and the Rise of Capitalist Urban Agriculture. Unpublished MSc thesis, Agrarian and Environmental Studies, Erasmus University, Hague, Netherlands.

Hathaway, M.D., 2016. Agroecology and permaculture: addressing key ecological problems by rethinking and redesigning agricultural systems. *Journal of Environmental Studies and Sciences* 6(2): 239-250.

Howland, A, Kim, N and Marks, A. 2012. ADVANCED FOOD TECHNOLOGIES. [Internet]. Massachusetts Institute of Technology. Available from: https://static1.squarespace.com/static/51352c64e4b00e99bdc21d13/t/513a5cade4b0be1eb03e6b6c/1362779309755/AdvFoodTechFinalPaper.pdf. [Accessed: 01-03-2017].

Incrocci, L, Pardossi, A, Minuto, A and Diara, C.2010. Reusing Greenhouse Growing Media. *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 927*, 793-800. International Society for Horticultural Science.

Jenkins, D. 2017. Rise to the Challenge Vertical Farming within the Urban Environment. Unpublished MSc Dissertation, Architecture, Unitec Institute of Technology, Auckland, New Zealand.

Kalantari, F, Tahir, O, Lahijani, A and Kalantri, S. 2017. A Review of Vertical FArmin Technology: A Guide for Implementation of Building Integrated Agr. *Advanced Engineering Forum* 24 (2017): 76-91.

Koscica, M. 2014. Agropolis: the role of urban agriculture in addressing food insecurity in developing cities. *Journal of International Affairs* 67 (2): 177 - 186.

Krebs, J. and Bach, S., 2018. Permaculture—Scientific evidence of principles for the agroecological design of farming systems. *Sustainability* 10 (9):3218 – 3242.

Lakkireddy, K, Kasturi, K and KRS, SR. 2012. Role of Hydroponics and Aeroponics in Soilless Culture in Commercial Food Production. *Journal of Agricultural Science & Technology* 1 (1): 26-35.

Lee, S and Lee, J. 2015. Beneficial bacteria and fungi in hydroponic systems: types and characteristics of hydroponic food production methods. *Scientia Horticulturae* 195(2015): 206-215.

Mugundhan, M. 2011. "Hydroponics"-a novel alternative for geoponic cultivation of medicinal plants and food crops. *International Journal of Pharma and Bio Sciences* 2 (2): 286-296.

Pandey, R, Jain, V, Pandey, KSR and Singh, K. 2009. Hydroponics Agriculture: Its Status, Scope and Limitations. [Internet]. Researchgate. Available from: https://www.researchgate.net/profile/Renu_Pandey/publication/259786326_Hydroponics_Agriculture_Its_Status_Scope_and_Limitations/links/00b4952de76be8b665000000.pdf. [Accessed: 06-06-2017].

Patil, P, Kakade, S, Kantale, S and Shinde, D. 2016. Automation in Hydroponic System Using PLC. *International Journal of Scientific and Technical Advancements* 2 (2): 69-71.

Pattillo, DA. 2017. An Overview of Aquaponic Systems: Hydroponic Components.19. NCRAC Technical Bulletins, Ames, Iowa, USA.

Pinho, P, Jokinen, K and Halonen, L. 2012. Horticultural lighting–present and future challenges. *Lighting Research & Technology* 44 (4): 427-437.

Rahman, MA and Amin, MR. 2016. Aquaponics: A Potential Integrated Farming System for Sustainable Agriculture and Aquaculture. *International Journal of Biological, Ecological and Environmental Sciences* 5 (1): 42-45.

Sabzalian, MR, Heydarizadeh, P, Zahedi, M, Boroomand, A, Agharokh, M, Sahba, MR and Schoefs, B. 2014. High performance of vegetables, flowers, and medicinal plants in a red-blue LED incubator for indoor plant production. *Agronomy for Sustainable Development* 34 (4): 879-886.

Sardare, MMD and Admane, MSV. 2013. A review on plant without soil-hydroponics. *Int J Res Eng Technol* 2 (3): 299-305.

Sarkar, A and Majumder, M. 2015. Opportunities and Challenges in Sustainability of Vertical Eco-Farming: A Review. *Journal of Advanced Agricultural Technologies* 2 (2): 98-105.

Savvas, D, Gianquinto, G, Tuzel, Y and Gruda, N. 2013. Soilless culture. In: eds. Wilfried, B, Remi, N-W, Nebambi, L, Alison, H, Nicolás, C, Cherubino, L, Stefania, DP, Muien, Q and Duffy, R, *Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate Areas*. Ch. 12, 303 - 354. Food And Agriculture Organization of The United Nations, Rome, Italy.

Sheikh, B. 2006. Hydroponics: key to sustain agriculture in water stressed and urban environment. *Pakistan Journal of Agriculture, Agricultural Engineering and Veterinary Sciences* 22 (2): 53-57.

Singh, D, Basu, C, Meinhardt-Wollweber, M and Roth, B. 2015. LEDs for energy efficient greenhouse lighting. *Renewable and Sustainable Energy Reviews* 49 (2015) 139-147.

Specht, K, Siebert, R, Hartmann, I, Freisinger, UB, Sawicka, M, Werner, A, Thomaier, S, Henckel, D, Walk, H and Dierich, A. 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values* 31 (1): 33-51.

Suh, J., 2014. Towards sustainable agricultural stewardship: Evolution and future directions of the permaculture concept. *Environmental Values* 23 (1): 75-98.

Tamulaitis, G, Duchovskis, P, Bliznikas, Z, Breive, K, Ulinskaite, R, Brazaityte, A, Novičkovas, A and Žukauskas, A. 2005. High-power light-emitting diode based facility for plant cultivation. *Journal of Physics D: Applied Physics* 38 (17): 3182-3187.

Tester, M and Langridge, P. 2010. Breeding technologies to increase crop production in a changing world. *Science* 327 (5967): 818-822.

Tomlinson, L. 2015. Indoor Aquaponics in Abandoned Buildings: A Potential Solution to Food Deserts. *Sustainable Dev. L. & Pol'y* 16 (2015): 16-24.

Van der Schans, J, Renting, H and Van Veenhuizen, R. 2014. Innovations in urban agriculture. *Urban Agriculture magazine* 28 (2014): 3-12.

Venter, G. 2017. Understanding semi-hydroponic systems. *Farmer's Weekly* 2017 (17010): 24-25.

Wollaeger, HM. 2013. Growth and morphological acclimation of seedlings to blue, green, and red light from light-emitting diodes. Unpublished thesis, Horticulture, Michigan State University, East Lansing, USA.

Yeh, N and Chung, J-P. 2009. High-brightness LEDs—Energy efficient lighting sources and their potential in indoor plant cultivation. *Renewable and Sustainable Energy Reviews* 13 (8): 2175-2180.

Zezza, A and Tasciotti, L. 2010. Urban agriculture, poverty, and food security: empirical evidence from a sample of developing countries. *Food Policy* 35 (4): 265-273.

3. THE ASSESSMENT OF VERTICAL HYDROPONIC STRUCTURES AGAINST PLANTING IN SOIL UNDER DIFFERENT LIGHT CONDITIONS

Abstract

Currently, there is a gap in literature on quantitative analysis of the performance of small-scale vertical hydroponic structures as compared to growing crops in soil. Therefore, the aim of the research was to evaluate the performance, in terms of plant growth, of small-scale vertical hydroponic structures compared to planting in soil. Fordhook Giant Swiss chard (*Spinacea oleracea*) was grown over 2 cropping seasons between February and November 2019, in the Engineering Practicals Laboratory at the Ukulinga Research Farm in Mkondeni, Pietermaritzburg. The main factor of the experiment was the growing method (plants grown in soil in plant pots vs vertical hydroponics). The sub-factors were light provision (sunlight vs light emitting diode grow lights), and nutrient solution concentration (1.4 $g.l^{-1}$ vs 1.9 $g.l^{-1}$). It was hypothesized that the biometric attributes of plants grown hydroponically under different light treatments would not differ from those grown in soil under different light treatments. An ANOVA was conducted, with a 95% confidence interval, to assess if the plant biometric attributes of the treatments were significantly different from each other. Plants grown hydroponically had a significantly higher relative growth rate than plants grown in soil (0.090 $g.g^{-1}.day^{-1}$ vs 0.080 $g.g^{-1}.day^{-1}$ in cropping season one (CS1), and 0.085 $g.g^{-1}.day^{-1}$ vs 0.079 $g.g^{-1}.day^{-1}$ in CS2), $p = 0.030$ in CS1, and $p = 0.011$ in CS2. There was a statistically significant difference between the total leaf area per plant of plants grown hydroponically and those grown in soil in plant pots (1 263.39 mm^2 vs 914.32 mm^2 in CS1, and 1 286.98 mm^2 896.63 mm^2 in CS2), $p < 0.0005$ in both cropping seasons. There was a significant difference between the total plant dry weight of plants grown hydroponically and plants grown in soil in plant pots (19.01 g vs 12.53 g in CS1, and 19.42 g vs 14.52 g in CS2), $p < 0.0005$ in CS1 and $p = 0.001$ in CS2. The null hypotheses were disproved. The vertical hydroponic system under LED grow lights performed better than the other treatments. The results indicate that the use of small-scale vertical hydroponic structures is a viable alternative for plant production in place of conventional agricultural systems. The study has contributed new quantitative information about the performance of vertical hydroponic structures, which may aid potential farmers in decision making.

Keywords: vertical farming, hydroponics, LED grow lights, relative growth rates, Swiss chard

3.1 Introduction

It is estimated that by the year 2050 there will be a global population of over 9 billion (UN, 2015). It is further estimated that food production will need to be increased by 70% to adequately meet the food requirements of this population. To achieve this, food production will have to be increased by an average 44 million metric tonnes annually (Tester and Langridge, 2010). However, achieving this goal will be challenging. This is because several drivers, such as spikes in population numbers, arable land limitations and climate change, amongst others, have impacted and will continue to impact food production. Therefore, there exists a need for high-yielding food production methods that are sustainable as well. Consequently, an increasing focus has been put into developing technologies that move agriculture away from traditional practices (Howland *et al.*, 2012).

The concept of using the vertical plane for food production is an example of the application of such technologies. Banerjee and Adenaeuer (2014) define vertical farming as a method of farming where fungi, plants, animals and other life forms are cultivated by artificially stacking them vertically. Graff (2012) further describes it as being practised in soilless media under controlled environmental conditions. Vertical farming can be conducted in repurposed abandoned warehouses and factories, greenhouses, existing buildings, and new buildings specifically designed for indoor farming (Howland *et al.*, 2012;Aswath *et al.*, 2016;Birkby, 2016).

There are currently three systems that can be used to conduct vertical farming. These are aeroponics, aquaponics and hydroponics (Birkby, 2016). In these systems, soil is not used. This is known as soilless culture. Savvas *et al.* (2013) defined soilless culture as any plant growing method that does not rely on soil as a rooting medium. Nutrients for such systems are delivered with the irrigation water. Sardare and Admane (2013c) defined hydroponics as the growth of plants by immersing their roots in a nutrient solution in the absence of soil. According to Birkby (2016), hydroponic systems are currently the most widely used system in vertical farming.

In soilless culture, such as hydroponics, a growing medium is required to anchor plants. Inertness, bio-stability, and a physical structure that creates a balance between aeration and water retention are crucial attributes for growing media effectiveness (Wahome *et al.*, 2011;Gruda *et al.*, 2013). In addition to these properties, according to Maršić and Jakše (2010) and Gruda *et al.* (2013), expanded clay pellets have good drainage properties, are lightweight, can be reused, and are chemically neutral.

A crucial component of hydroponic systems is the nutrient solution. It supplies the plants with macro- and micro-nutrients (Kumari *et al.*, 2018b). According to Trejo-Téllez *et al.* (2012), electrical conductivity (EC) is a suitable indicator of the concentration of nutrients in the solution. EC values should range between 1.5 and 2.5 $dS.m^{-1}$ for hydroponic systems (Trejo-Téllez *et al.*, 2012;Kumari *et al.*, 2018b). According to Trejo-Téllez *et al.* (2012), the pH of the nutrient solution is also very important for plant nutrient uptake and should be between 5.5 and 6.5 to ensure nutrient availability for plants.

Insufficient sunlight penetration can be problematic in vertical farming or other forms of indoor farming. This creates a need for artificial lighting systems (Howland *et al.*, 2012). Several options are available for indoor light provision. According to Singh *et al.* (2015), the use of Light Emitting Diode (LED) grow lights provides more technical advantages over using conventional grow lights. LEDs are more durable; they can have a lifespan of greater than 50 000 hours as compared to fluorescent lamps (10 000 hours), high pressure sodium (HPS) lamps (8 000 hours), and incandescent lamps (3 000 hours) (Caglayan and Ertekin, 2010). Furthermore, they have high operating efficiencies, emit low heat and are compact in size (Frąszczak, 2013;Sabzalian *et al.*, 2014;Bantis *et al.*, 2018).

Another advantage of using LED grow lights is that they supply light within the range of wavelengths required by plants. These wavelengths are between 400 and 700 nm (Wollaeger, 2013a;Singh *et al.*, 2015). Therefore, red and blue LEDs are used as their combined wavelengths fall within this range (Metallo *et al.*, 2018). According to Caglayan and Ertekin (2010), blue light is not as influential on plant growth as red light. As a result, its use can vary between 1 and 20% depending on the type of plant that is grown.

Vertical farming is not without limitations. Plants grown hydroponically and aeroponically are sensitive to environmental changes. Minor system failures could lead to rapid plant damage. Thus, there is a need for constant and precise control and monitoring. Consequently, vertical farming operations have high initial costs due to the high energy- and skilled labour requirements. In addition, the variety of plants that can be grown under these conditions is limited. Besides technical challenges, social acceptance of the concept of vertical farming may prove difficult to attain as well (Çİçeklİ, 2013;Banerjee and Adenaeuer, 2014;Sarkar and Majumder, 2015). Nevertheless, use of the vertical plane for plant growth has the potential to transform the future of farming. The adoption of artificial inputs into vertical farming allows a level of control and management that is limited in conventional farming. Vertical farming can allow small-scale urban farmers to produce good quality vegetables in limited spaces.

Currently, there is a gap in literature on quantitative analysis of the performance of small-scale vertical farming structures as compared to soil farming. Therefore, the aim of the research was to evaluate the performance of small-scale vertical hydroponic structures compared to soil farming. The growth parameters that were evaluated were the plant dry weights, mean total leaf areas per plant, relative growth rates, and the leaf area indices. The objectives of the study were:

a) to compare the growth parameters of plants grown in vertical hydroponic structures under sunlight and LED grow lights to that of soil grown plants in plant pots under sunlight and under LED grow lights for two nutrient concentration levels, and
b) to determine the difference between biometric attributes of plants grown hydroponically under LED grow lights and those grown hydroponically under sunlight.

There were two null hypotheses that were posited. The first was that there would not be a significant difference between the plant growth parameters of Fordhook Giant Swiss chard (*Spinacea oleracea*) grown in vertical hydroponic structures under LED grow lights and sunlight and that grown in soil in plant pots under LED grow lights and sunlight for the two nutrient concentration levels. The second was that the biometric attributes of plants grown in vertical hydroponic structures under LED grow lights and those grown in vertical hydroponic structures under sunlight would not be significantly different from each other.

3.2 Materials and Methods

A hydroponic vertical design was selected for this study. This is because, for small-scale applications, aeroponic and aquaponic systems can be very complex, require high capital investment and have high maintenance requirements (Chiipanthenga *et al.*, 2012;Rahman and Amin, 2016). Swiss Chard was selected because it is a highly nutritious leafy vegetable, and it can be grown in a wide range of hydroponic systems (Parkell, 2016). The research project was conducted in the Engineering Practicals Laboratory at the Ukulinga Research Farm in Mkhondeni, Pietermaritzburg. The geographic coordinates of the farm are 29°39'S and 30°24'E and it is situated 825 m above sea level (Google Earth, 2019). The study was conducted over two cropping seasons, one starting in February and ending in March, and the other starting in October and ending in November 2020.

3.2.1 Experimental design

The study was a complete randomised block design and consisted of three factors, each comprising two levels. The main factor was the growing method: soil planting vs vertical hydroponics. The first sub-factor was light provision: natural sunlight vs artificial light. Red – blue Light Emitting Diode (LED) strip grow lights were used in a ratio of 4:1, thus providing light in the photosynthetically active radiation range. The light was provided at an intensity of 260 $\mu mol.m^{-2}.s^{-1}$ for an 18 hour photoperiod as recommended by (Kang *et al.*, 2013).

The second sub-factor was the concentration of the nutrient solution. Concentration level one (C1) was 1.4 $g.l^{-1}$ and concentration level two (C2) was 1.9 $g.l^{-1}$ ((Kumari *et al.*, 2018a)). These recommended minimum and maximum concentrations were used to observe whether there would be significant variation between the treatments across low and high nutrient concentrations. The treatments were replicated four times. Fordhook Giant Swiss Chard (*Spinacea oleracea*) was used for the experiment. Seven-week-old seedlings were procured from Sunshine Seedlings (Pietermaritzburg). The plants were the experimental units.

Gromor potting medium (Amelework *et al.*, 2016) and plant pots were used for the soil-grown plants. A total 160 plant pots were used for plants for each lighting condition, each plant pot carried one plant. Within each lighting condition, 80 plant pots were irrigated with C1 and the remaining 80 were irrigated with C2.

The plant pots were marked to indicate which would be irrigated with which concentration level. The marked pots were then placed randomly within each light treatment. The total area occupied by the plant pots was 5 m^2 for each lighting setup.

For the vertical setup, 1200 mm long polyvinyl chlorine (PVC) pipes with a 120 mm diameter were attached to a frame made of 38x38x3 mm steel sections. The experiment consisted of two vertical hydroponic structures. In each lighting treatment, one vertical hydroponic structure carried a total of 160 plants. Each PVC pipe column acted as a replication and carried twenty plants. For each lighting treatment, each structure had a 45L reservoir, where a 2 m (maximum head), 1 200 $L.hr^{-1}$ (maximum flow rate) submersible fountain pump was used to recirculate the nutrient solution. In the first reservoir, the nutrient solution concentration was C1. And in the second, it was C2. Micro-sprayers were used to deliver the nutrient solution to the plant roots. The nutrient solution flowed down to the bottom of the PVC pipes by gravity, where it was collected in gutters and returned to the reservoir. The plants were secured in 50 mL net pots, with 55 mm top- and 35 mm bottom diameters and a 52 mm height. Each net pot carried one plant. Expanded clay pellets were used as the growing medium. Figure 3.1 is a simplified schematic that shows the experimental setup. The total number of plant pots are not accurately displayed in the diagram.

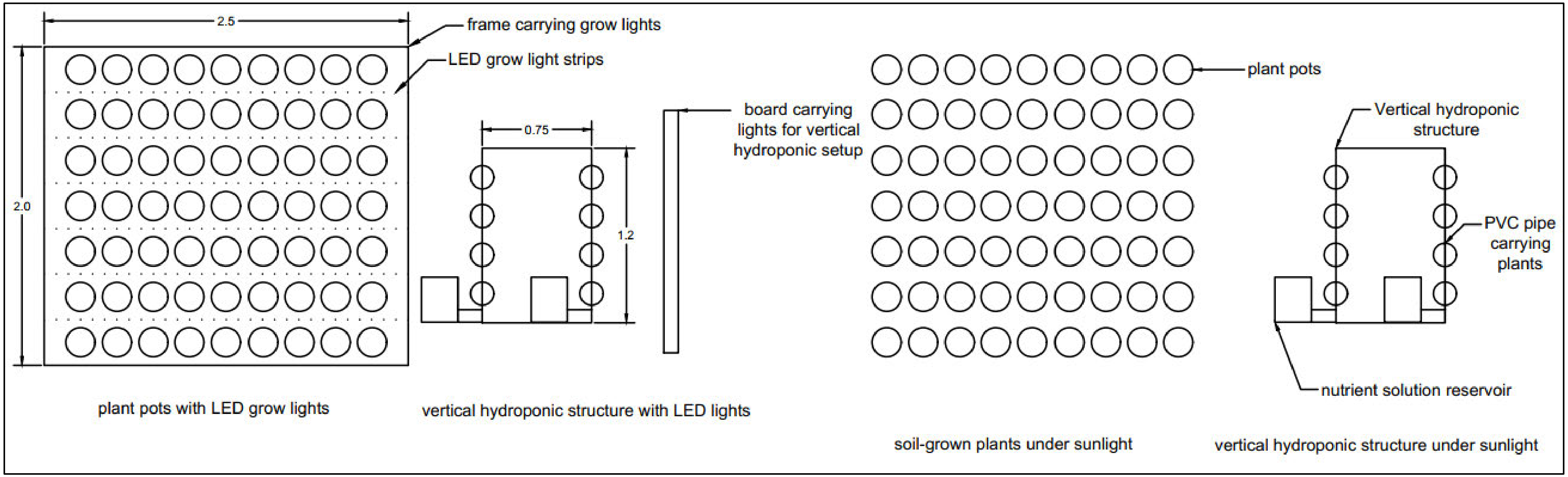

Figure 3.1 Top view sketch (not to scale) of the experimental setup

3.2.2 Fertigation and Irrigation

The nutrient solution selected for the experiment was Nutrifeed by Stark Aryes (Xego *et al*., 2016). This nutrient solution was selected because it could be used for hydroponic and soil plant growth and comprised the following macro- and micro-nutrients: Nitrogen (6.5%), Phosphorus (2.7%), Potassium (13%), Calcium (7.0%), Magnesium (2.2%), Sulphur (7.5%), and Iron, Manganese, Boron, Zinc, Copper and Molybdenum. Trichoderma was used in conjunction with the nutrient solution at the beginning of transplanting as biological control, as it can protect against diseases such as leaf spot and wilt in leafy vegetables (Bhale *et al.*, 2012). Diatomaceous earth was coated bi-weekly onto the plants to control pests such as aphids and thrips (Buss and Brown, 2006).

The Irrigation Design Manual (Burger *et al.*, 2003) was used to calculate irrigation requirements of the soil grown plants. It was determined that the spinach would need to be irrigated with 5 mm of water every 3 days. The nutrient solution was applied with every second irrigation. The TEROS 21 soil water potential meter (METER Group, Inc. USA) with ± 10% accuracy (Eliades *et al*., 2018) in conjunction with a Decagon ProCheck readout device (Bart *et al.*, 2015) that displayed the data instantaneously, were used to monitor soil moisture to ensure that the plants were not under- or over irrigated.

For the hydroponic structures, the nutrient solution was replenished every week. When the nutrient solution was being replaced, the "old" solution from the previous week was discarded. This was done to prevent the pumps from being clogged by the precipitation that would collect at the bottom of the reservoir. An ECO Testr EC meter (Stanley *et al*., 2014) with a ± 1% accuracy (Eutech Intsruments, Singapore) was used to monitor the electrical conductivity to ensure that it was within recommended values of 1.5 and 2.5 $dS.m^{-1}$ (Kumari *et al.*, 2018a). When the solution was above this range, it would be diluted with water. When it fell below these values, more nutrient solution would be added. The pH was also checked to ensure that it ranged between 5.5 and 6.5 as recommended for hydroponic systems (Sardare and Admane, 2013b). In cases where these values were exceeded, a pH up/down solution was used to return the solution to permissible values.

3.2.3 Data collection

Destructive sampling was conducted on three randomly selected plants from each treatment every second week. The following biometric measures were taken; leaf area, stem, and root lengths, and leaf-, stem- and root fresh and dry weights. The roots for soil grown plants were washed in order to remove soil and obtain accurate weights. Leaf area was determined using the Leaf-IT application with a ± 0.5% accuracy (Schrader *et al.*, 2017). A pair of vernier callipers were used to measure stem and root lengths. The weights of the different plant components were determined using the Kern-SOHN ALS250-4A analytical balance. The plants were dried in an oven dryer at 65°C for 24 hours to obtain dry weights.

3.2.4 Data analysis

Plant growth analysis measures, leaf area indices and relative growth rates, were derived from the biometric attributes according to methods described by Hunt (1990). The leaf area index (LAI) demonstrates the relationship between the total plant leaf area and that of the soil surface. If the sun's energy is used efficiently, this value should be greater than 1. If the LAI is less than 1, then some of the solar energy is wasted on the soil or weeds (Winch, 2007). LAI is calculated using Equation (3.1) (Hunt, 1990).

$$\bar{L} = \frac{\frac{L_{A1}}{P_1} + \frac{L_{A2}}{P_2}}{2} \tag{3.1}$$

where

$\bar{L} =$ average leaf area index [unitless].

$P_n =$ total ground area upon which the plant stands at time *n* [g].

The plant relative growth rate (RGR) is the rate at which new dry mass accumulates for each unit of existing dry mass (Lowry and Smith, 2018). Hoffmann and Poorter (2002) distinguished RGR as the most important growth characterisation parameter. RGR is determined using equation (3.2) (Hunt, 1990).

$$\bar{R} = \frac{\log_e W_2 - \log_e W_1}{T_2 - T_1} \tag{3.2}$$

where

$\bar{R} =$ average relative growth rate [g.g^{-1}.week^{-1}].

$W_n =$ total dry weight per plant at time *n* [g].

$T_n =$ time of harvest [week].

An analysis of variation (ANOVA) at a 95% confidence interval using IBM SPSS Statistics 26 (Dytham, 2011) was used to conduct statistical analysis of the results of two cropping seasons. The analysis was conducted by comparing the dry weight, leaf area, LAI, and RGR values of the different treatments and determining whether a significant difference existed amongst them. Once a significant difference was established, pairwise comparisons were then used to establish between which treatments the significant difference existed.

3.3 Results and Discussion

This section presents the plant growth rates that were derived from plant biometric measurements. In the analysis involving plant weights, plant dry weights were used. The classical approach equations described by Hunt (1990) were used to perform plant growth analysis in terms of relative growth rate, total leaf area per plant, leaf area index, and total plant dry weight. An analysis of variation (ANOVA) using IBM SPSS Statistics 26 (Dytham, 2011) was used to conduct statistical analysis of the results of two cropping seasons (Feb-March and Oct-Nov). A three-way ANOVA was used to assess interactions between the plant growing method, light provision, and the nutrient solution concentration for the different plant variables as described in the subsequent analyses. The nutrient solution concentration levels did not have a significant effect on the plant growth parameters. This means that the interpretations of the results obtained in the study are admissible across recommended nutrient solution concentration levels.

3.3.1 The effect of the growing method on plant growth parameters

The type of growing method had a significant effect on the plant growth parameters that were evaluated in the study. The mean growth parameters of plants grown in vertical hydroponic structures and those grown in soil, as well as the corresponding probability values are summarised in Table 3.1 for both cropping seasons. The mean total plant dry weights, mean total leaf areas per plant, and LAIs of plants grown in vertical hydroponic structures were significantly higher than those grown in soil. This was because the plants grown in vertical hydroponic structures had a significantly higher RGR than plants grown in soil in plant pots.

This means that the plants grown in vertical hydroponic structures developed at a significantly higher rate than plants grown in soil, even though both treatments received the same nutrient solution in the same concentrations. This result is in line with reports by Gruda *et al.* (2013) that the use of inert artificial growing media in hydroponics improves nutrient use efficiency in plants. Gashgari *et al.* (2018) reported a similar finding; that plants grown hydroponically had a significantly higher growth rate than plants grown in soil. This can be attributed to the fact that in hydroponically grown plants, the photosynthetic rates are higher and photosynthates are partitioned to above-ground plant matter more than in soil grown plants (Anver *et al.,* 2005). In hydroponic systems, the nutrients are provided directly to the roots through direct and constant contact with the nutrient solution which results in better plant growth and development (Sardare and Admane, 2013a).

Table 3.1 The mean growth parameters in cropping season one (CS1) and two (CS2) of plants grown in vertical hydroponic structures and in soil in plant pots

		CS1			CS2		
		Vertical hydroponics	**Soil**	**Probability**	**Vertical hydroponics**	**Soil**	**Probability**
Mean Growth Parameter	**Relative growth rate ($g.g^{-1}.day^{-1}$)**	0.0903	0.0803	0.0300	0.0853	0.0790	0.0110
	Total plant dry weight (g)	19.00	12.53	< 0.0005	19.42	14.52	0.0010
	Total leaf area per plant (mm^2)	1 263.39	914.32	< 0.0005	1 286.98	896.63	< 0.0005
	Leaf area index	5.59	4.06	< 0.0005	5.69	3.95	< 0.0005

3.3.2 The combined effect of growing method and LED grow lights on plant growth parameters

The LED grow lights had a significant effect on plant growth parameters. LED grow lights resulted in significantly higher plant growth parameters for both plants grown in vertical hydroponic structures and those grown in soil in plant pots. This was because the LED grow lights enhanced plants' photosynthetic capacity (Li *et al.* 2019). Interestingly, the difference between the biometric attributes of plants grown under LED grow lights and those grown under sunlight was more distinct in the vertical hydroponic treatment than in the soil treatment. This is evident in the mean total leaf areas per plant graphs (Figure 3.2 and Figure 3.3) and in the mean total dry weights per plant graphs (Figure 3.4 and Figure 3.5). This finding implies that growing plants hydroponically results in more efficient use of artificial grow lights, resulting in higher plant production than in soil growth. This suggests that, in plant production applications where artificial grow lights are used, plant growth in soil can be replaced by hydroponic systems for more optimum plant development.

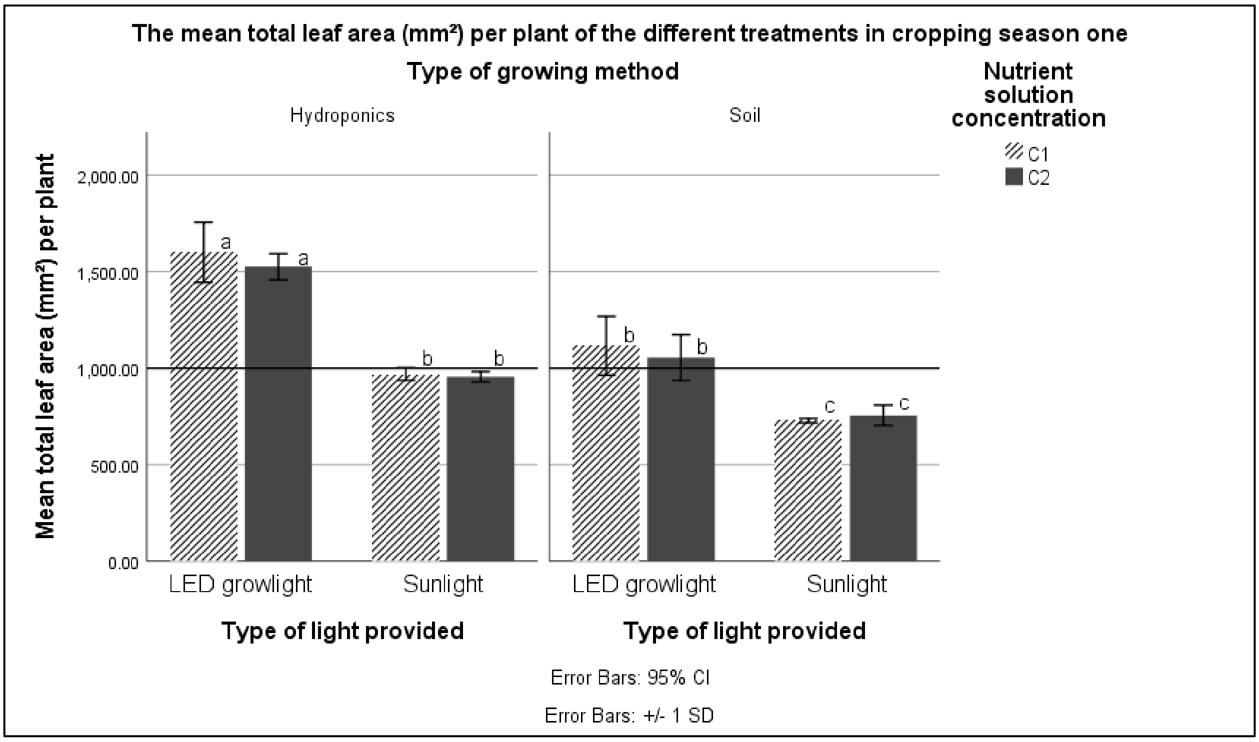

Figure 3.2 The mean total leaf area per plant (mm^2) in the first cropping season. Similar letters indicate no significant difference between treatments for a 95% confidence interval

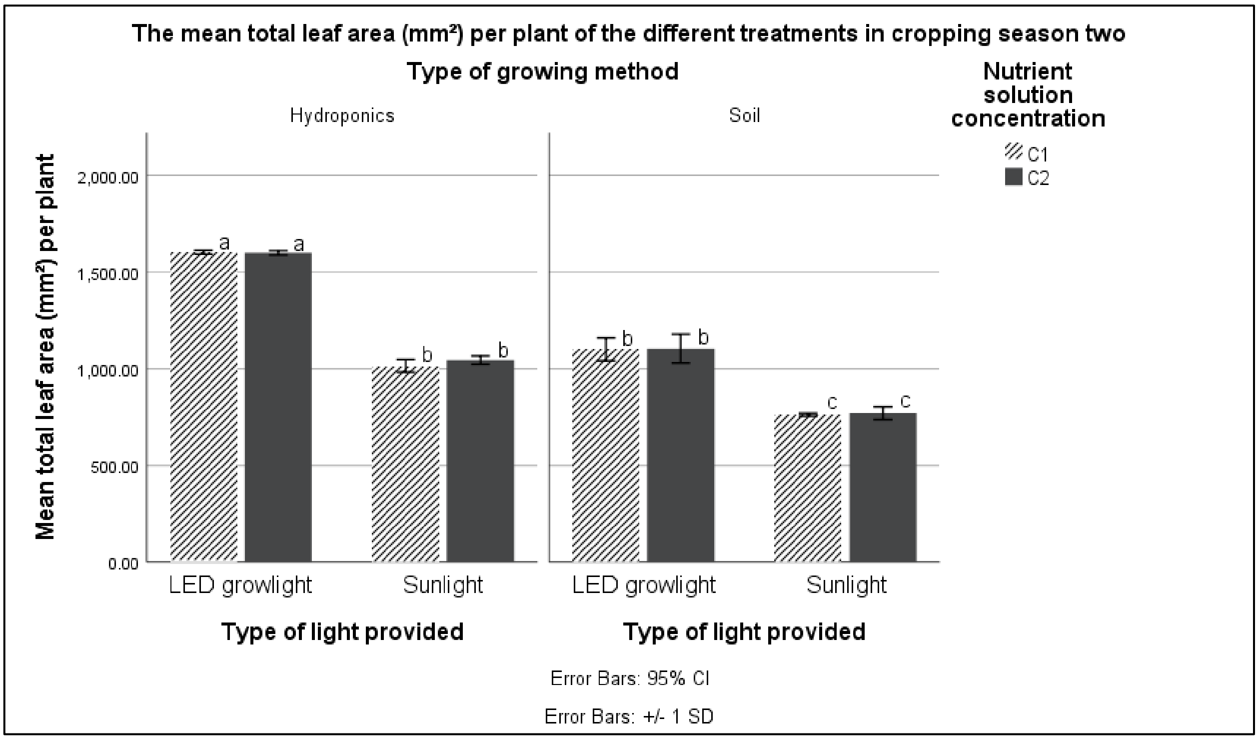

Figure 3.3 The mean total leaf area per plant (mm^2) in the second cropping season. Similar letters indicate no significant difference between treatments for a 95% confidence interval

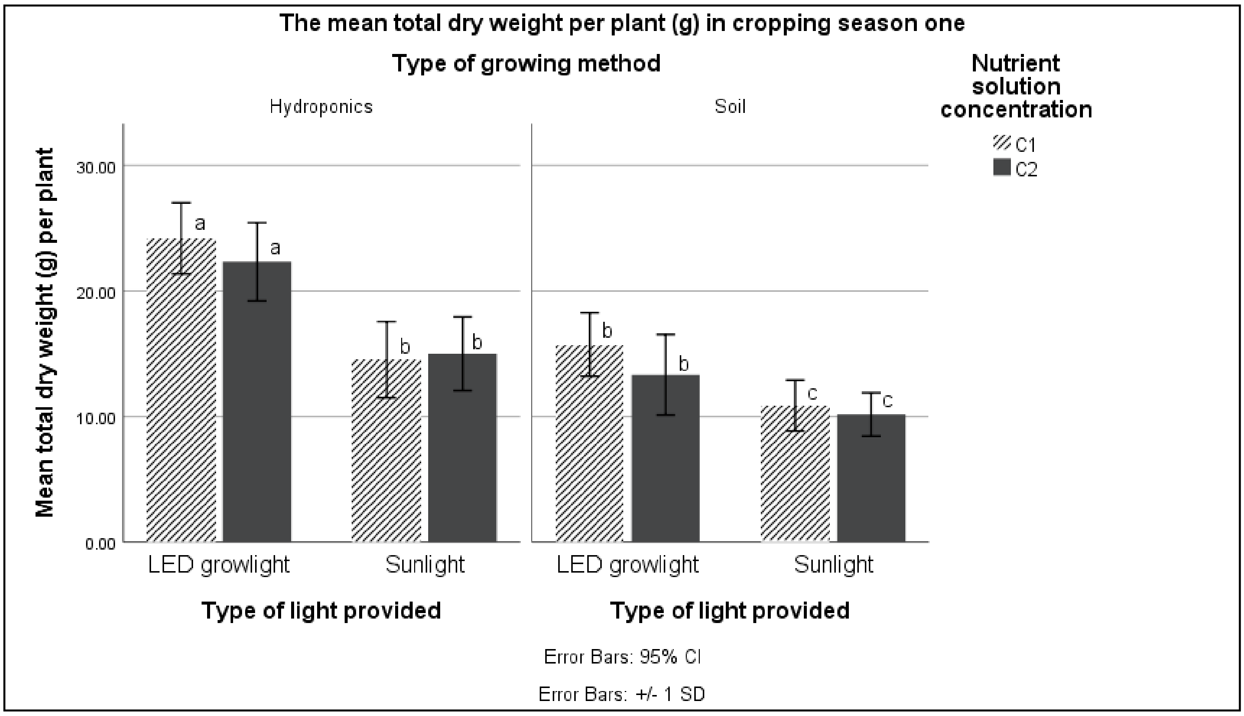

Figure 3.4 The mean total plant dry weight, (g) in the first cropping season. Similar letters indicate no significant difference between treatments for a 95% confidence interval

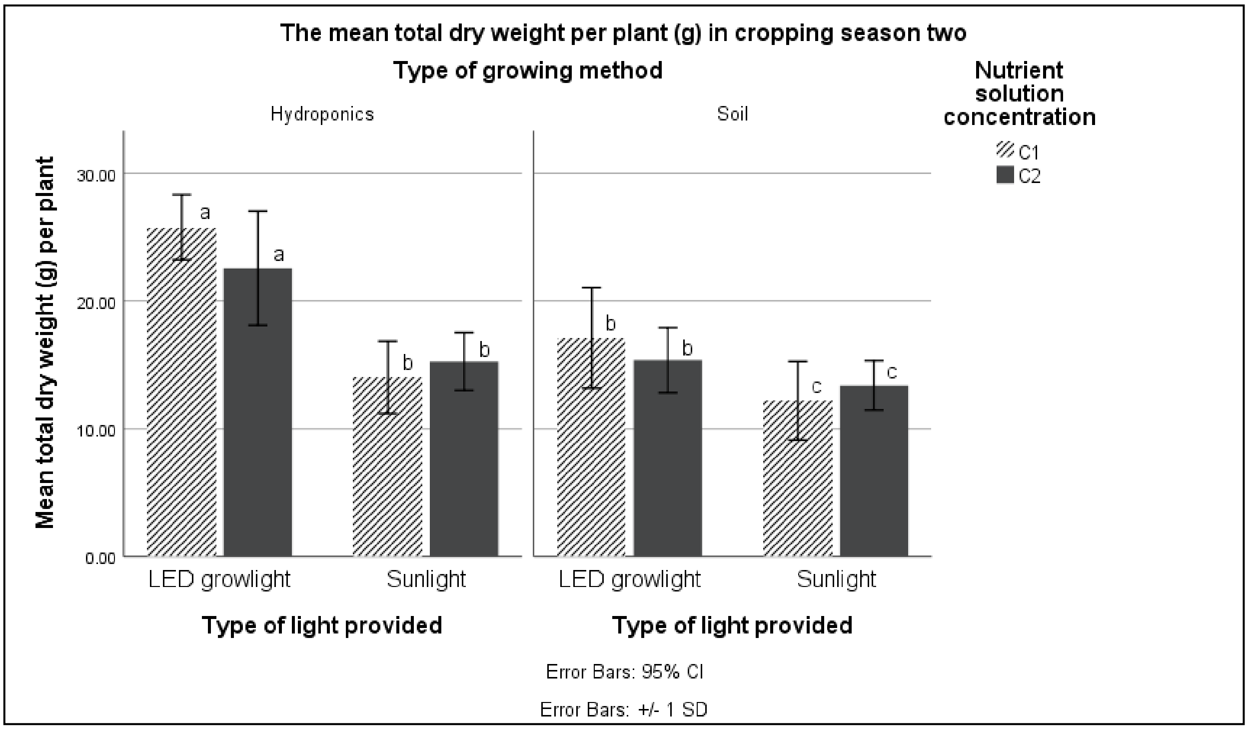

Figure 3.5 The mean total plant dry weight, (g) in the second cropping season. Similar letters indicate no significant difference between treatments for a 95% confidence interval

An interesting finding was that biometric attributes of plants grown in vertical hydroponic structures under sunlight were not significantly different from those grown in soil under LED grow lights. This was because the difference between the RGRs of these two treatments was not statistically significant. The mean growth parameters of plants grown in vertical hydroponic structures under sunlight and in soil under LED grow lights, and their probability values are summarised in Table 3.2 for both cropping seasons. This result implies that growing plants hydroponically under adequate sunlight is statistically equivalent to the addition of LED grow lights to soil farming in controlled environments. This is an important finding because artificial grow lights have been identified as one of the highest energy consumers in controlled environmental agriculture (CEA). This finding can aid farmers in decision making. For instance, small-scale vertical hydroponic systems could replace soil-based CEA systems where sunlight is supplemented with artificial grow lights during dark hours. This result is especially important because small-scale vertical hydroponic systems can operate using low-energy consuming low-pressure pumps, such as submersible fountain pumps.

Table 3.2 The mean growth parameters in cropping season one (CS1) and two (CS2) of plants grown in vertical hydroponic structures and in soil in plant pots, where VHSL – vertical hydroponics under sunlight, and SGL – soil-grown plants under LED grow lights

		CS1			CS2		
		VHSL	**SGL**	**Probability**	**VHSL**	**SGL**	**Probability**
Mean Growth Parameter	**Relative growth rate ($g.g^{-1}.day^{-1}$)**	0.0848	0.0842	0.910	0.0793	0.0818	0.463
	Total plant dry weight (g)	14.77	14.53	0.892	14.65	16.24	0.380
	Total leaf area per plant (mm^2)	963.19	1086.27	0.063	1006.25	1029.78	0.763

	Leaf area index	4.13	4.81	0.053	4.45	4.56	0.757

3.3.3 Comparison of growth parameters of plants grown hydroponically under different light treatments

The plants grown hydroponically under LED grow lights had the highest mean total leaf areas per plant, as shown in Figure 3.2 and Figure 3.3. The mean total leaf areas per plant of plants grown in vertical hydroponic structures under LED grow lights were significantly higher than those in vertical hydroponic structures under sunlight, $p < 0.0005$ in both cropping seasons. Plants grown hydroponically under LED grow lights also had the highest mean total dry weights per plant, as shown in Figure 3.4 and Figure 3.5. The mean total dry weights per plant of plants grown in vertical hydroponic structures under LED grow lights were significantly higher than those in vertical hydroponic structures under sunlight, $p < 0.0005$ in both cropping seasons. The significant difference between the biometric attributes of plants grown in vertical hydroponic structures under different light treatments was due to the LED grow lights.

As previously stated, LED grow lights enhanced the plants' photosynthetic capacity (Li *et al.*, 2019). Additionally, the LED grow lights provided controlled radiation. The vertical hydroponic system that was under LED grow lights received consistent radiation. The quality of the grow lights' radiation was not affected by external conditions such as weather or particles in the atmosphere, unlike the system under solar radiation. Therefore, a hydroponic system under LED grow lights can be expected to produce uniform and consistent results in different planting cycles that would be independent of atmospheric conditions.

3.4 Conclusions and Recommendations

The research aimed to evaluate the performance of small-scale vertical farming structures compared to soil farming. Based on the plant biometric attributes that were assessed and analysed, it can be concluded that small-scale vertical hydroponic structures are a viable option to replace conventional plant growth in soil.

The results showed that growing plants in vertical hydroponic structures significantly enhances plant development. Furthermore, the results suggest that plants grown in vertical hydroponic structures use radiation from LED grow lights more efficiently and more productively than plants grown in soil. Therefore, the null hypotheses were rejected for these treatments as the results that were obtained disproved them. However, the results revealed that growing plants hydroponically under sunlight is statistically equivalent to growing plants in soil under LED grow lights. Therefore, the null hypothesis was true for these treatments.

Although the conducted research has demonstrated the viability of small-scale vertical hydroponic structures, the design used in the study can only accommodate a limited variety of plants that can be grown hydroponically. Nevertheless, an opportunity exists for further research to examine and compare different designs of small-scale vertical hydroponic structures to create diverse alternatives for different farming setups.

To explore the practicality of using hydroponics to replace soil-based planting in CEA where supplemental lighting is used, further research should be conducted. The research could compare the resource use efficiencies of the two systems to ascertain whether use of hydroponic systems under sunlight would be more sustainable.

The research that was conducted in this study has made a contribution to closing the gap in literature on quantitative information on the performance of small-scale vertical hydroponic structures compared to conventional farming. Considering the challenges associated with large-scale vertical farming, this study has demonstrated that, whether under artificial or natural radiation, small-scale vertical hydroponic structures produce larger plants than the soil. The results obtained are a cornerstone for further research on starting with small-scale systems to eventually replace conventional farming systems.

3.5 References

Anver, M A M S, Bandara, D C, & Premathilake, K R E (2005). Comparison of the carbon partitioning and photosynthetic efficiency of lettuce (Lactuca sativa L.) under hydroponics and soil cultivation. *Tropical Agricultural Research* 17 (2005): 194 – 202.

Aswath, C, Selvakumar, G, Zimmerman, C and Bajikar, M. 2016. Utilization of vertical spaces for horticultural crop production in urban and peri-urban areas. *Current Science* 110 (11): 2048-2049.

Banerjee, C and Adenaeuer, L. 2014. Up, up and away! The economics of vertical farming. *Journal of Agricultural Studies* 2 (1): 40-60.

Bantis, F, Smirnakou, S, Ouzounis, T, Koukounaras, A, Ntagkas, N and Radoglou, K. 2018. Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). *Scientia Horticulturae* 235 (2018): 437-451.

Bart, D, Davenport, T, & Carpenter, Q. (2015). Stress and land-use legacies alter the relationship between invasive-and native-plant richness. *Journal of Vegetation Science* 26 (1): 80-88.

Bhale, U, Ambuse, M, Chatage, V and Rajkonda, J. 2012. Bioefficacy of Trichoderma isolates against pathogenic fungi inciting spinach (Spinacea oleracea L.). *Journal of Biopesticides* 5 (2): 222.

Birkby, J. 2016. Vertical Farming. [Internet]. National Center of Appropriate Technology. Available from: https://attra.ncat.org/attra-pub/viewhtml.php?id=512. [Accessed: 04-05-2017].

Burger, J, Heyns, P, Hoffman, E, Kleynhans, E, Koegelenberg, F, Lategan, M, Mulder, D, Smal, H, Stimie, C, Uys, W, van der Merve, F, van der Stoep, I and Viljoen, P. 2003. *Irrigation Design Manual*. Agricultural Research Council - Institute for Agricultural Engineering, Pretoria, South Africa.

Buss, E and Brown, S. 2006. Natural Products for Insect Management. [Internet]. University of Florida. Available from: https://www.researchgate.net/profile/Eileen_Buss/publication/237391484_Natural_Products_for_Insect_Pest_Management1/links/00b4952a5dbef7e2b4000000.pdf. [Accessed: 02 May 2020].

Caglayan, N and Ertekin, C. 2010. Using of LED Lighting Technologies to Substitute Traditional Lighting Systems in Greenhouses. *Energetic and Ecological Aspects of Agricultural Production* (2010): 93-104.

Chiipanthenga, M, Maliro, M, Demo, P and Njoloma, J. 2012. Potential of aeroponics system in the production of quality potato (Solanum tuberosum l.) seed in developing countries. *African Journal of Biotechnology* 11 (17): 3993-3999.

Çİçeklİ, M. 2013. Vertical farming. *Ege Üniversitesi Ziraat Fakültesi Dergisi* (Special Issue Volume 2): 383-388.

Dytham, C. 2011. *Choosing and Using Statistics: A Biologist's Guide*. Wiley-Black, West Sussex, United Kingdom.

Eliades, M., Bruggeman, A., Djuma, H., & Lubczynski, M. W. (2018). Tree water dynamics in a semi-arid, Pinus brutia forest. *Water* 10 (8): 1039 - 1060.

Frąszczak, B. 2013. Effect of short-term exposure to red and blue light on dill plants growth. *Horticultural Science* 40 (4): 177-185.

Gashgari, R, Alharbi, K, Mughrbil, K, Jan, A and Glolam, A.2018. Comparison between growing plants in hydroponic system and soil based system. *Proceedings of the 4th World Congress on Mechanical, Chemical, and Material Engineering*, 1-7. ICMIE Madrid, Spain,

Graff, GJ. 2012. Skyfarming. Unpublished MSc thesis, Department of Architecture, University of Waterloo, Ontario, Canada.

Gruda, N, Qaryotui, MM and Leonardi, C. 2013. Growing Media. In: eds. Wilfried, B, Remi, N-W, Nebambi, L, Alison, H, Nicolás, C, Cherubino, L, Stefania, DP, Muien, Q and Duffy, R, *Good agricultural practices for greenhouse vegetable crops: principles for mediterranean climate areas*. Ch. 11, 271 - 302. Food And Agriculture Organization Of The United Nations, Rome, Italy.

Hoffmann, WA and Poorter, H. 2002. Avoiding Bias in Calculations of Relative Growth Rate. *Annals of Botany* 90 (1): 37-42.

Howland, A, Kim, N and Marks, A. 2012. ADVANCED FOOD TECHNOLOGIES. [Internet]. Massachusetts Institute of Technology. Available from: https://static1.squarespace.com/static/51352c64e4b00e99bdc21d13/t/513a5cade4b0be1eb03e6b6c/1362779309755/AdvFoodTechFinalPaper.pdf. [Accessed: 01-03-2017].

Hunt,R.1990. Basic Growth Analysis Plant growth for beginners. Unwin Hyman Ltd, London, UK.

Kang, JH, KrishnaKumar, S, Atulba, SLS, Jeong, BR and Hwang, SJ. 2013. Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system. *Horticulture, Environment, and Biotechnology* 54 (6): 501-509.

Kumari, S, Pradhan, P, Yadav, R and Kumar, S. 2018. Hydroponic techniques: A soilless cultivation in agriculture. *Journal of Pharmacognosy and Phytochemistry* 7 (2018): 1886 - 1891.

Li, Q, Liu, Y, Tian, S, Liang, Z, Li, S, Li, Y, Wei, M and Zhang, D. 2019. Effect of supplemental lighting on water transport, photosynthetic carbon gain and water use efficiency in greenhouse tomato. *Scientia Horticulturae* 256 (2019):1-8.

Lowry, CJ and Smith, RG. 2018. Chapter 5 - Weed Control Through Crop Plant Manipulations. In: eds. Jabran, K and Chauhan, BS, *Non-Chemical Weed Control*. Academic Press. London,UK.

Maršić, NK and Jakše, M. 2010. Growth and yield of grafted cucumber (Cucumis sativus L.) on different soilless substrates. *Journal of Food, Agriculture & Environment* 8 (2): 654-658.

Metallo, RM, Kopsell, DA, Sams, CE and Bumgarner, NR. 2018. Influence of blue/red vs. white LED light treatments on biomass, shoot morphology, and quality parameters of hydroponically grown kale. *Scientia Horticulturae* 235 (2018): 189-197.

Parkell, NB, Hochmuth, RC, Laughlin, WL. 2016. Leafy Greens in Hydroponics and Protected Culture in Florida. [Internet]. Institute of Food and Agricultural Sciences. Gainesville,USA. Available from: https://growables.com/information/documents/HydroLeafyGreenUF.pdf [Accessed 19 June 2017].

Rahman, MA and Amin, MR. 2016. Aquaponics: A Potential Integrated Farming System for Sustainable Agriculture and Aquaculture. *International Journal of Biological, Ecological and Environmental Sciences* 5 (1): 42-45.

Ranawade, P, Tidke, S and Kate, A. 2017. Comparative cultivation and biochemical analysis of Spinacia oleraceae grown in aquaponics, hydroponics and field conditions. *International Journal of Current Microbiology and Applied Sciences* 6 (4): 1007-1013.

Sabzalian, MR, Heydarizadeh, P, Zahedi, M, Boroomand, A, Agharokh, M, Sahba, MR and Schoefs, B. 2014. High performance of vegetables, flowers, and medicinal plants in a red-blue LED incubator for indoor plant production. *Agronomy for Sustainable Development* 34 (4): 879-886.

Sardare, MD and Admane, SV. 2013. A review on plant without soil-hydroponics. *International Journal of Research in Engineering and Technology* 2 (3): 299-304.

Sarkar, A and Majumder, M. 2015. Opportunities and Challenges in Sustainability of Vertical Eco-Farming: A Review. *Journal of Advanced Agricultural Technologies* 2 (2): 98-105.

Savvas, D, Gianquinto, G, Tuzel, Y and Gruda, N. 2013. Soilless culture. In: eds. Wilfried, B, Remi, N-W, Nebambi, L, Alison, H, Nicolás, C, Cherubino, L, Stefania, DP, Muien, Q and Duffy, R, *Good agricultural practices for greenhouse vegetable crops: principles for mediterranean climate areas*. Ch. 12, 303 - 354. Food And Agriculture Organization Of The United Nations, Rome, Italy.

Schrader, J, Pillar, G and Kreft, H. 2017. Leaf-IT: An Android application for measuring leaf area. *Ecology and Evolution* 7 (22): 9731-9738.

Singh, D, Basu, C, Meinhardt-Wollweber, M and Roth, B. 2015. LEDs for energy efficient greenhouse lighting. *Renewable and Sustainable Energy Reviews* 49 (2015): 139-147.

Stanley, JN, Lamb, DW, Falzon, G, and Schneider, DA. (2014). Apparent electrical conductivity (ECa) as a surrogate for neutron probe counts to measure soil moisture content in heavy clay soils (Vertosols). *Soil Research* 52(4): 373-378.

Tester, M and Langridge, P. 2010. Breeding technologies to increase crop production in a changing world. *Science* 327 (5967): 818-822.

Trejo-Téllez, I, L, Gómez-Merino and C, F. 2012. Nutrient solutions for hydroponic systems. *Hydroponics-a Standard Methodology for Plant Biological Researches* 23 (2012): 1-22.

UN. 2015. World Population Prospects key findings & advance tables 2015 revision. [Internet]. United Nations Department of Economic and Social Affairs Population Division. Available from: https://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf. [Accessed: 09/05/2017].

Wahome, PK, Oseni, TO, Masarirambi, MT and Shongwe, VD. 2011. Effects of different hydroponics systems and growing media on the vegetative growth, yield and cut flower quality of gypsophila (Gypsophila paniculata L.). *World Journal of Agricultural Sciences* (6): 692-698.

Winch, T. 2007. *Growing Food a Guide to Food Production*. Springer, Dordrecht, Netherlands.

Wollaeger, HM. 2013. Growth and morphological acclimation of seedlings to blue, green, and red light from light-emitting diodes. Unpublished thesis, Michigan State University, East Lansing, USA.

Xego, S., Kambizi, L., & Nchu, F. (2016). Threatened medicinal plants of South Africa: case of the family Hyacinthaceae. *African Journal of traditional, complementary and alternative medicines* 13(3): 169-180.

4. EVALUATION OF THE RESOURCE USE EFFICIENCIES OF SMALL-SCALE VERTICAL HYDROPONIC STRUCTURES AGAINST GROWING PLANTS IN SOIL

Abstract

Currently, there is limited quantitative research on the applicability of small-scale vertical farming systems for replacing conventional farming for future food production. Therefore, the aim of this research was to investigate the use of small-scale vertical farming structures as an alternative to improving resource use efficiency in agriculture. To achieve this, Fordhook Giant Swiss chard (*Spinacea oleracea*) was grown over two cropping seasons between February and November 2019, in the Engineering Practicals Laboratory at the Ukulinga Research Farm in Mkondeni, Pietermaritzburg. It was postulated that the resource use efficiency of vertical hydroponic structures would not differ from that of growing plants conventionally in plant pots. The main factor was the growing method (growing plants in soil in plant pots vs vertical hydroponics). The sub-factors were light provision (sunlight vs light emitting diode grow lights), and nutrient solution concentration (1.4 $g.l^{-1}$ vs 1.9 $g.l^{-1}$). An ANOVA was conducted, with a 95% confidence interval, to assess if the resource use efficiencies of the treatments were significantly different from each other. The hydroponic structures had a significantly higher land use efficiency than the plant pot setup (3 041.05 $g.m^{-2}$ vs 405.89 $g.m^{-2}$ in cropping season one (CS1), and 3 106.41 $g.m^{-2}$ vs 464.53 $g.m^{-2}$ in CS2), $p < 0.0005$ in CS1 and CS2. The crop water productivity of the hydroponic structures was significantly higher than that of the plant pot setup (8.45 $g.l^{-1}$ vs 5.72 $g.l^{-1}$ in CS1, and 8.44 $g.l^{-1}$ vs 6.59 $g.l^{-1}$ in CS2) , $p < 0.0005$ in CS1, and $p = 0.014$ in CS2. The energy use efficiency of plants grown hydroponically under sunlight (104.25 $g.kWh^{-1}$ in CS1 and 103.43 $g.kWh^{-1}$ in CS2) was significantly higher than that of plants grown hydroponically under grow lights (12.30 $g.kWh^{-1}$ in CS1 and 12.80 $g.kWh^{-1}$ in CS2). It was also significantly higher than plants grown in soil under grow lights (8.16 $g.kWh^{-1}$ in CS1 and 9.29 $g.kWh^{-1}$ in CS2), $p < 0.0005$ in CS1 and CS2. The results, therefore, disproved the null hypothesis. Small-scale vertical hydroponic structures have higher agricultural productivity than conventional farming. These results provide quantitative information which can allow potential farmers to make informed decisions about changing to vertical farming.

Keywords: vertical hydroponics, LED grow lights, land use efficiency, crop water productivity, energy use efficiency

4.1 Introduction

The productivity of an entity can be defined as the ratio of a quantitative measure of its outputs to a quantitative measure of the inputs used to obtain those outputs. It can be determined for a wide range of production scales - from a single farm to multiple farms on a national level (Mechri *et al.*, 2017). Productivity can be used to assess the efficiency with which a production system operates. The outputs can be quantified using physical or financial terms, whilst the inputs are the resources used in the entity to produce the outputs (Dhehibi *et al.*, 2015).

Two kinds of measures are used to determine productivity: Total Factor Productivity (TFP) and Partial Factor Productivity (PFP). The TFP is a ratio that is determined by averaging the outputs produced relative to the average inputs used (Link, 1987). In TFP determination, the various inputs used in production are accounted for in one measurement. According to Murray and Sharpe (2016), determining TFP is instrumental for assessing the economic growth of an entity in the long run. In fact, TFP can only be interpreted when it is expressed in terms of growth rates.

In contrast, PFP can be determined in terms of growth rates and absolute levels (Murray and Sharpe, 2016). When determining PFP, the outputs produced are related to a single input (Link, 1987). That is, it is a ratio of the outputs produced relative to a single input (Gray *et al.*, 2011). In practical analyses of productivity, PFP measures can provide more information to an analyst compared to TFP measures. This is because with PFP measures, analyses can be focused on single inputs of interest to determine the efficiency with which they are used (Murray, 2016).

The need for more sustainable agriculture has led to the development of new food production methods, such as urban agriculture. One of the most important concerns of these methods is optimising resource use efficiency that can ultimately lead to increased agricultural productivity (Rufí-Salís *et al.*, 2020). Currently, 38% of the earth's land surface is occupied by agricultural activity, making agriculture the largest type of land use (Foley *et al.*, 2011). Rapidly increasing global population numbers mean that more food needs to be produced to adequately meet future food security requirements. However, expanding agricultural land is becoming increasingly difficult because of climate change, land degradation and land resources competition, amongst other factors (Germer *et al.* (2011).

Furthermore, conventional agriculture, itself, poses a threat to the natural environment and thus its physical expansion would further add to negative environmental impacts (Foley *et al.*, 2011;Touliatos *et al.*, 2016). Therefore, the more sustainable option is to intensify agriculture on land that is already used for agriculture or by implementing technologies that allow farming in spaces that normally would not accommodate food production. Eigenbrod and Gruda (2015) presented vertical farming on a large scale as a technique that can achieve agricultural intensification. However, small scale vertical farming systems can also contribute to increasing land use efficiency (LUE) by extending food production into the vertical plane, thus increasing yield per unit area.

Conventional agriculture requires large volumes of water to guarantee satisfactory crop growth and achieve high yields. Conventional agriculture exerts pressure on already dwindling water resources as it uses up to 70% of water that is withdrawn from freshwater sources (Valenzano *et al.*, 2008;Rufí-Salís *et al.*, 2020). As with LUE, hydroponic systems can increase water use efficiency (WUE). In hydroponic systems, water consumption is decreased through nutrient solution recirculation, thus decreasing water waste (Al-Karaki and Al-Momani, 2011). Savvas *et al.* (2013) reported that closed-hydroponic systems can also substantially reduce fresh-water resource contamination by fertilizers. Water recovered from closed systems can be filtered and reused in other crop cycles or it can be reused for purposes other than agriculture, thereby reducing reliance on fresh-water sources (Rufí-Salís *et al.*, 2020). Furthermore, Pennisi *et al.* (2019) identified the potential to recover plant transpiration water as a further advantage of hydroponic systems.

One of the biggest shortcomings of large-scale hydroponic systems is the high and constant energy requirements, with energy for light provision being one of the largest contributors to energy use (Graamans *et al.*, 2018). However, Barbosa *et al.* (2015) suggested that, in place of expensive large-scale hydroponic systems, simplified hydroponics could be used for food production as they are able to produce up to three or four times more crops than conventional agriculture on an area basis. Furthermore, the resource use efficiency of hydroponic systems can be improved by making use of small-scale vertical farming structures. These structures would maximise the efficiency which with space is used by making use of multiple growing levels. And, although the provision of light results in high energy consumption, the presence of grow lights can improve the overall resource use efficiency of hydroponic systems (Pennisi *et al.*, 2019).

Large-scale vertical farming systems are associated with high capital costs and high energy requirements. These limitations may deter current and potential producers from moving away from conventional farming systems (Çİçeklİ, 2013;Banerjee and Adenaeuer, 2014;Sarkar and Majumder, 2015). Currently, there is limited quantitative research on the applicability of small-scale vertical farming systems in replacing conventional farming systems for future food production.

Therefore, the aim of this research was to assess the resource use efficiency of small-scale vertical hydroponic structures compared to planting in soil, in terms of land-, energy-use efficiencies and crop water productivity, under sunlight and Light Emitting Diode (LED) grow lights. This was done to evaluate the potential use of small-scale vertical farming systems in agricultural intensification. It was postulated that the resource use efficiencies of vertical hydroponic structures under sunlight and LED grow lights will not differ from the resource use efficiencies of soil planting under sunlight and LED grow lights.

4.2 Materials and Methods

A hydroponic vertical design was selected for this study. This is because, for small-scale applications, aeroponic and aquaponic systems can be very complex, require high capital investment and have high maintenance requirements (Chiipanthenga *et al.*, 2012;Rahman and Amin, 2016). Swiss Chard was selected it because it is a highly nutritious leafy vegetable, and it can be grown in a wide range of hydroponic systems (Parkell, 2016). The research project was conducted in the Engineering Practicals Laboratory at the Ukulinga Research Farm in Mkhondeni, Pietermaritzburg. The geographic coordinates of the farm are 29°39'S and 30°24'E and it is situated 825 m above sea level (Google Earth, 2019). The study was conducted over two cropping seasons, one starting in February and ending in March, and the other starting in October and ending in November 2020.

4.2.1 Experimental design

The study made use of a randomised complete block design and consisted of three factors, each comprising two levels. The main factor was the growing method: planting in soil vs vertical hydroponics. The first sub-factor was light provision: natural sunlight vs artificial light. Red – blue Light Emitting Diode (LED) strip grow lights were used in a ratio of 4:1, thus providing light in the photosynthetically active radiation range.

The light was provided at an intensity of 260 $\mu mol.m^{-2}.s^{-1}$ for an 18 hour photoperiod as proposed by (Kang *et al.*, 2013). The second sub-factor was the concentration of the nutrient solution. Concentration level one (C1) was 1.4 $g.l^{-1}$ and concentration level two (C2) was 1.9 $g.l^{-1}$ (Kumari *et al.*, 2018a). These recommended minimum and maximum concentrations were used to observe whether there would be significant variation between the treatments across low and high nutrient concentrations. The treatments were replicated four times. Fordhook Giant Swiss Chard (*Spinacea oleracea*) was used for the experiment. Seven-week-old seedlings were procured from Sunshine Seedlings (Pietermaritzburg). The plants were the experimental units.

Gromor potting medium (Amelework *et al.,* 2016) and plant pots were used for the soil-grown plants. A total 160 plant pots were used for plants for each lighting condition, each plant pot carried one plant. Within each lighting condition, 80 plant pots were irrigated with C1 and the remaining 80 were irrigated with C2. The plant pots were marked to indicate which would be irrigated with which concentration level. The marked pots were then placed randomly within each light treatment. The total area occupied by the plant pots was 5 m^2 for each lighting setup. The pots were kept in position after sampling so as to not change total area occupied by the plant pots.

For the vertical setup, 1200 mm long polyvinyl chlorine (PVC) pipes with a 120 mm diameter were attached to a frame made of 38x38x3 mm steel sections. The experiment consisted of two vertical hydroponic structures. In each lighting treatment, the vertical hydroponic structures carried a total of 160 plants. Each PVC pipe column carried twenty plants.

For each lighting treatment, each structure had a 45L reservoir, where a 2 m (maximum head), 1 200 $L.hr^{-1}$ (maximum flow rate) submersible fountain pump was used to recirculate the nutrient solution. In the first reservoir, the nutrient solution concentration was C1 and in the second, it was C2. Micro-sprayers were used to deliver the nutrient solution to the plant roots.

The nutrient solution flowed down to the bottom of the pipes by gravity, where it was collected in gutters and returned to the reservoir. The plants were secured in 50 mL net pots, with 55 mm top- and 35 mm bottom diameters and a 52 mm height. Each net pot carried one plant. Expanded clay pellets were used as the growing medium. Figure 4.1 is a simplified schematic that shows the experimental setup. The total number of plant pots are not accurately displayed in the diagram.

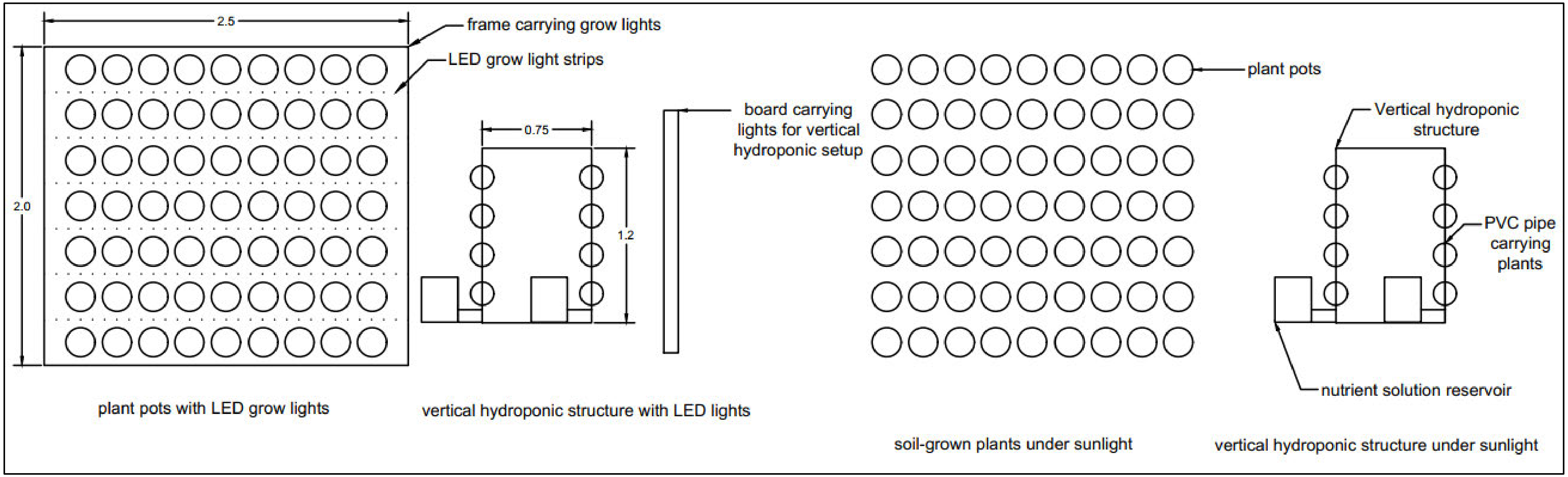

Figure 4.1 Top view sketch (not to scale) of the experimental setup

4.2.2 Fertigation and Irrigation

The nutrient solution selected for the experiment was Nutrifeed by Stark Aryes (Xego *et al*., 2016). This nutrient solution was selected because it could be used for hydroponic and soil plant growth and comprised the following macro- and micro-nutrients: Nitrogen (6.5%), Phosphorus (2.7%), Potassium (13%), Calcium (7.0%), Magnesium (2.2%), Sulphur (7.5%), and Iron, Manganese, Boron, Zinc, Copper and Molybdenum. Trichoderma was used in conjunction with the nutrient solution at the beginning of transplanting as biological control, as it can protect against diseases such as leaf spot and wilt in leafy vegetables (Bhale *et al.*, 2012). Diatomaceous earth was coated bi-weekly onto the plants to control pests such as aphids and thrips (Buss and Brown, 2006).

The Irrigation Design Manual (Burger *et al.*, 2003) was used to calculate irrigation requirements of the soil grown plants. It was determined that the spinach would need to be irrigated with 5 mm of water every 3 days. The nutrient solution was applied with every second irrigation. The TEROS 21 soil water potential meter (METER Group, Inc. USA) with ± 10% accuracy (Eliades *et al*., 2018) in conjunction with a Decagon ProCheck readout device (Bart *et al.*, 2015) that displayed the data instantaneously, were used to monitor soil moisture to ensure that the plants were not under- or over irrigated.

For the hydroponic structures, the nutrient solution was replenished every week. When the nutrient solution was being replaced, the “old” solution from the previous week was discarded. This was done to prevent the pumps from being clogged by the precipitation that would collect at the bottom of the reservoir. An ECO Testr EC meter (Stanley *et al*., 2014) with a ± 1% accuracy (Eutech Intsruments, Singapore) was used to monitor the electrical conductivity to ensure that it was within recommended values of 1.5 and 2.5 $dS.m^{-1}$ (Kumari *et al.*, 2018a). When the solution was above this range, it would be diluted with water. When it fell below these values, more nutrient solution would be added. The pH was also checked to ensure that it ranged between 5.5 and 6.5 as recommended for hydroponic systems (Sardare and Admane, 2013b). In cases where these values were exceeded, a pH up/down solution was used to return the solution to permissible values.

4.2.3 Data collection

Destructive sampling was conducted on three randomly selected plants from each treatment every second week. The following biometric measures were taken; leaf area, stem, and root lengths, and leaf-, stem- and root fresh and dry weights. The roots for soil grown plants were washed in order to remove soil and obtain accurate weights. Leaf area was determined using the Leaf-IT application with a ± 0.5% accuracy (Schrader *et al.*, 2017). A pair of vernier callipers were used to measure stem and root lengths. The weights of the different plant components were determined using the Kern-SOHN ALS250-4A analytical balance. The plants were dried in an oven dryer at 65°C for 24 hours to obtain dry weights.

The areas occupied by the structures and plant pots were determined using a measuring tape. Quaye *et al.* (2010) reported that agricultural land use efficiency (LUE) is calculated by dividing the total yield produced by the total area of land used to produce that yield. In the study, the total yield produced was determined by multiplying the total number of plants by the average sample dry weight. Therefore, the land use efficiency was determined using Equation 4.1.

$$LUE = \frac{N_T}{A} \times w_D \tag{4.1}$$

where

LUE = land use efficiency [g.m^{-2}],

N_T = total number of plants,

A = area occupied by growing system [m^2], and

w_D = plant dry weight [g].

Ali and Talukder (2008) defined crop water productivity (CWP) as the crop production per unit volume of applied water. Total dry matter yield can be used to express crop production (Ali and Talukder, 2008). CWP was determined using Equation 4.2.

$$CWP = \frac{N_T}{W_T} \times w_D \qquad (4.2)$$

where

CWP = crop water productivity [g.l^{-1}], and

W_T = total water used for irrigation during growing period [l].

For the hydroponic systems under sunlight, the pump energy consumption was calculated to determine the energy use efficiency (EUE). For the hydroponic system under LED grow lights, the pump and grow lights energy consumption were calculated to determine the EUE. For the soil setup under grow lights, the lights' electricity consumption was used to determine the EUE. Equation 4.3 was used to determine the energy use efficiency of the different treatments.

$$EUE = \frac{N_T}{P \times t} \times w_D \qquad (4.3)$$

where

EUE = energy use efficiency [g.kWh^{-1}],

P = power rating of equipment [kW], and

t = total run time of equipment [hours].

4.3 Data analysis

An analysis of variation (ANOVA) at a 95% confidence interval using IBM SPSS Statistics 26 (Dytham, 2011) was used to conduct statistical analysis of the results of two cropping seasons. The analysis was conducted by comparing the LUE, CWP, and EUE values of the different treatments and determining whether a significant difference existed amongst them. Once a significant difference was established, pairwise comparisons were then used to establish between which treatments the significant difference existed.

4.4 Results and Discussion

This section presents the comparison of the resource use efficiencies of the different treatments. Land-, energy use efficiencies and crop water productivity were used as measures of resource use efficiencies. The nutrient solution concentration levels did not have a significant effect on the plant growth parameters. This means that the interpretations of the results obtained in the study are admissible across recommended nutrient solution concentration levels. Therefore, the interpretations of the results obtained in the study are admissible across recommended nutrient solution concentration levels.

4.4.1 Land use efficiency

The average dry matter output per unit area ($g.m^{-2}$) was used as a measure of land use efficiency (LUE). There was a statistically significant difference between the LUE of plants grown hydroponically and those grown in soil, $p < 0.0005$ in both cropping seasons. This means that, irrespective of light provision, the hydroponic systems had a higher LUE than the plants grown in soil in plant pots.

Furthermore, the difference between the LUE of plants grown hydroponically under grow lights and plants grown in soil under grow lights was statistically significant, $p < 0.0005$. This was because use of the vertical plane enabled the hydroponic structures to occupy a smaller horizontal area whilst producing more plants per unit area. The vertical structures were able to produce 5 times more plants per unit area than the soil set up for both light treatments, as each column could carry 20 plants. This result is important because, with increasing food requirements and dwindling arable land, small-scale hydroponic vertical structures use occupied space more efficiently than conventional planting in soil. Rufí-Salís *et al.* (2020) reported a higher LUE for large-scale vertical farms, stating that such systems could have LUE values that are 12.5 – 25 times higher than the conventional greenhouse production of lettuce. The LUE of small-scale vertical farming structures could be increased by increasing column height. But factors, such as column stability, shading effects, ergonomics for planting/harvest time, and ergonomics for maintenance would have to be considered before scaling up column sizes.

In both cropping seasons, the LUE of plants grown hydroponically under grow lights was significantly different to that of plants grown hydroponically under sunlight, $p < 0.0005$. Even though both systems occupied the same space, thus producing the same number of plants per unit area, the dry mass per unit area of the plants grown hydroponically under grow lights was significantly higher than that of plants grown hydroponically under sunlight. This means that the presence of grow lights resulted in higher plant mass production. This is because grow lights produce controlled and more consistent radiation than sunlight.

Unlike sunlight, the radiation from grow lights is not influenced by factors such as weather conditions. Additionally, artificial grow lights have the added benefit of providing a photoperiod that can be altered to suit plant needs. In the study, plants grown u nder grow lights had an 18-hour photoperiod, whereas the photoperiod for plants grown under sunlight depended on when the sun rose and set. Figure 4.2 and Figure 4.3 display the land use efficiencies for the different treatments in CS1 and CS2, respectively.

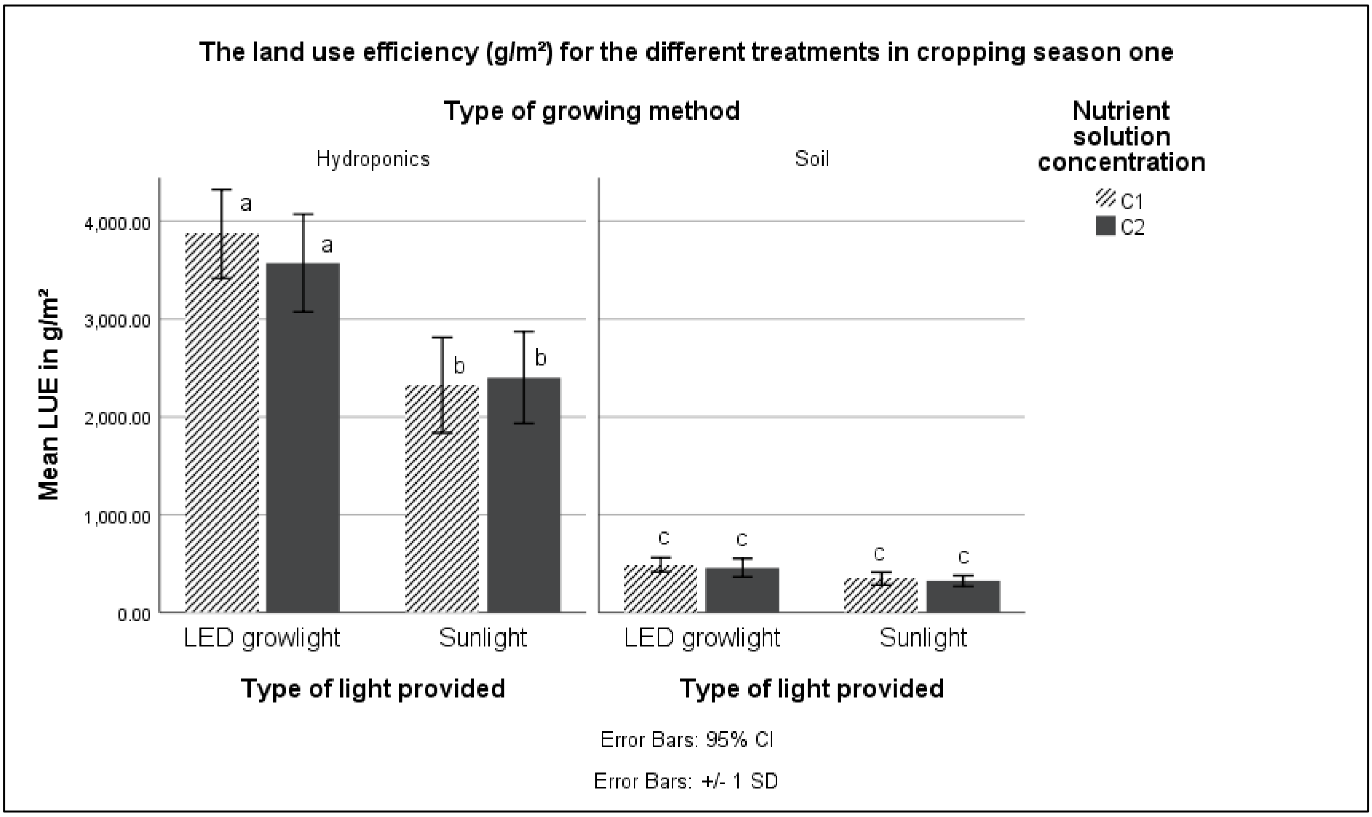

Figure 4.2 The land use efficiency in g.m^{-2} of the different treatments in cropping season one. The same letters indicate that the difference was not statistically significant between the treatments at $p = 0.05$

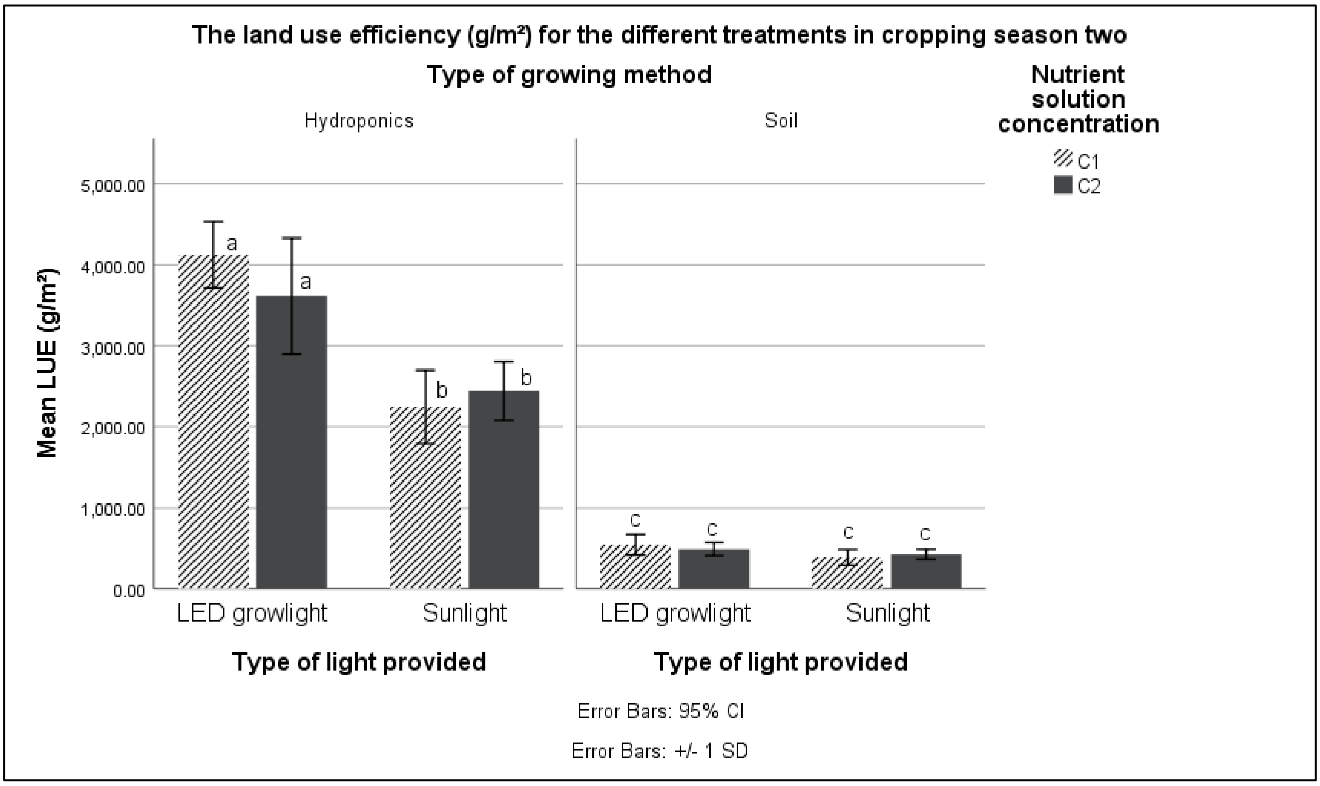

Figure 4.3 The land use efficiency in $g.m^{-2}$ of the different treatments in cropping season two. The same letters indicate that the difference was not statistically significant between the treatments at $p = 0.05$

The LUE of plants grown hydroponically under sunlight was significantly higher than that of plants grown in soil under LED grow lights, $p < 0.0005$. The result indicates that when comparing hydroponic systems under sunlight with plants grown in soil under grow lights, the use of the vertical plane outperforms the benefits associated with grow lights. This is because the vertical structures occupied a smaller horizontal area than the plant pots. Therefore, they produced more plants per unit area than the plants grown in soil under grow lights. This is an important result for controlled environmental agriculture (CEA) where grow lights are used to supplement sunlight during dark hours. Grow lights have been identified as one of the highest energy consumers in CEA. Therefore, this result suggests that vertical hydroponic structures could be an alternative to soil-based plant growth in cases where grow lights supplement sunlight, as they use space more efficiently.

In this study, it was observed that the leaf areas of plants grown hydroponically under sunlight decreased in size along the length of the columns from top to bottom. Due to sample number restrictions, it could not be determined whether this variation was significant. This appears to be a limitation that is inherent to column-type vertical farming structures, as Touliatos *et al.* (2016) noted similar trends for lettuce grown in vertical columns under metal halide lamps. In the study by Touliatos *et al.* (2016), the grow lights were placed above plants. However, in this undertaken study, the leaf area sizes did not vary along the column lengths of plants grown hydroponically under grow lights because the lights were placed in front of the structures. This limitation, therefore, only poses a restriction for increasing column height for plants grown under sunlight or in cases where grow lights are placed above the columns.

4.4.2 Crop water productivity

The dry matter produced per litre of total water used ($g.l^{-1}$) was used as a measure of crop water productivity. Plants grown hydroponically and those grown in soil used a comparable amount of water in terms of total water consumption over the growing period. This was because in the study, the nutrient solution used by the hydroponic systems was discarded weekly. This was done to prevent the pumps from being clogged by the precipitate that would collect at the bottom of the reservoir. However, the difference between the mean CWP of plants grown hydroponically and those grown in soil was statistically significant in both cropping seasons, $p < 0.0005$ in CS1 and in CS2, $p = 0.014$. Figure 4.4 and Figure 4.5 display the CWP for the treatments in CS1 and CS2, respectively.

Barbosa *et al.* (2015) reported a similar trend when comparing the large-scale hydroponic production of lettuce against conventional greenhouse production. In the study by Barbosa *et al.* (2015), hydroponically- and soil-grown lettuce consumed a comparable volume of water, but the hydroponically grown lettuce consumed less water per plant or, inversely, produced more yield per litre of water than the soil system. This can be attributed to the fact that, in hydroponic systems, a higher fraction of the supplied water is allocated to plant production than in soil systems. In soil systems, some of the water supplied is lost to the soil environment surrounding the plant. In hydroponic systems, because the nutrient solution is collected at the roots and recirculated, there is minimal water loss to the surroundings.

This is an important finding for agriculture because fresh-water availability is a big concern. These results show that vertical hydroponic structures produce significantly higher yields than soil planting from the same volume of water. What is more, the mean CWP of the vertical hydroponic structures could further be improved if the 'old' nutrient solution was not discarded every week, as was done in the study, but rather recovered and reused. Rufí-Salís *et al.* (2020) investigated techniques for nutrient solution recovery in hydroponics and found that direct leachate recirculation was the best option in terms of nutrient solution re-use, and it had a lower carbon footprint than the other options investigated.

In this system, the recovered nutrient solution could be filtered and sterilised. The remaining nutrients would then be analysed to assess which nutrients needed to be re-added to meet plant requirements. Such a system would have a two-fold impact as it would not only decrease the amount of water added to the system, but it would also decrease the overall amount of nutrients supplied as well.

Although the water consumption for both treatments was the same, there was a significant difference in both seasons ($p < 0.0005$) between the mean CWP of plants grown hydroponically under LED grow lights and plants grown hydroponically under sunlight. This means that the presence of LED grow lights improved the hydroponic system's yield production per litre of water consumed. In their study of greenhouse tomatoes, Li *et al.* (2019) found that plants grown under supplementary LED lighting had a higher water use efficiencies (WUE) than plants grown under sunlight, even though water consumption was similar. The higher WUE by the hydroponic system under grow lights was because the LED grow lights enhanced plant photosynthesis, thereby increasing WUE without changing water consumption (Li *et al.*, 2019).

There was no significant difference between the CWP of plants grown hydroponically under sunlight and those grown in soil under grow lights, $p = 0.969$ in CS1 and $p = 0.099$ in CS2. This result suggests that the effect of collecting and recirculating the nutrient solution in small-scale vertical hydroponic systems under sunlight is equivalent to the addition of grow lights in growing plants in soil. However, if a filtration system would be incorporated in the structures' design as formerly described, growing plants in vertical hydroponic structures under sunlight would have a higher CWP than growing plants in soil under LED grow lights.

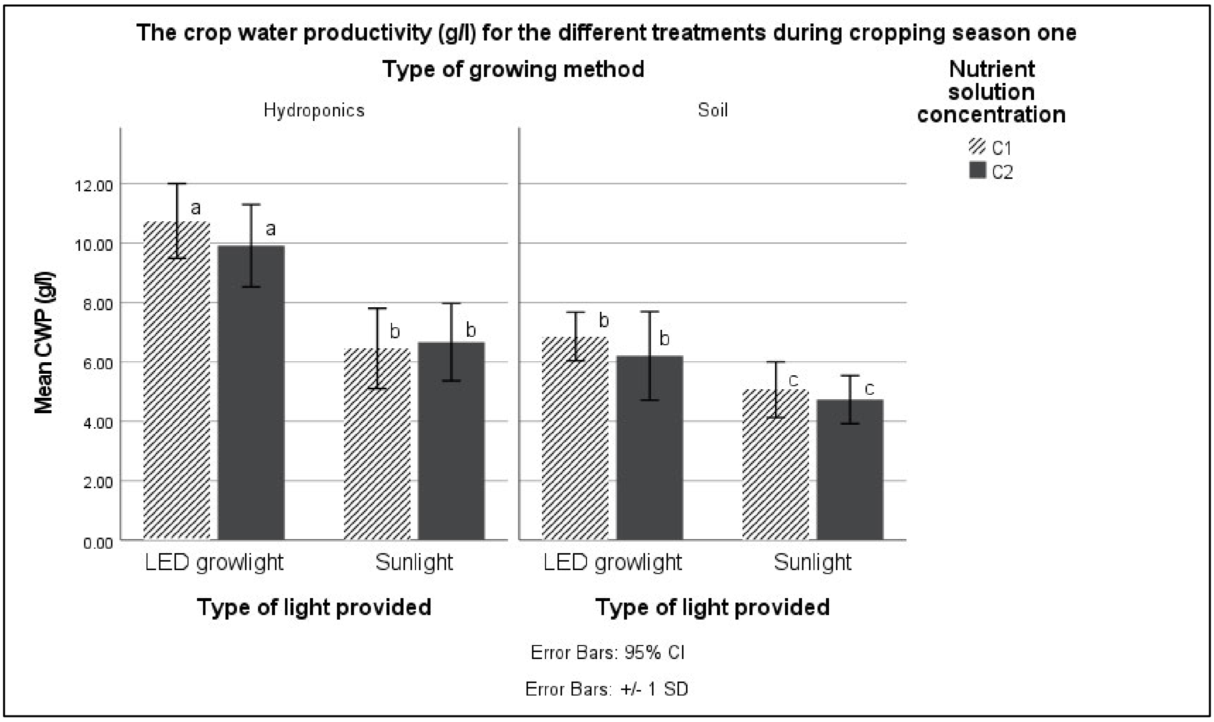

Figure 4.4 The crop water productivity in $g.l^{-1}$ of the different treatments in cropping season one. The same letters indicate that the difference was not statistically significant between the treatments at p = 0.05

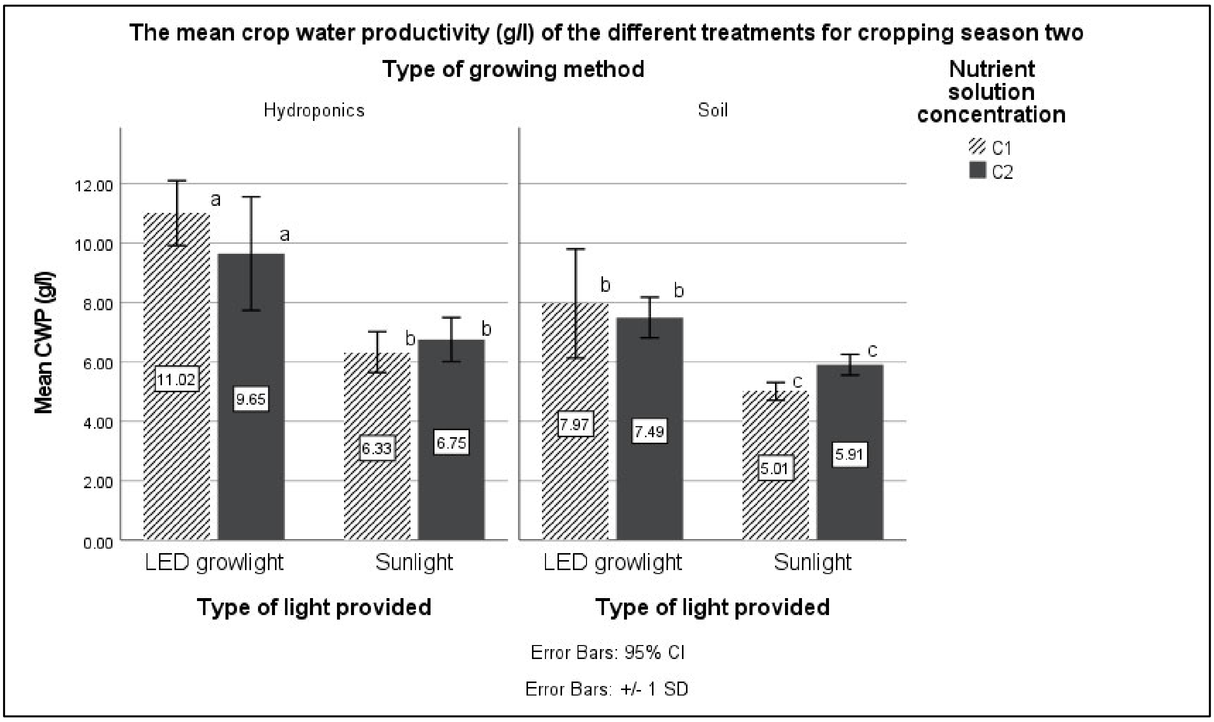

Figure 4.5 The crop water productivity in $g.l^{-1}$ of the different treatments in cropping season two. The same letters indicate that the difference was not statistically significant between the treatments at p = 0.05

4.4.3 Energy use efficiency of the vertical hydroponic systems

The difference between the mean EUE between plants grown hydroponically under sunlight and those grown hydroponically under grow lights was statistically significant, $p < 0.0005$ in both cropping seasons. This result was because the grow lights' energy consumption was high enough to result in a significant difference between the hydroponic systems' EUE. This was not surprising as indoor lighting has been identified as one of the largest energy consumers in CEA (Sparks, 2016). Barbosa *et al.* (2015) documented that the large-scale hydroponic production of lettuce can require 82 times or more energy per kilogram than conventional lettuce production. The high energy consumption in this study was because the grow lights operated for 18 hours a day to meet the ideal photoperiod requirements for plants. Although this has been proven to be beneficial in terms of LUE and CWP, the large difference in EUE is a concern, especially when the aim of vertical farming is to minimise negative environmental impacts. Figure 4.6 displays the EUE for the plants grown hydroponically under the different light settings in CS1 and CS2.

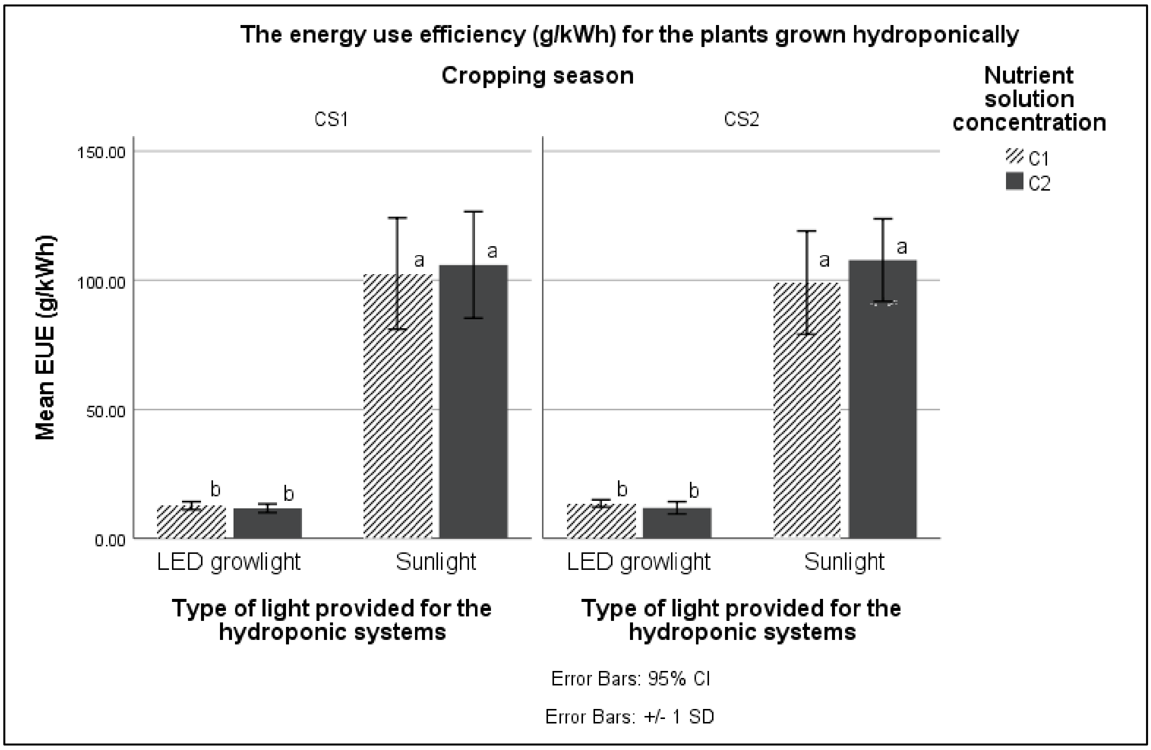

Figure 4.6 The energy use efficiency in $g.kWh^{-1}$ of the plants grown hydroponically under different light treatments in cropping season one (CS1) and two (CS2). The same letters indicate that the difference was not statistically significant between the treatments at $p = 0.05$

The mean EUE of plants grown hydroponically under grow lights was significantly different from the mean EUE of soil grown plants under grow lights, p = 0.002 in CS1 and p = 0.013 in CS2. Even though the hydroponic system under grow lights had additional energy consumption from the pump, its EUE was still significantly higher than that of the soil grown plants under grow lights. This meant that, despite the vertical hydroponic system under grow lights having a higher energy consumption than soil-based growth under grow lights, the hydroponic system was more productive in terms of EUE. Use of the vertical plane in conjunction with water recirculation resulted in a more efficient use of energy.

This result is important for soil-based CEA where artificial grow lights are used to completely replace sunlight. Since these types of CEA applications already need artificial grow light, replacing soil plant growth with small-scale vertical hydroponic systems would result in more efficient use of energy. Figure 4.7 displays the EUE of the plants grown hydroponically and those grown in soil under sunlight.

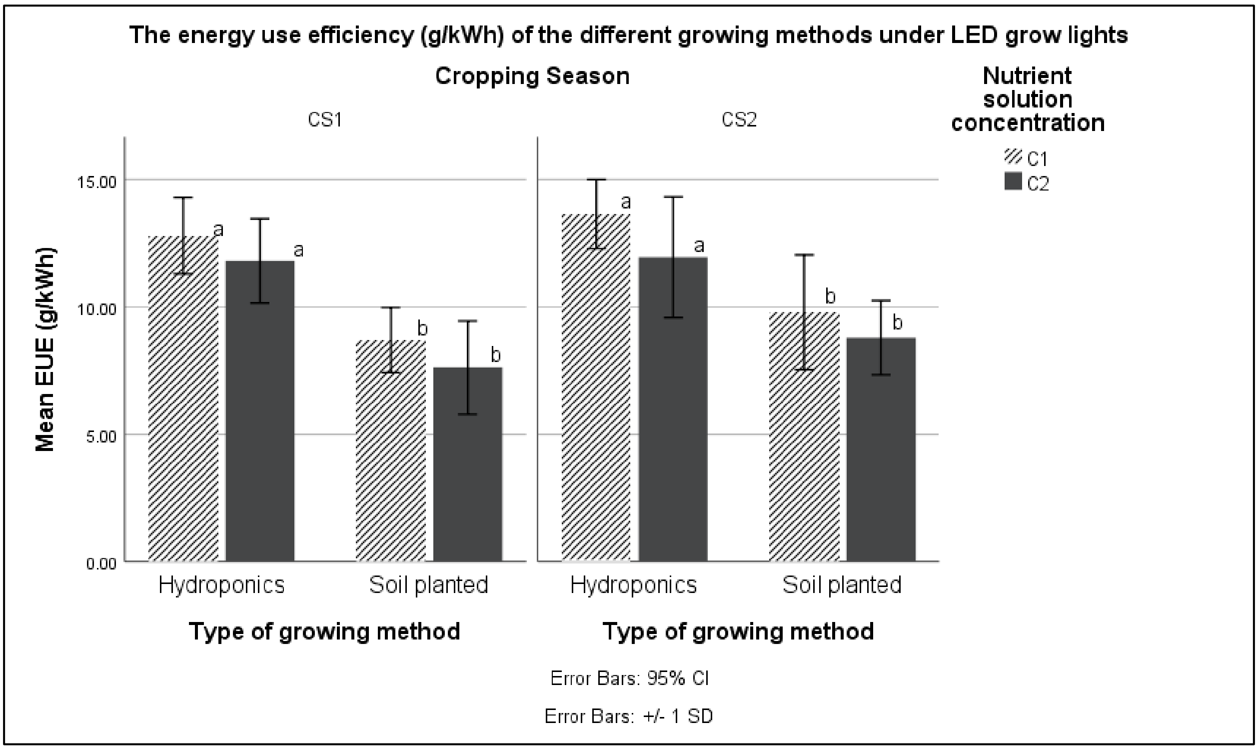

Figure 4.7 The energy use efficiency in g.kWh^{-1} of the different growing methods under LED grow lights in cropping season one (CS1) and two (CS2). The same letters indicate that the difference was not statistically significant between the treatments at p = 0.05

There was a significant difference ($p < 0.0005$ in both cropping seasons) between the EUE of plants grown hydroponically under sunlight and plants grown in soil under grow lights. This was due to the high energy consumption associated with grow lights. Even though the hydroponic system under sunlight made use of a pump for water recirculation, the energy consumption of the grow lights of the soil system was higher than that of the pump.

An advantage of small-scale hydroponic systems is that they can operate using light-duty fountain pumps that do not have high energy requirements. Figure 4.8 illustrates the EUE of the hydroponic system under sunlight and the soil system under grow lights.

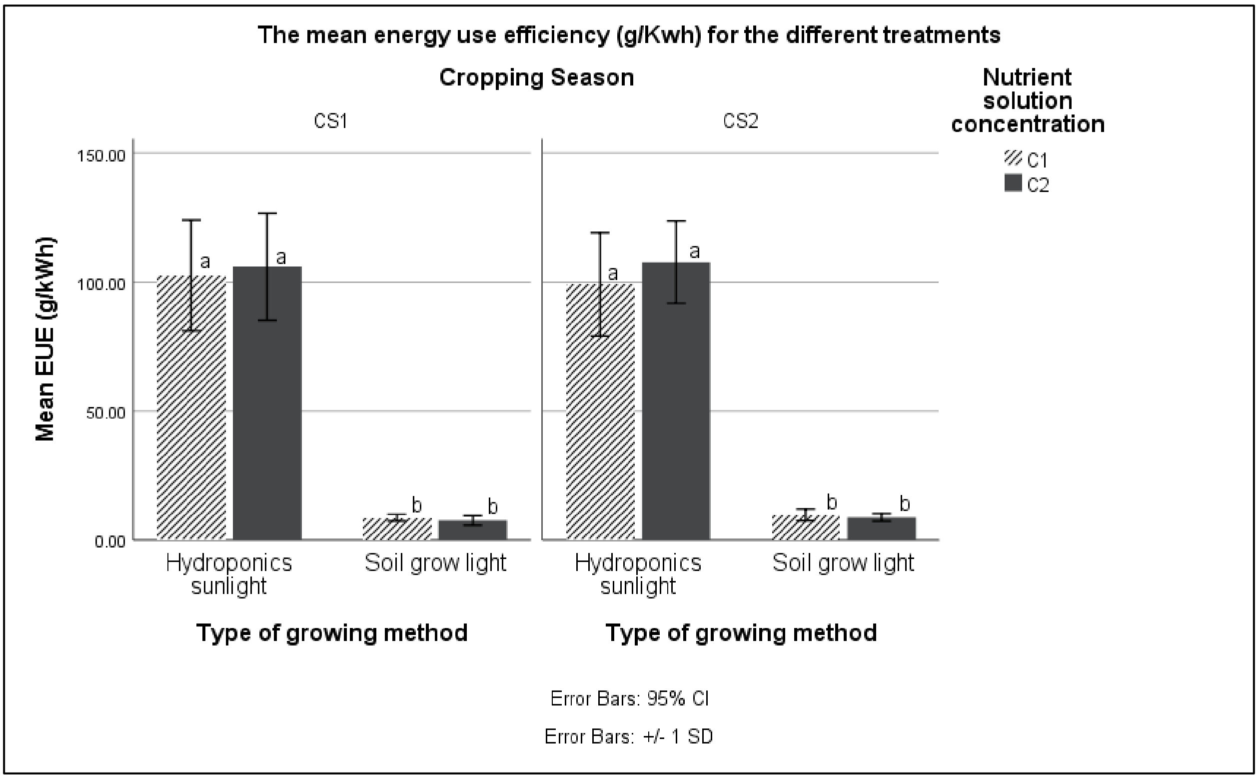

Figure 4.8 The energy use efficiency in $g.kWh^{-1}$ of the different treatments in cropping season one (CS1) and two (CS2). The same letters indicate that the difference was not statistically significant between the treatments at $p = 0.05$

Whilst the energy consumption of the grow lights resulted in low EUE for both the hydroponic and the plant pot systems, the study demonstrated that the presence of grow lights can improve resource use efficiency. Pennisi *et al.* (2019) also reported that use of grow lights can increase the overall resource use efficiency of plant production. In the LUE graphs and CWP graphs, the difference between the light treatments is more distinct in the hydroponics treatment than in the soil treatment. This observation suggests that hydroponic systems use LED grow lights more efficiently than growing plants in soil.

There are several ways in which the energy consumption of systems that use grow lights could be decreased. In regions with sufficient sunlight radiation, these systems could be designed such that grow lights are used seasonally or during times of low radiation. This presents an opportunity for the development of affordable devices that can detect radiation and produce instantaneous results about whether the use of grow lights is necessary at a certain period.

Furthermore, grow lights can be used to mitigate the variance of plant size along the length of columns in vertical hydroponic systems. In such systems, grow lights can be applied to the lower sections to supplement sunlight. Another alternative would be to use grow lights for a shorter photoperiod. That is, to have the grow lights operate for a few hours during dark hours to extend time for photosynthesis whilst reducing electricity consumption. For example, Frąszczak (2013) found that exposing dill plants to red LED light or white light at the end of the night for 30 minutes stimulated plant growth. Therefore, there are several options that can be explored where LED grow lights can be used in such a manner that optimises plant growth, whilst decreasing energy consumption in vertical hydroponics.

4.5 Conclusions and Recommendations

The study aimed to establish whether small-scale vertical farming structures would be a more productive alternative to conventional farming. This was achieved by evaluating the resource use efficiencies of growing plants using small-scale vertical hydroponic structures against growing plants in soil under different light treatments. Based on land use efficiency and crop water productivity, it can be concluded that use of vertical hydroponic structures in conjunction with LED grow lights results in the most efficient use of input resources.

However, the energy use efficiency of vertical hydroponic structures under LED grow lights was low because of the lights' energy consumption. Therefore, all RUEs considered, it can be concluded that growing plants in vertical hydroponic structures under sunlight results in the most efficient use of input resources. The results obtained disproved the null hypothesis. Consequently, the null hypothesis that was postulated was rejected.

Whilst the research has demonstrated the productive capabilities of the combination of vertical hydroponic structures and LED grow lights, it has raised the question of the feasibility and sustainability thereof. The low EUE of this setup may be a deterrent to the implementation of these systems. Therefore, further research, such as cost-benefit analysis comparing vertical hydroponic structures and growing plants in soil, is required to establish whether the benefits associated with the combination of vertical hydroponic structures and LED grow lights outweigh the limitations of the low EUE.

On the other hand, the vertical hydroponic structures under sunlight had high RUEs all-round. The RUE of these systems could further be improved by using solar energy to power the pumps, thus reducing reliance on grid electricity. Future studies could explore solar system designs that would be able to provide reliable power to the systems.

Research presents vertical farming as a possible solution to the challenges associated with conventional farming. Use of the vertical plane and artificial inputs has been stated to improve yield quantities and qualities. However, thus far, there has been a deficit of information on whether yield improvements are achieved at a greater input cost than the conventional growth of plants in soil. This study has contributed to increasing knowledge on the resource use efficiencies of small-scale vertical hydroponic systems. The research conducted has proven that small-scale vertical hydroponic structures use resources more efficiently than growing plants in soil under LED grow lights as well as under sunlight for recommended nutrient solution concentrations.

4.6 References

Akil, K, Sivasakthi, M and Maha, K. 2016. AQUAPONICS–THE FUTURE FARMING. *International Journal of Innovative Research in Technology, Science & Engineering* 2 (4): 1-4.

Al-Karaki, GN and Al-Momani, N. 2011. Evaluation of some barley cultivars for green fodder production and water use efficiency under hydroponic conditions. *Jordan Journal of Agricultural Sciences* 173 (798): 1-21.

Ali, M and Talukder, M. 2008. Increasing water productivity in crop production—a synthesis. *Agricultural water management* 95 (11): 1201-1213.

AlShrouf, A. 2017. Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)* 27 (1): 247-255.

Amelework, A, Laing, M and Shimelis, H. 2016. Evaluation of effective gametocides for selective induction of male sterility in sorghum. *Czech Journal of Genetics and Plant Breeding* 52 (4): 163-170.

Aswath, C, Selvakumar, G, Zimmerman, C and Bajikar, M.2016. Utilization of vertical spaces for horticultural crop production in urban and peri-urban areas. 2048-2049. Indian Academy of Sciences,

Banerjee, C and Adenaeuer, L. 2014. Up, up and away! The economics of vertical farming. *Journal of Agricultural Studies* 2 (1): 40-60.

Bantis, F, Smirnakou, S, Ouzounis, T, Koukounaras, A, Ntagkas, N and Radoglou, K. 2018. Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). *Scientia Horticulturae* 235 437-451.

Barbosa, GL, Gadelha, FDA, Kublik, N, Proctor, A, Reichelm, L, Weissinger, E, Wohlleb, GM and Halden, RU. 2015. Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health* 12 (6): 6879-6891.

Benke, K and Tomkins, B. 2017. Future food-production systems: vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy* 13 (1): 13-26.

Bhale, U, Ambuse, M, Chatage, V and Rajkonda, J. 2012. Bioefficacy of Trichoderma isolates against pathogenic fungi inciting spinach (Spinacea oleracea L.). *Journal of Biopesticides* 5 (2): 222.

Birkby, J. 2016. Vertical Farming. [Internet]. National Center of Appropriate Technology. Available from: https://attra.ncat.org/attra-pub/viewhtml.php?id=512. [Accessed: 04-05-2017].

Burger, J, Heyns, P, Hoffman, E, Kleynhans, E, Koegelenberg, F, Lategan, M, Mulder, D, Smal, H, Stimie, C, Uys, W, van der Merve, F, van der Stoep, I and Viljoen, P. 2003. *Irrigation Design Manual*. Agricultural Research Council - Institute for Agricultural Engineering, Pretoria, South Africa.

Buss, E and Brown, S. 2006. Natural Products for Insect Management. [Internet]. University of Florida. Available from: https://www.researchgate.net/profile/Eileen_Buss/publication/237391484_Natural_Products_for_Insect_Pest_Management1/links/00b4952a5dbef7e2b4000000.pdf. [Accessed: 02 May 2020].

Caglayan, N and Ertekin, C. 2010. USING OF LED LIGHTING TECHNOLOGIES TO SUBSTITUTE TRADITIONAL LIGHTING SYSTEMS IN GREENHOUSES. *Energetic and Ecological Aspects of Agricultural Production*

Chiipanthenga, M, Maliro, M, Demo, P and Njoloma, J. 2012. Potential of aeroponics system in the production of quality potato (Solanum tuberosum l.) seed in developing countries. *African Journal of Biotechnology* 11 (17): 3993-3999.

Cho, R. 2015. How sustainable is vertical farming? [Internet]. Columbia University. Available from: https://phys.org/print369046891.html. [Accessed: 10 February 2018].

ÇİçeklÍ, M. 2013. Vertical farming. *Ege Üniversitesi Ziraat Fakültesi Dergisi* (Special Issue Volume 2): 383-388.

Craig, DS. 2012. Determining effective ratios of red and far-red light from light-emitting diodes that control flowering of photoperiodic ornamental crops. Unpublished Dissertation thesis, Horticulture, Michigan State University, East Lansing.

Danila, E and Lucashe, D. 2013. Cost Effectiveness of Growing Plant Lighting System. *Journal of Electrical Engineering* 320 (2013): 400nm.

Dannehl, D, Suhl, J, Ulrichs, C and Schmidt, U. 2015. Evaluation of substitutes for rock wool as growing substrate for hydroponic tomato production. *Journal of Applied Botany and Food Quality* 88 (1):

Despommier, D. 2012. Advantages of the vertical farm. In: *Sustainable Environmental Design in Architecture*. Springer, New York, USA.

Despommier, D. 2013. Farming up the city: the rise of urban vertical farms. *Trends in biotechnology* 31 (7): 388.

Despommir, D and Ellington, E.2008. The vertical farm: the sky-scraper as vehicle for a sustainable urban agriculture. *CTBUH 8th World Congress on Tall & Green: Typology for a Sustainable Urban Future*, 311-318. ResearchGate, Dubai, United Arab Emirates.

Dhehibi, B, Frija, A, Aw-Hassan, A, Akroush, S and Ibrahim, A. 2015. Approaches to Total Factor Productivity Measurements in the Agriculture Economy. [Internet]. CRP Dryland Systems. Available from: https://mel.cgiar.org/reporting/download/hash/TS3DKNYY. [Accessed: 10 February 2018].

Dytham, C. 2011. *Choosing and Using Statistics: A Biologist's Guide*. Wiley-Black, West Sussex, United Kingdom.

Eigenbrod, C and Gruda, N. 2015. Urban vegetable for food security in cities. A review. *Agronomy for Sustainable Development* 35 (2): 483-498.

Foley, JA, Ramankutty, N, Brauman, KA, Cassidy, ES, Gerber, JS, Johnston, M, Mueller, ND, O'Connell, C, Ray, DK and West, PC. 2011. Solutions for a cultivated planet. *Nature* 478 (7369): 337-342.

Frąszczak, B. 2013. Effect of short-term exposure to red and blue light on dill plants growth. *Horticultural Science* 40 (4.): 177-185.

Garnett, T, Appleby, M, Balmford, A, Bateman, I, Benton, T, Bloomer, P, Burlingame, B, Dawkins, M, Dolan, L and Fraser, D. 2013. Sustainable intensification in agriculture: premises and policies. *Science* 341 (6141): 33-34.

Gashgari, R, Alharbi, K, Mughrbil, K, Jan, A and Glolam, A.2018. Comparison between growing plants in hydroponic system and soil based system. *Proceedings of the 4th World Congress on Mechanical, Chemical, and Material Engineering*, 1-7. ICMIE Madrid, Spain,

George, P and George, N. 2016. HYDROPONICS-(SOILLESS CULTIVATION OF PLANTS) FOR BIODIVERSITY CONSERVATION. *International Journal of Modern Trends in Engnieering and Science* 3 (6):

Germer, J, Sauerborn, J, Asch, F, de Boer, J, Schreiber, J, Weber, G and Müller, J. 2011. Skyfarming an ecological innovation to enhance global food security. *Journal für Verbraucherschutz und Lebensmittelsicherheit* 6 (2): 237-251.

Girón González, E. 2012. LEDs for general and horticultural lighting. Unpublished Dissertation thesis, Electronics, Aalto University, Greater Helsinki.

Godfray, HCJ and Garnett, T. 2014. Food security and sustainable intensification. *Philosophical transactions of the Royal Society B: biological sciences* 369 (1639): 1-10.

Gopinath, P. 2017. Aeroponics Soilless Cultivation System for Vegetable Crops. *Chemical Science Review and Letters* 6 (22): 838-849.

Graamans, L, Baeza, E, Van Den Dobbelsteen, A, Tsafaras, I and Stanghellini, C. 2018. Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems* 160 31-43.

Graff, GJ. 2012. Skyfarming. Unpublished MSc thesis, Department of Architecture, University of Waterloo, Ontario, Canada.

Gray, E, Jackson, T and Zhao, S. 2011. *Agricultural Productivity: Concepts, measurement and factors driving it*. 10/161. Canberra, Australia.

Gruda, N, Qaryotui, MM and Leonardi, C. 2013. Growing Media. In: eds. Wilfried, B, Remi, N-W, Nebambi, L, Alison, H, Nicolás, C, Cherubino, L, Stefania, DP, Muien, Q and Duffy, R, *Good agricultural practices for greenhouse vegetable crops: principles for mediterranean climate areas*. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome.

Gruner, RL, Orazi, D and Power, D. 2013. Global versus local: an exploration on how vertical farms can lead the way to more sustainable supply chains. *IEEE Engineering Management Review* 41 (2): 23-29.

Hallock, LS. 2013. Vertical Farms, Urban Restructuring and the Rise of Capitalist Urban Agriculture. Unpublished MSc thesis, Agrarian and Environmental Studies, Erasmus University, Hague, Netherlands.

Hoffmann, WA and Poorter, H. 2002. Avoiding Bias in Calculations of Relative Growth Rate. *Annals of Botany* 90 (1): 37-42.

Howland, A, Kim, N and Marks, A. 2012. ADVANCED FOOD TECHNOLOGIES. [Internet]. Massachusetts Institute of Technology. Available from: https://static1.squarespace.com/static/51352c64e4b00e99bdc21d13/t/513a5cade4b0be1eb03e6b6c/1362779309755/AdvFoodTechFinalPaper.pdf. [Accessed: 01-03-2017].

Incrocci, L, Pardossi, A, Minuto, A and Diara, C.2010. Reusing Greenhouse Growing Media. *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 927*, 793-800. International Society for Horticultural Science,

Kalantari, F, Tahir, O, Lahijani, A and Kalantri, S. 2017. A Review of Vertical FArmin Technology: A Guide for Implementation of Building Integrated Agr. *Advanced Engineering Forum* 24 (2017): 76-91.

Kalantari, F, Tahir, OM, Joni, RA and Fatemi, E. 2018. Opportunities and challenges in sustainability of vertical farming: A review. *Journal of Landscape Ecology* 11 (1): 35-60.

Kang, JH, KrishnaKumar, S, Atulba, SLS, Jeong, BR and Hwang, SJ. 2013. Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system. *Horticulture, Environment, and Biotechnology* 54 (6): 501-509.

Koscica, M. 2014. Agropolis: the role of urban agriculture in addressing food insecurity in developing cities. *Journal of International Affairs* 67 (2): 177.

Kumari, S, Pradhan, P, Yadav, R and Kumar, S. 2018a. Hydroponic techniques: A soilless cultivation in agriculture. *Journal of Pharmacognosy and Phytochemistry* 7 (2018): 1886 - 1891.

Kumari, S, Pradhan, P, Yadav, R and Kumar, S. 2018b. Hydroponic techniques: A soilless cultivation in agriculture. *Journal of Pharmacognosy and Phytochemistry* 2018 1886-1891.

Kurukulasuriya, P and Rosenthal, S. 2013. *Climate change and agriculture: A review of impacts and adaptations*. The World Bank, Washington DC, USA.

Lakkireddy, K, Kasturi, K and KRS, SR. 2012. Role of Hydroponics and Aeroponics in Soilless Culture in Commercial Food Production. *Journal of Agricultural Science & Technology* 1 (1): 26-35.

Lee, S and Lee, J. 2015. Beneficial bacteria and fungi in hydroponic systems: types and characteristics of hydroponic food production methods. *Scientia Horticulturae* 195 (2015): 206-215.

Li, Q, Liu, Y, Tian, S, Liang, Z, Li, S, Li, Y, Wei, M and Zhang, D. 2019. Effect of supplemental lighting on water transport, photosynthetic carbon gain and water use efficiency in greenhouse tomato. *Scientia Horticulturae* 256 108630.

Link, N. 1987. *Technological Change and Productivity*. Harwood Academic Publishers, Chur, Switzerland.

Lowry, CJ and Smith, RG. 2018. Chapter 5 - Weed Control Through Crop Plant Manipulations. In: eds. Jabran, K and Chauhan, BS, *Non-Chemical Weed Control*. Academic Press.

Maršić, NK and Jakše, M. 2010. Growth and yield of grafted cucumber (Cucumis sativus L.) on different soilless substrates. *Journal of Food, Agriculture & Environment* 8 (2): 654-658.

Mechri, A, Lys, P and Cachia, F. 2017. *Productivity and Efficiency Measurement in Agriculture Literature Review and Gaps Analysis*. GO-19-2017.

Metallo, RM, Kopsell, DA, Sams, CE and Bumgarner, NR. 2018. Influence of blue/red vs. white LED light treatments on biomass, shoot morphology, and quality parameters of hydroponically grown kale. *Scientia Horticulturae* 235 189-197.

Mugundhan, M. 2011. “HYDROPONICS”-A NOVEL ALTERNATIVE FOR GEOPONIC CULTIVATION OF MEDICINAL PLANTS AND FOOD CROPS MURALI MUGUNDHAN. R*, SOUNDARIA. M, MAHESWARI. V, SANTHAKUMARI. P AND GOPAL. V. *International Journal of Pharma and Bio Sciences* 2 (2): 286-296.

Murray, A. 2016. Partial versus Total Factor Production Measures: An Assessment of their Strengths and Weaknesses. [Internet]. Centre for the Study of Living Standards. Available from: www.csls.ca/ipm/31/murray.pdf. [Accessed: 10 February 2018].

Murray, A and Sharpe, A. 2016. Partial versus Total Factor Productivity: Assessing Resource Use in Natural Resource Industries in Canada. [Internet]. Smart Prosperity Institute. Available from: http://institute.smartprosperity.ca/library/research/partial-versus-total-factor-productivity-assessing-resource-use-natural-resource. [Accessed: 10 Febraury 2018].

Pandey, R, Jain, V, Pandey, KSR and Singh, K. 2009. Hydroponics Agriculture: Its Status, Scope and Limitations. [Internet]. Researchgate. Available from: https://www.researchgate.net/profile/Renu_Pandey/publication/259786326_Hydroponics_Agriculture_Its_Status_Scope_and_Limitations/links/00b4952de76be8b665000000.pdf. [Accessed: 06-06-2017].

Patil, P, Kakade, S, Kantale, S and Shinde, D. 2016. Automation in Hydroponic System Using PLC. *International Journal of Scientific and Technical Advancements* 2 (2): 69-71.

Pattillo, DA. 2017. An Overview of Aquaponic Systems: Hydroponic Components.

Pennisi, G, Orsini, F, Blasioli, S, Cellini, A, Crepaldi, A, Braschi, I, Spinelli, F, Nicola, S, Fernandez, JA and Stanghellini, C. 2019. Resource use efficiency of indoor lettuce (Lactuca sativa L.) cultivation as affected by red: blue ratio provided by LED lighting. *Scientific reports* 9 (1): 1-11.

Pinho, P, Jokinen, K and Halonen, L. 2012. Horticultural lighting–present and future challenges. *Lighting Research & Technology* 44 (4): 427-437.

Quaye, AK, Hall, CAS and Luzadis, VA. 2010. Agricultural land use efficiency and food crop production in Ghana. *Environment, Development and Sustainability* 12 (6): 967-983.

Rahman, MA and Amin, MR. 2016. Aquaponics: A Potential Integrated Farming System for Sustainable Agriculture and Aquaculture. *International Journal of Biological, Ecological and Environmental Sciences* 5 (1): 42-45.

Rufí-Salís, M, Calvo, MJ, Petit-Boix, A, Villalba, G and Gabarrell, X. 2020. Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. *Resources, Conservation and Recycling* 155 104683.

Sabzalian, MR, Heydarizadeh, P, Zahedi, M, Boroomand, A, Agharokh, M, Sahba, MR and Schoefs, B. 2014. High performance of vegetables, flowers, and medicinal plants in a red-blue LED incubator for indoor plant production. *Agronomy for sustainable development* 34 (4): 879-886.

Sardare, MD and Admane, SV. 2013a. A review on plant without soil-hydroponics. *International Journal of Research in Engineering and Technology* 2 (3): 299-304.

Sardare, MMD and Admane, MSV. 2013b. A review on plant without soil-hydroponics. *Int J Res Eng Technol* 2 299-305.

Sardare, MMD and Admane, MSV. 2013c. A review on plant without soil-hydroponics. *Int J Res Eng Technol* 2 (3): 299-305.

Sarkar, A and Majumder, M. 2015. Opportunities and Challenges in Sustainability of Vertical Eco-Farming: A Review. *Journal of Advanced Agricultural Technologies* 2 (2): 98-105.

Savvas, D, Gianquinto, G, Tuzel, Y and Gruda, N. 2013. Soilless culture. In: eds. Wilfried, B, Remi, N-W, Nebambi, L, Alison, H, Nicolás, C, Cherubino, L, Stefania, DP, Muien, Q and Duffy, R, *Good agricultural practices for greenhouse vegetable crops: principles for mediterranean climate areas*. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome.

Schrader, J, Pillar, G and Kreft, H. 2017. Leaf-IT: An Android application for measuring leaf area. *Ecology and Evolution* 7 (22): 9731-9738.

Sheikh, B. 2006. Hydroponics: key to sustain agriculture in water stressed and urban environment. *Pakistan Journal of Agriculture, Agricultural Engineering and Veterinary Sciences* 22 (2): 53-57.

Singh, D, Basu, C, Meinhardt-Wollweber, M and Roth, B. 2015. LEDs for energy efficient greenhouse lighting. *Renewable and Sustainable Energy Reviews* 49 139-147.

Sparks, RE. 2016. Mapping and analyzing energy use and efficiency in a modified hydroponic shipping container. Unpublished Dissertation thesis, Engineering, Purdue University, West Lafayette, USA.

Specht, K, Siebert, R, Hartmann, I, Freisinger, UB, Sawicka, M, Werner, A, Thomaier, S, Henckel, D, Walk, H and Dierich, A. 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. *Agriculture and human values* 31 (1): 33-51.

Tamulaitis, G, Duchovskis, P, Bliznikas, Z, Breive, K, Ulinskaite, R, Brazaityte, A, Novičkovas, A and Žukauskas, A. 2005. High-power light-emitting diode based facility for plant cultivation. *Journal of Physics D: Applied Physics* 38 (17): 3182.

Tester, M and Langridge, P. 2010. Breeding technologies to increase crop production in a changing world. *Science* 327 (5967): 818-822.

Tomlinson, L. 2015. Indoor Aquaponics in Abandoned Buildings: A Potential Solution to Food Deserts. *Sustainable Dev. L. & Pol'y* 16 (2015): 16-24.

Touliatos, D, Dodd, IC and McAinsh, M. 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and Energy Security* 5 (3): 184-191.

Trejo-Téllez, I, L, Gómez-Merino and C, F. 2012. Nutrient solutions for hydroponic systems. *Hydroponics-a standard methodology for plant biological researches* 1-22.

UN. 2015. World Population Prospects key findings & advance tables 2015 revision. [Internet]. United Nations Department of Economic and Social Affairs Population Division. Available from: https://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf. [Accessed: 09/05/2017].

Valenzano, V, Parente, A, Serio, F and Santamaria, P. 2008. Effect of growing system and cultivar on yield and water-use efficiency of greenhouse-grown tomato. *The Journal of Horticultural Science and Biotechnology* 83 (1): 71-75.

Van der Schans, J, Renting, H and Van Veenhuizen, R. 2014. Innovations in urban agriculture. *Urban Agriculture magazine* 28 (2014): 3-12.

Venter, G. 2017. Understanding semi-hydroponic systems. *Farmer's Weekly* 2017 (17010): 24-25.

Wahome, PK, Oseni, TO, Masarirambi, MT and Shongwe, VD. 2011. Effects of different hydroponics systems and growing media on the vegetative growth, yield and cut flower quality of gypsophila (Gypsophila paniculata L.). *World Journal of Agricultural Sciences* 7 (6): 692-698.

Winch, T. 2007. *Growing Food a Guide to Food Production*. Springer, Dordrecht, Netherlands.

Wollaeger, HM. 2013a. Growth and morphological acclimation of seedlings to blue, green, and red light from light-emitting diodes. Unpublished thesis, Michigan State University,

Wollaeger, HM. 2013b. Growth and morphological acclimation of seedlings to blue, green, and red light from light-emitting diodes. Unpublished thesis, Horticulture, Michigan State University, East Lansing, USA.

Yeh, N and Chung, J-P. 2009. High-brightness LEDs—Energy efficient lighting sources and their potential in indoor plant cultivation. *Renewable and Sustainable Energy Reviews* 13 (8): 2175-2180.

Zezza, A and Tasciotti, L. 2010. Urban agriculture, poverty, and food security: empirical evidence from a sample of developing countries. *Food policy* 35 (4): 265-273.

5. CONCLUSIONS AND RECOMMENDATIONS

Current farming challenges, such as climate change, dwindling fresh-water resources, and diminishing arable land, amongst others, pose a threat to the long-term sustainability of conventional agriculture. There exists a need for more sustainable and reliable means of food production that are not as dependent on natural resources. Vertical farming has been identified as a possible solution to the challenges associated with conventional farming. However, large-scale vertical farms have limitations, such as high capital costs and high energy consumption, which can delay their establishment. Small-scale vertical hydroponic structures, on the other hand, have potential to outperform conventional farming without the high requirements of large-scale vertical farms.

This research was conducted to establish whether small-scale vertical farming structures would be a viable alternative for improving agricultural productivity for plants that can be grown hydroponically. The basis of the structures' viability would be plant biometric attributes as well as the efficiency with which the structures would use resources in growing plants. The study aimed to meet two global objectives. The first was to ascertain whether the biometric attributes of plants grown in small-scale vertical hydroponic structures would be significantly higher than those grown in soil under different light treatments. The second objective was to then establish whether the small-scale vertical hydroponic structures would use input resources more efficiently than growing plants in soil under different light treatments.

The null hypotheses were disproved as the plant biometric attributes and RUEs of plants grown in vertical hydroponic structures were significantly different from growing plants in soil under the different light treatments. From the results, it can be concluded that small-scale vertical hydroponic structures are a viable alternative to improving agricultural productivity for plants that can be grown hydroponically. The results indicate that vertical hydroponic structures not only produce plants with larger biometric attributes, but they also use resources in a more efficient manner than plants growth in soil. These results were obtained for plants grown under sunlight and LED grow lights for the recommended nutrient solution concentrations. Therefore, small-scale vertical hydroponic structures are more agriculturally productive than conventional plant growth in soil.

The study has contributed towards closing the gap in literature on quantitative information on the performance of small-scale vertical farming structures as compared to growing plants in soil. The study has also provided knowledge on how efficiently these structures use resources as compared to conventional farming. Additionally, the study has contributed new knowledge in terms of plant biometric attributes that result from growing plants in vertical hydroponic structures as well as how efficiently the structures use resources compared to growing plants in soil. The results suggest that biometric attributes of plants grown in vertical hydroponic structures under sunlight are statistically equivalent to growing plants in soil under LED grow lights. Moreover, vertical hydroponic structures under sunlight use resources more efficiently than growing plants in soil under LED grow lights. These results have important implications for decision making in controlled environmental agriculture.

Whilst the research has demonstrated the productive capabilities of the combination of vertical hydroponic structures and LED grow lights, it has raised the question of the feasibility and sustainability thereof. The low EUE of this setup may be a deterrent to the implementation of these systems. Therefore, further research, such as cost-benefit studies, is required to establish whether the benefits associated with the combination of vertical hydroponic structures and LED grow lights outweigh the limitations of the low EUE. Although the study revealed important information about small-scale vertical hydroponic structures, there is still a gap in literature about the performance of different configurations of vertical hydroponic structures. Thus, future research can be conducted to compare the performance and resource use efficiencies of different designs of small-scale vertical hydroponic structures. Research can also be done to compare the performance and productivity of small-scale hydroponic-, aquaponic-, and aeroponic vertical structures.

This research has presented small-scale vertical hydroponic structures as a viable replacement for conventional agriculture for plants that can be grown hydroponically based on their ability to grow larger plant whilst using resources more efficiently. Potential research areas have also been identified to further improve the structures' productivity. Although vertical farming stands to revolutionise future agriculture, the challenges associated with large-scale systems may deter its widespread implementation. Nevertheless, small-scale systems appear to be a viable starting point in improving agricultural productivity. The structures not only produced larger plant biometric attributes overall, but they did so using less resources than when the plants were grown in soil.