

Experimental processes for optimized lighting techniques: enhancing vertical farming crop growth and yield efficiency

by

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Abstract

The demand for year-round crop production pushes farmers to find innovative solutions. Researchers are actively exploring vertical farming to determine its potential for commercial crop production. Vertical farms offer a dual advantage: they minimize the need for extensive horizontal land usage and they enable year-round crop cultivation due to their enclosed interior environments. Usually, the sun is the primary source of light for plant development, but electric lighting can accommodate further production in these applications. Recent research is developing spaces without access to sunlight, leading to electric lighting being the only source of light exposure for plant growth.

This report investigates the relationship between lighting and plant growth, seeking the optimal lighting conditions for controlled vertical farming environments. Experimental recommendations for optimal lighting conditions for various crops, including strawberries, lettuce, peppers, and tomatoes, are provided. Using Light Emitting Diode (LED) technology, recommendations for specific wavelengths, intensity, and duration are assessed. The ability to change the conditions will impact plant development and provide the ideal conditions for each crop. The various combinations are determined to find the most significant production yield, whether growth or fruit production. This report will consider the effects of photosynthetic photon flux density (PPFD), crop photoperiods, color of light exposure, and plant production. These will be the primary determinations for growth for this experiment.

The report begins with an overview of the connection between lighting design and horticulture over the years. This historical perspective helps to contextualize the significance of lighting in plant growth and development, highlighting the evolution of lighting technologies and their applications in agriculture. It also explores the pivotal role of light intensity, duration, and

quality in influencing photosynthesis, flowering, and overall crop yield. This section sets the stage for a comprehensive examination of the impacts of lighting on various aspects of plant biology. Delving into the experimental framework involves assessing the effects of different light spectra on the growth patterns of diverse plant species as our specific objectives. The measurement methodologies above will allow us to closely monitor and quantify the responses of each plant species to distinct lighting treatments, thereby facilitating a thorough analysis of the relationships between light and growth.

The lighting in the controlled environment is specified, including fixture descriptions, output values for intensity, source color, and the control system used in the experiment. Each source will emit light of varying spectra and intensity, allowing us to investigate the unique effects of different wavelengths on plant physiology. Detailed information about these light sources' spectral characteristics, including peak wavelengths and spectral distribution, is provided.

Once the experimental setup is defined, hypotheses for each crop are formulated, specifying their assumed reactions. These hypotheses guide the analysis of the anticipated responses from each plant species under the specified lighting conditions. By systematically assessing how plants respond to various wavelengths and durations of light exposure, the aim is to provide valuable insights that can inform optimized lighting strategies for horticultural practices. Furthermore, the report discusses the potential practical applications of the findings, which could contribute to more efficient and sustainable crop production methods.

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Dedications

To Ian Van Horn, my dear friend who passed too soon.

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Chapter 1 - Introduction

As the world's population grows and cities expand, there are considerations for more sustainable crop production. A sustainable approach is to bring the farms closer to the consumers; however, there is a limit to horizontal land available, and cities, are not well suited for crop production. Vertical farming is becoming a more popular idea to combat this issue. Vertical farming takes away the issues that come with needing horizontal space for crop cultivation. Establishing farms in greenhouses provides adequate exposure to sunlight, or vertical farms can occur within a regulated environment that includes supplementary electric lighting. This report focuses on providing electric lighting for plants in controlled environments; highlighting photoperiod, photosynthetically active radiation, and photosynthetic photon flux densities.

1.1 – Objective

This report aims to compile hypotheses for the effects of lighting attributes on various species of plants and outline a lighting installation that can provide optimal production for the specified crops in controlled environments. This report encompasses a variety of content that is crucial for understanding the effect light plays in the growth of crops and can lead researchers and farmers to a successful vertical farm application.

1.2 – Scope of Report

This report walks through how the ideas of lighting and horticulture can lead to the implementation of vertical farming and how one might benefit from these concepts. The report begins with Chapter 2 – The History of Lighting in Horticulture, which discusses the

history of electric lighting and how it eventually became implemented into horticulture design. In Chapter 3 – The Correlations Between Lighting and Horticulture, the fundamentals of lighting in horticulture are laid out to explain how these two topics correlate. Chapter 3 also outlines essential terminology and the three main characteristics for consideration: light intensity, duration, and color. Chapter 4 – Outlining Testing Conditions, defines fundamental details for proposing an experiment, such as the crop choices and what devices properly track testing data. This chapter also dives into the specific lighting desires for each crop, which outlines base values for an experiment. Then Chapter 5 – Layout Overview, considers how to lay out an experiment by considering different growing mediums and what to consider when selecting a light source. Lastly, Chapter 6 – Experimental Design, defines hypotheses for each crop, where the three primary considerations, intensity, photoperiod, and color, provide anticipated results for potential experimentations. This chapter also discovers the implementation of lighting into a physical testing space. To conclude, Chapter 7 – , summarizes the ideas and conclusions this report aims to achieve.

Chapter 2 – The History of Lighting in Horticulture

The evolution of electric lighting has not only transformed human experience but has revolutionized the world of horticulture. Incorporating electric lighting into horticulture has evolved the understanding of plant responses to lighting and has allowed for the development of controlled plant-growing environments. The context provided in this chapter will establish the ideas of lighting and horticulture and signify the importance of continual research on how electric lighting impacts the growth of different plant species.

2.1 Lighting History

The history of electric lighting began in the ancient world with fire. Fires kept people warm through the night and provided evening illumination in accompaniment to moonlighting. The use of oil lamps and candles in homes arose in popularity for centuries while researchers made early attempts to harness electricity for illumination. Notable progress occurred in the late 18th Century when scientists like Michael Faraday and Sir Humphry Davy led research on electricity and introduced electric arc lamps in 1802 (Editors of the Encyclopedia Britannica, 2023).

Further developments in the 19th Century, credited to Thomas Edison, led to the commercialization of electric lighting. Edison's incandescent lamp includes a glass bulb with a filament inside, which heats up when an electric current runs through it, producing light. Edison produced the incandescent lamp in 1879 with aid from Joseph Swan's experimental work on filaments (*Electrifying: The Story of Lighting Our Homes* | Science Museum, 2020). This innovation transformed the world and lighting by allowing activities to occur outside of daylight

hours. People used incandescent lamps for well over one hundred years, mostly phasing them out of use in 2023 due to energy code compliance issues in the United States of America.

The introduction of electric lighting revolutionized human perception of the environment and added an interactive nightscape for people. Lighting during the nighttime extends the hours for various activities and provides a level of safety to the lit space. Cities become vibrant with a transformed urban landscape. Lighting enhances the exterior environment and elongates the indoor experiences since daylighting constrains productivity and leisure time throughout the day. An electric lamp allows for consistency, controllability, flexibility, and a new sense of freedom in daily life.

As time went on, the incandescent lamp advanced, but eventually, researchers established light-emitting diodes (LEDs) in the mid to late 1900's. LEDs were first used for music players in the 1960s, producing only one red light. In the 1970s, the first commercial manufacturer began producing LEDs for lighting use. By the early 21st Century, LEDs had been improved for efficiency, durability, and color rendering (Holmes, 2017). Due to all these advancements, LEDs became suitable for widespread applications, especially in homes. LEDs have the advantage of long lamp life and energy efficiency. The emergence of LEDs has transformed the lighting industry and significantly contributed to energy conservation in the United States of America (*Learn About LED Lighting*, n.d.).

The energy efficiency of LEDs makes them stand out against other light sources because LEDs have better efficacy. Efficacy is the number of lumens emitted from a lamp per amount of power consumed. LEDs have an efficacy of around 150 lm/w, whereas an incandescent has 8-20 lm/w (Hasler, 2022). Additionally, improvements in LED technologies allow for specialized applications, leading toward a range of offered illuminance and light distribution patterns.

Offering more options for designers, LEDs allow lighting to be unique to each space and customized for comfort and need.

Lastly, LEDs can specify assorted color renderings and temperatures. Both attributes correspond to how the designers want the space to be perceived. The color temperature dictates how warm or cool the light feels and how occupants react to the space. If a space requires focus throughout the day, cooler lighting can be chosen, and if a designer wants a space to be more relaxing, warmer lighting can be used. Color rendering is how objects' colors appear in a space. For some designers, this concept is far more important to their space than others. LED lighting improvements allow lighting designers to consider what each space needs, while promoting well-being and productivity, and the regulation of circadian rhythms.

2.2 Approach to Vertical Farming

Over the many centuries of growing civilizations, farming has become a necessity for human survival. Therefore, searching for newer and more efficient methods of agricultural production has always been critical to keep pace with an increasing population. The concept and application of vertical farming dates back to 600 B.C.E. in the Hanging Gardens of Babylon, where plant growth was maximized to take up vertical space (Despommier, 2020). Beyond the ancient world, Mesoamerican Aztecs, a thousand years ago, originated the idea of hydroponics for plant growth (Farming, 2023). Today, we are still trying to improve the efficiency of crop production for our worlds growing population.

Crop production was brought into interior spaces as early as 30 C.E. when the first greenhouse was used in the Roman Empire (Faber et al., 2017). Greenhouses benefit from utilizing sunlight while separating plants from extreme weather to maintain certainty of

production. While greenhouses allow growers improved control over outdoor conditions, self-contained controlled environments have been proven advantages for crop production. NASA pioneered the idea of controlled environments for growing plants in the 1980's by using the decommissioned altitude chamber from Project Mercury (Hall, 2021). Various crops were grown hydroponically in this chamber where each component of the plant's environment was able to be controlled. This application began the research for controlled environments and highlighted the potential for indoor agriculture. Other researchers began exploring, in the 20th Century, the effects of electric lighting on various crops. Their studies began to determine the ideal light spectrum, intensity, and duration for various plant species.

Vertical farms are commonly grown in controlled environments where each type of crop can get optimum combinations of color, light intensity, and lighting duration. The application of cultivating plants under strictly electric lighting took time to thoroughly research. Understanding what light a particular plant species grows best under, took extensive experimentation, while also being complicated by the inefficiencies and limitations of early electric lighting. Vertical farms are advantageous compared to traditional horizontal farms due to their space optimization through stacking crops. The minimization of space is ideal for urban environments where there is less horizontal land.

The invention of LED lighting technology was a huge benefit for vertical farming. The mid-20th Century used fluorescent and high-intensity discharge (HID) lamps where controllability and color selection were limited. Early LED technology also lacked customizability for plant growth. However, LED advancements have improved lighting capabilities that outweigh what fluorescent and HID lighting can offer. Beyond the customizability aspects of lighting intensity and color, the energy efficiency of LEDs allow for

less power to be consumed in vertical farms, making it an ideal light source for these applications. LEDs are not only energy efficient but can individualize the light wavelengths emitted to tailor to the requirements necessary for specific plant production even throughout different plant growth cycles.

Current research is determining how each wavelength of light impacts the growth of each plant species. From prior research, it is known that blue light promotes vegetative growth, while red lighting will stimulate flowering and fruiting. The ability to manipulate the light spectra can accelerate plant growth leading toward rapid optimization of the farming industry.

Overall, the ability to integrate electric lighting into crop growth has proven to be a successful method of optimization. Even when lighting technology was starting out, the ability to control a plant's exposure to lighting provided great benefits. Electric lighting in controlled environments allow for year-round crop production which has the potential to redefine the future of sustainable food production. Throughout this report, the concepts of vertical farming will be outlined to further investigate how this form of farming can be a viable option for farmers.

Chapter 3 – The Correlations Between Lighting and Horticulture

Light is a key factor in the growth of plants and the yield of crops. This idea is important for controlled environments since daylight is not accessible. The targeted manipulation of electric lighting can also be used to accelerate crop yield. This section discusses the basics of lighting in horticulture and how these aspects correspond to horticulture and crop yield. Overall, the topics covered in this section include defining the light spectrum, lighting intensity, duration, photosynthesis, and other physiological processes that may affect plants' growth.

3.1 Significant Terminology

Before defining each lighting condition, it is crucial to understand the terminology related to lighting and horticulture. To begin, inter-canopy lighting refers to placing lighting into the plant canopy of tall growing plants like tomatoes or peppers. This allows the plant to refrain from shading itself and enhance the photosynthesis process. Photosynthesis is a plant's physiological process to produce oxygen, glucose, and other byproducts. Photosynthesis begins when a plant is exposed to light, specifically photosynthetic active radiation (PAR). PAR defines the specific electromagnetic radiation range plants utilize in the photosynthesis process: 400nm to 700nm wavelengths. Crops will also use wavelengths outside the visible spectrum, extending the range from 280nm to 800nm. This extended range is called PBAR (Plant Photo Biologically Active Radiation), which includes infrared, also called Far-Red, 700nm to 800nm, and the 200nm to 400nm ultraviolet wavelengths (*Horticulture Lighting Terms*, n.d.). Figure 1 shows a visualization of what these two terms mean.

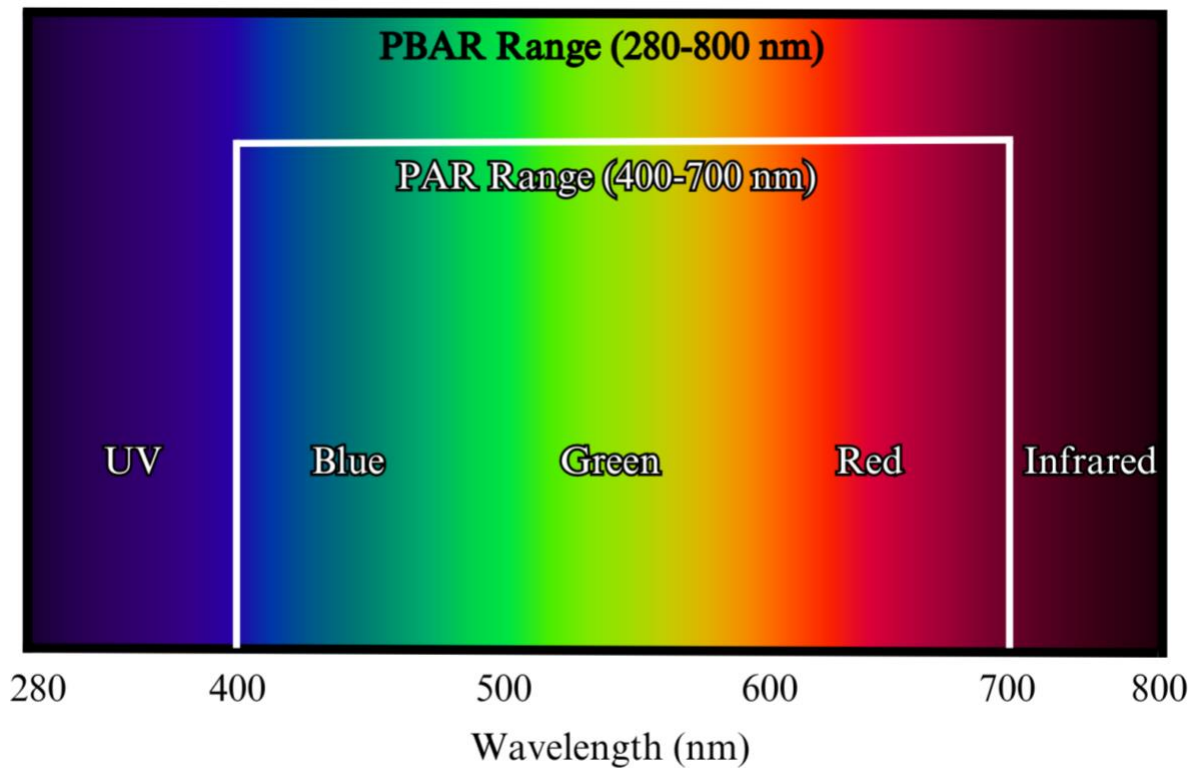


Figure 1 - PAR vs PBAR range

To continue focusing on terms involved in horticultural biology, morphogenesis refers to the growth patterns of plants. Therefore, photomorphogenesis corresponds to how plants grow in conjunction with the lighting they experience, whether that exposure relates to lighting duration, intensity, or light color (Nemhauser & Chory, 2002). PPFD is a common acronym that stands for Photosynthetic Photon Flux Density. PPFD refers to how many photons reach a plant's surface area over a given amount of time, which allows for the ability to quantify a portion of the photosynthesis process. The measurement for this factor is $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ (micromoles of photons per square meter per second) (*Horticulture Lighting Terms*, n.d.). PPFD is an important parameter for growers because it helps determine how much light plants receive and whether it meets their specific light requirements (Cocetta et al., 2017). Since different plants have varying light requirements, PPFD measurements can be used to optimize the placement and intensity of

electric lighting in indoor, controlled growing environments to maximize plant growth and crop yield.

3.2 Light Intensity

For typical plant growth, crops are dependent on sun light to provide the adequate intensity needed for their production; however, in controlled environments the light intensity is from the electric lighting. When it comes to horticulture, using the same measurement techniques used for human perception, in lux or footcandles, would yield an underestimation of what plants truly require for maximum growth (Cocetta et al., 2017). To understand the best desired lighting intensity for horticultural circumstances, PPFD should be the measurement considered for the light intensity related to the particular types of crops grown.

As defined previously, PPFD ($\mu\text{mol}/(\text{m}^2 \cdot \text{s})$) allows for a quantifiable value of how many photons are striking a plant's surface over time (*Horticulture Lighting Terms*, n.d.). The physiological process of photosynthesis requires determining how many photons are desired for the plant to adequately grow and produce crops. According to the ANSI/IES recommendation RP-45-21 Lighting Horticultural Facilities, anywhere from 100 to 1,000 $\mu\text{moles}/(\text{m}^2 \cdot \text{sec})$ can be desired for a plant depending on species (IES Horticultural Lighting Committee, 2021). Since this range is so broad, understanding the plant type aids the decision on how much intensity is needed; for example, plants that naturally grow near the equator will desire more intense lighting. Consideration of the correct PPFD measurements is necessary for proper plant growth, and it is important for morphogenesis since avoiding abnormal fruit and plant shapes and sizes are ideal for the food and crop production industry (Cocetta et al., 2017). Later in this report, specific PPFD goals are highlighted for the crops that are being researched.

3.3 Duration and Photoperiods

Lighting duration is defined in this report as the amount of time a crop is exposed to lighting and corresponds to a plant's photoperiod. Photoperiod is a similar idea except it is the specific duration of illumination for a plant or organism (*Photoperiod, n. Meanings, Etymology and More* | *Oxford English Dictionary*, n.d.). The idea of photoperiod can be broadly compared to circadian rhythms that affect humans and animals, because plants also need to experience cycles of darkness and lightness for their photobiological growth.

Different plants naturally desire different amounts of exposure to sunlight. These exposure requirements fall into three groups that plants will fall into: long-day, short-day, and day-neutral plants. The delineation between these three groups depends on what stage the plant begins to flower, meaning certain plants will only begin to flower when they experience more darkness and vice versa. Day-neutral plants start flowering no matter what their lighting looks like because their flowering process depends entirely on their growth stage. Plants classified as long-day varieties bloom when exposed to predominantly ample light, while short-day plants initiate flowering in response to reduced light exposure. (Roeber et al., 2022).

3.4 Color

Plants use a wide range of light wavelengths for their physiological processes. One of the fundamental processes in plant growth is photosynthesis which is highly influenced by the color of the wavelengths received by the plant. These wavelengths are categorized into PAR and PBAR color ranges which were expressed in further detail in 3.1 Significant Terminology. Each

wavelength provides differing effects on plant growth and development. The importance of this section is to define each of these effects related to each color.

3.4.1 Ultraviolet (100nm-400nm)

There are three types of ultraviolet radiation: A, B, and C. Each has a different range of wavelengths and different effects on plant growth. Ultraviolet A is 315nm-400nm, UV-B is 280nm-315nm, and UV-C is 100nm-280nm (IES Horticultural Lighting Committee, 2021). Researchers found UV-A lighting to have either a positive or negative effect on plants depending on the particular species (IES Horticultural Lighting Committee, 2021). Although UV-A is the least researched regarding its effects on plants, it is known that it will have effects on plant growth similar to UV-B.

UV-B radiation has the biggest impact on plant photosynthesis, reducing the production by 15% and changing the plant's ability to flower properly and timely (Blaustein & Sengsavanh, 2001). An effect on a plant's flowering time shifts a pollinator's ability to pollinate the surrounding crops which is necessary to continue the cycle of growth for plants. However, UV-B has one benefit for plants which is the ability to promote an environment for secondary metabolites (Schreiner et al., 2012). Metabolites aid a plant in maintaining a defense system against insects and infections but do not directly affect its growth. In a controlled environment, this defense system is not as important since there is more monitoring of the atmosphere, however if metabolites become an issue UV can be implemented to combat these issues.

UV-C radiation, ranging from 100nm-280nm, is outside of the PBAR range, meaning it will not affect plant growth. UV-C radiation is used after crops have been harvested, and the radiation assists in maintaining the freshness of the production by eliminating harmful bacteria or

insects (Aarrouf & Urban, 2020). Overall, ultraviolet waves have a few benefits for plants but ultimately are not the best lighting source to use for plant growth and to optimize production.

Ultraviolet radiation is not typically considered as an important wavelength to be used in a controlled environment for plant growth. However, for certain circumstances where the wavelength could provide a positive outcome, it should be considered. Before implementing UV into a space there are important considerations related to the safety of the workers. Direct UV radiation exposure can be harmful to humans, so establishing the proper UV controls is imperative to protect the people working in these environments (CDC, 2023). For this report, UV will not be considered for the experiments.

3.4.2 Blue (400nm-500nm)

Recently there has been a lot of news surrounding blue wavelengths of light and how they impact human circadian rhythms. Similarly, blue lighting has beneficial effects for plant growth. One of the benefits of blue lighting is that it protects plants from any stresses they might receive from harmful UV rays due to an increase in secondary metabolites (IES Horticultural Lighting Committee, 2021). Blue lighting also enhances shade-avoidance syndrome which is a response from plants that are not getting their desired light intake due to surrounding plants or trees, therefore causing these plants to shoot and elongate their stems to get out of the shade and reach sunlight yielding larger crop biomass overall (IES Horticultural Lighting Committee, 2021).

Blue lighting can also impact photosynthetic capacities and functions. Chlorophyll A is responsible for the absorption of light to aid the photosynthesis process and is most active in the blue and red wavelengths. For chlorophyll A, research has shown blue lighting to be most

important for this specific portion of photosynthesis. Inter-canopy blue lighting research shows support for an increase in photosynthesis and shows improvement in fruit grade in comparison to red, white, or UV-A light (Hao et al., 2020). However, increasing exposure to blue wavelength lighting can have a negative effect if the exposure has high photosynthetic photon flux levels (IES Horticultural Lighting Committee, 2021). Despite the positive attributes discussed above, an excessive intensity of blue lighting can reduce the growth of some crops such as lettuce.

3.4.3 Green & Yellow (500nm-600nm)

While green and yellow wavelengths are less influential for plant growth than red and blue, but there are still effects to consider. Green lighting cannot be easily absorbed by chlorophylls A and B and other photopigments and therefore will penetrate deeper into the plant canopy (Y. Wang & Folta, 2013). For specific plants, such as lettuce, the addition of supplemental green lighting can increase leaf growth without affecting the photosynthetic process (Battle et al., 2020).

Alongside ultraviolet wavelengths, yellow wavelengths range of light is not commonly studied when it comes to plant growth. This is because there have been no discoveries that the effects of yellow light are as substantial in comparison to other wavelengths. Yellow is beneficial in similar aspects to photosynthesis of plants and promoting secondary metabolites, but none of these have proven to be significant enough to consider in design (IES Horticultural Lighting Committee, 2021). However, assorted studies have shown that yellow and yellow-green wavelengths can have an antagonistic effect on any blue wavelengths by inhibiting the beneficial effects blue lighting can provide (McCoshum & Kiss, 2011).

3.4.4 Red & Far-Red (600nm-800nm)

The wavelength of red (600nm-700nm) is one of the most important wavelengths for plant growth due to the benefits during photosynthesis and in regulating a plant's ability to flower and produce fruit. Red lighting is absorbed in chlorophyll A and B which are the photopigments that are a part of the photosynthesis process. When testing the effects of wavelengths by themselves on plants, red lighting is the most beneficial, but it will lead to the plant being elongated and having thin leaves (Erik Runkle, 2016). Red lighting also aids seedlings in germination; monochromatic red lighting and far-red radiation are highly beneficial for the beginning processes of growth (IES Horticultural Lighting Committee, 2021). Red lighting is a pertinent part of crop growth and is most beneficial when provided in a ratio of other wavelengths. For example, the photomorphogenesis of plants is highly dependent on the ratio of red to far-red radiation (Benveniste et al., 2018).

Since far-red radiation is outside of the PAR range (700nm-800nm) it does not have a direct effect on photosynthesis. However, a mixture of far-red radiation and red wavelengths inside the PAR range can increase the rate of photosynthesis. This idea is referred to as the Emerson Effect (Rabinowitch, 1969). From numerous studies over time, it has been proven that the rate of photosynthesis is far higher with the mixture of red and far-red radiation than with monochromatic red wavelength exposure. Even though it may seem advantageous to always expose plants to the Emerson Effect, the use of radiation can be consequential for plants as well, leading toward stem elongation which makes the plant focus its growth on height instead of fruit production.

When it comes to crop production, lighting is an important aspect to promote growth. The three main aspects of lighting defined in this chapter: intensity, duration, and color, play a key

part in this process. Each category has a different, but important effect on plants, whether that is to promote photosynthesis or to begin the flowering and fruiting stage of the plant's life. These three components are the most important aspects of lighting design to consider for horticulture applications and they will be further examined throughout this report.

Chapter 4 – Outlining Testing Conditions

In this report, the focus is to express the proposed setup and outcomes for a hypothetical experiment. For example, establishing what the lighting layout will be and what methods should be used for a proper investigation of plant growth. This report provides a compilation of information to establish a successful experiment in vertical farming. There are many reasons we should continue experimenting with vertical farming, but one big one is providing farmers with the ability to keep growing crops year-round (Lubna et al., 2022).

There are a variety of different conditions a plant can thrive in, and each plant is partial to specific lighting outcomes. When defining an experiment, it is important to consider what kind of measurement technology is needed to accurately determine the change in plant behavior. The consideration of how the experiment should be measured and tracked is an important aspect especially when there are distinct parts of the lighting design to analyze.

4.1 Defining Crops

Vertical farms offer a plethora of advantages for the farming community, including year-round production, specialization for plant needs, and efficient use of spaces. To maximize these advantages, proper crops should be chosen that will best perform in the vertical farming environment. Several factors go into determining which crops are the right ones to grow, including crop demand, vertical suitability, and crop characteristics (Despommier, 2020). Not only is the species of plant important, but the layout and ability to implement them into a vertical space affects what crops can be chosen.

It is equally important to determine what plants would be in high demand that can be brought closer to the customer as vertical farming expands. However, some staple crops like wheat, corn, rice, potatoes, and more, are uneconomical to be produced in vertical farms. This is because of crop height and how much space they occupy. Additionally, farming would increase the prices of these particular crops which consumers would not find ideal (Lubna et al., 2022). Therefore, leafy greens and fruiting crops are more suitable for vertical farming environments. The crops selected to review in this report are lettuce, tomatoes, strawberries, and peppers.

4.1.1 Lettuce

Lettuce (*Lactuca sativa*) is a highly researched crop in vertical farm cultivation. This is a very suitable crop because of its small size, shorter growth cycle, and requires less light intensity for growth. Additionally, lettuce is a high-demand crop which makes it a very desirable choice to be grown in vertical farms. For the implementation of any crop, it is important to understand how to optimize the lighting system for maximum yield and quality.

For lettuce, its growth can benefit from each section of the PAR range: red, green, and blue (RGB). Red and blue lighting, for any plant, promotes the photosynthesis process since both wavelengths get absorbed by the main photopigments (chlorophyll A and B). The blue wavelength specifically plays a role in leaf development (X. Y. Wang et al., 2015). Recent research determined green light (500nm-600nm) can benefit lettuce as well. Green wavelengths penetrate deeper into the plant before being absorbed and have been proven for lettuce to enhance photosynthesis, producing a more flavorful lettuce (Terashima et al., 2009). A study done in 2022, outlining a similar intent to this report, produced ideal results with baseline results

of 70 percent red, 10 percent green, and 20 percent blue wavelengths (Matysiak et al., 2022). Since the results concluded an ideal baseline, this will be the same baseline outlined in this report.

A study done in 2020 researched the effects of photoperiod, day light integral (DLI), and Photosynthetically Photon Flux Density (PPFD) on lettuce. This study found that when lettuce is exposed to higher levels of PPFD and DLI, lengthening the photoperiod will increase the rate of photosynthesis which, in turn, increases crop yield. (Kelly et al., 2020). This study was researching photoperiods for lettuce between 16 hours and 24 hours. Other studies have shown that high PPFD levels with extensive photoperiods can cause tip-burn on the leaves (Carotti et al., 2021). A variety of researchers have done measurements showing a 16 hour lettuce photoperiod. Lettuce is categorized as a long-day plant since its ideal photoperiod is 16 hours, and this fact is helpful to understand that lettuce will bloom more productively when days are longer (Pokorny, 2022). Incorporating this knowledge in an experimental design will aid in making sure the plant bloom as planned.

As discussed, PPFD levels correspond with the photoperiod each plant will experience. Both parameters work together to ensure crops are getting enough light and to protect them from getting too much light. In comparison to other crops, lettuce desires lower light levels, which is another reason it an ideal crop choice for vertical farming (Kelly et al., 2020). The targeted PPFD range for lettuce to grow under is 150-250 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ (Matysiak et al., 2022). It is important to adjust the light intensity based on the growth stage, with lower levels for germination and seedling growth and increased intensity as the plant matures.

Table 1 – Lettuce Base Values

Lettuce		
		Citation
PAR	70 % R, 10% G, 20% B	(Terashima et al., 2009) (Matysiak et al., 2022)
Day-Length	Long-Day	(Pokorny, 2022)
Photoperiod	16 hr	(Carotti et al., 2021)
PPFD	150-300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	(Matysiak et al., 2022)

In consideration of these three main characteristics, Table 1 specifies the base values that were determined through previous research. The PAR ratio is 7:1:2, the photoperiod is 16 hours, and PPFD is ideally ranged between 150-300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$. The base values were derived from the successful experiments which were conducted for determining what would be ideal outcomes for each crop. These baseline values will be used for outlining the experimental processes discussed in Chapter 6 – Experimental Design. Having these specific values can allow farmers or researchers to determine which values are most important for optimal lettuce growth.

4.1.2 Tomatoes

Tomatoes (*solanum lycopersicum*) are a viable choice for vertical farms because their growth direction can be influenced, which supports the ability for growers to save space. Tomatoes are also a crop that is high in demand year-round, so it is valuable to implement their production into vertical farms. In 2022, the United States of America had a production value of utilized tomatoes in upwards of \$1.7 billion (*Vegetables 2022 Summary 02/15/2023*, 2022).

Many researchers begin by looking into how a red and blue light mixture affects the growth of tomatoes. The impact of red and blue wavelengths on tomatoes closely resembles their

influence on lettuce since red and blue light are absorbed by the photopigments that facilitate photosynthesis (Lanoue et al., 2021). However, when white light, containing a mixture of half blue and red, and the other half green wavelengths is used, it significantly enhances the photosynthesis process (Lu et al., 2012). This mixture shows how green lighting can be more beneficial since it can penetrate deeper into a plant than red and blue light. Since tomato plants grow tall and eventually shade themselves, the ability to use green lighting can aid the physiological processes. There is also minimal evidence about infrared lighting and its effect on plant growth, but tomatoes are one of the few plants that have been shown to benefit from infrared wavelengths (IES Horticultural Lighting Committee, 2021). Red lighting has been shown to enhance the production of carotenoids in tomatoes, which are the pigments in the fruit that are responsible for its red color. The ability to provide higher carotenoids allows for a vibrant color in fruits allowing each tomato to be viewed as a higher quality fruit and increasing its likelihood of selling in grocery stores. Carotenoids in fruit also provide antioxidants and vitamin A compounds to humans when consumed which ensures human health (Benveniste et al., 2018). Therefore, a distribution of 80 percent red, 5 percent green, and 15 percent blue wavelengths provides a great baseline ratio of wavelengths to optimize tomato growth (Hao et al., 2020).

The duration of exposure for this crop determines what stage of growth the plant is in. Tomatoes are considered a day-neutral plant which means they do not use the length of sun exposure to determine when it is time to flower which differs from lettuce (Pokorny, 2022). The ideal photoperiod for tomatoes has been studied over many years, and it has been determined that 12-hour exposures are ideal (Aguirre-Becerra et al., 2020). Some recent research has shown that longer days beyond a 12-hour cycle can be advantageous when the plant is flowering (Lanoue et

al., 2021). Whereas other studies have proven a photoperiod longer than 17 hours causes chlorosis to occur in the plant leaves (Demers & Gosselin, 2002; Stadler et al., 2011). Chlorosis manifests as a deficiency in chlorophyll within plants, resulting in the gradual yellowing of their leaves, and is often detrimental to overall growth (*Chlorosis / RHS Gardening*, n.d.). In the pursuit of optimizing tomato cultivation, it is advisable to provide tomatoes with prescribed light exposure ranging from 12 to 14 hours.

It is important to understand what tomatoes desire to correctly imitate the sunlight with electric lighting. Even though tomatoes are considered day-neutral plants, they desire high levels of lighting for proper growth (Hodgson, 2021). Therefore, the PPFD suggested is in a range from 150 - 800 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ (Zhenchao et al., 2017). This range is broad due to the various stages of a tomato's growth. In the flowering and fruiting stages, higher PPFD is best. However, during germination and rooting which occurs at the beginning of the plant's life, lower intensities of PPFD are desirable. The higher portions of the range, 500-800 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$, are used mostly for providing flashes of light to the plants, which has been shown in recent research to be beneficial. However, that method will not be considered in this report since it is an advanced topic. The ideal middle ground for this report would be roughly 350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ for the optimal intensity to best grow tomatoes.

Table 2 - Tomato Base Values

Tomatoes		
		Citation
PAR	80% R, 5% G, 15% B	(Lanoue et al., 2021) (Lu et al., 2012) (Hao et al., 2020)
Day-Length	Neutral-day	(Pokorny, 2022)
Photoperiod	12-14 hr	(Lanoue et al., 2021)
PPFD	150-800 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	(Zhenchao et al., 2017)

Table 2 - Tomato Base Values, shows the baseline values laid out for Chapter 6 – Experimental Design. The values are determined from prior successful experiments to determine what idea ranges should be for tomatoes. The PAR ratio is 8:0.5:1.5, the photoperiod is 12-14 hours, and PPFD has a wider range between 150-800 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$.

4.1.3 Strawberries

The selection of growing strawberries (*Fragaria x ananassa*) in vertical farms is a good choice for a variety of reasons. The ability to grow strawberries in nearly any container is very possible because of their small size (Wortman et al., 2016). In 2021, strawberries were found to be the fifth most popular fresh fruit, while also being the most selected frozen fruit (U.S. Department of Agriculture, 2021). Growing strawberries is a smart choice due to their desirability among consumers since they can be sold fresh, or they can be frozen and shipped to other markets across the country.

The colors of light that most affect the growth of strawberries are blue and red wavelengths. Under monochrome red lighting, strawberries do not grow as well since it provides the effect of stem elongation which yields smaller fruit sizes. Therefore, mixed wavelength

lighting is preferred for ideal strawberry growth (Xiao et al., 2022). Researchers have found that strawberries grown under a higher percentage of red light have the best outcome. Nevertheless, blue lighting is still essential to allow balanced nutrients for plant growth. One study used their base testing to be 13 percent blue light (455nm) and 87 percent to be red light (640nm) (Samuolienė et al., 2010). This breakdown allows for the right blend of blue and red light to be presented to the plant.

Photoperiod for strawberries depends on which species is chosen, effecting whether it would be considered a short-day or neutral-day plant. For example, everbearing strawberries are long-day, while June bearers are short-day (Bradford et al., 2010). Most, however, are considered short-day plants which allows for shorter lighting requirements (Pokorny, 2022). Therefore, growing strawberries in a vertical farm environment requires less power than for plants that are classified as long-day varieties. This research will focus on short-day strawberries; however, long-day strawberries should also be considered for applications where other longer photoperiod crops are grown. Long-day strawberries have a desired photoperiod of 16 hours (Magar et al., 2018). The ideal duration of exposure for short-day strawberries is 12-14 hours (Bradford et al., 2010).

On top of duration and color, the intensity of the lighting needs consideration. Photosynthesis is the main factor affected by proper light intensity. When plants are not given the proper amount of light, they will lack in leaf growth and fruit development (Texas A&M University - Horticulture Department, n.d.). The intensity of the light is defined as photosynthetic photon flux density (PPFD). A study done in 2013, researched different PPFD rates on the photosynthetic rate. The determination found there was a drastic increase in photosynthesis from 0 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ to 400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$. After 400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$

there was a gradual increase until 1,200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$. Ultimately the researchers determined 400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ was the highest PPFD level strawberries desired because higher PPFD rates unnecessarily accelerated leaf growth (Hidaka et al., 2013). Other researchers use 200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ as a constant level to do testing of the effects on different wavelengths (Samuolienė et al., 2010). For this research, a range of 200-400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ is preferred for the ideal production of fruit.

Table 3 - Strawberry Base Values

Strawberries		
		Citation
PAR	15% R, 5% G, 80% B	(Samuolienė et al., 2010)
Day-Length	Short-day	(Bradford et al., 2010)
Photoperiod	12 - 14 hr	(Magar et al., 2018) (Bradford et al., 2010)
PPFD	200 - 400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	(Samuolienė et al., 2010) (Hidaka et al., 2013)

The baseline values that will be used in Chapter 6 – Experimental Design, are denoted above in Table 3 - Strawberry Base Values. The baseline values are determined from successful experiments with a theoretically ideal outcome. The PAR ratio is 1.5:0.5:8, the photoperiod is 12-14 hours, and PPFD ranges between 200-400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$.

4.1.4 Peppers

Peppers (*Capsicum annuum* L.) are also an adequate crop to grow in vertical farms. This research will focus specifically on sweet peppers since that is what most research has previously

covered. Although some attributes may stay the same, like critical day length, some attributes will vary between species.

Firstly, the light source color for the peppers to grow has a significant impact on the plant's photomorphogenesis and how it produces fruit. Various testing has been done to see what wavelengths of light are most desired. Research has shown the wavelengths most absorbed in the photosynthesis process are red-orange (610-720 nm) and blue-violet (400-510 nm) (Liu et al., 2019). The addition of far-red (700-740nm) wavelengths increased the height of the plant and allows for stronger stems in comparison to growth from red lighting alone (Olle & Alsiņa, 2019). The same researchers found the benefits of supplemental blue lighting to increase the photopigment concentrations, yielding higher photosynthesis rates. There has also been research to prove the addition of green lighting to be beneficial by having the ability to increase photopigments as well leading to increased plant weight and leaf area (Samuolienė et al., 2012). The growth of peppers benefits from red, blue, and green lighting; however, it is essential to define an optimal combination for ideal results. From all the research, red wavelengths should make up most of the combination to enhance the rate of photosynthesis. Therefore, a combination of 90 percent red, 5 percent green, and 5 percent blue will provide an ideal mixture.

Day-length is important to define for plant growth since each plant species has such a variation in need. Peppers are considered a long-day plant, which determines when it will flower based on having short nights (Sanchez, 2019). Due to being a long-day plant many researchers have investigated 24-hour cycles and their impact. A 20-hour maximum photoperiod was found to be optimal since longer lighting began to prove detrimental to the growth of sweet peppers. Researchers determined that, 20 hours was more effective than 14 hours (Demers & Gosselin, 2002).

Lighting intensity is also a key component to be considered for plant growth. Peppers desire high PPFD's in comparison to other crops. During the germination phase lower levels around 200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ are desired; whereas a mature pepper plant requires higher intensities around 350-650 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ (IES Horticultural Lighting Committee, 2021). Since pepper plants grow tall, there has been a variety of research done on inter-canopy lighting to improve plant growth. A maximum of 300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$ was used in this study throughout the canopy showing to improve the ideal outcomes (Jokinen et al., 2012). The ability to light the entirety of the plant would allow for more growth and the production of ideal produce.

Table 4 - Pepper Base Values

Peppers		
		Citation
PAR	90% R, 5% G, 5% B	(Liu et al., 2019) (Samuolienė et al., 2012)
Day-Length	Long-day	(Sanchez, 2019)
Photoperiod	20 hours	(Demers & Gosselin, 2002)
PPFD	350-650 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	(IES Horticulture Lighting Committee)

The last baseline value table is for peppers in Table 4 - Pepper Base Values. The baseline numbers laid out are determined by previous experiments' constant values that were proven to be ideal for pepper production outcome. The PAR ratio is 9:0.5:0.5, the photoperiod is 20 hours, and there is the highest PPFD range between 3500-650 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$.

4.2 Testing Devices & Measurement Tools

To understand the experimental process, it is important to know what methods and tools should be used to track measurements of light and plant growth. There are a variety of different metrics that need to be considered for vertical farming including temperature and environment, but those are not being defined in this report. The characteristics of light defined for plant growth are light duration (photoperiod), intensity (PPFD), and color. These three factors drive the tools required to measure a successful experiment.

To begin with, lighting duration is simple to track in an experiment since there are no meters required. Whatever method works best to keep track of time is an excellent choice. The implementation of automatic controls can simplify this process. Controls can provide tracking photoperiod with the ability to turn off or on the lighting as needed in the various stages of growth. Since lighting controls can be programmed in a variety of separate ways, the lighting can automatically shift in color spectrum if desired.

Equally as important, light intensity for plants is measured in photosynthetic photon flux density (PPFD $\mu\text{moles}/(\text{m}^2 \cdot \text{sec})$). To be able to measure PPFD accurately a variety of tools can be calibrated. There are two main devices that should be considered: PAR meters (or quantum meters) and spectroradiometers. Illuminance meters should not be considered since they measure Lux or Footcandles which does not encompass all wavelengths plants experience. Figure 2 shows why illuminance meters should not be considered. The bell curve shows the luminous flux humans can perceive in lumens, whereas the PAR range incorporates the whole spectrum between 400nm-700nm (Apogee Instruments Inc., 2016b). Quantum meters and spectroradiometers are better suited for measuring the outcomes of lighting in this experiment.

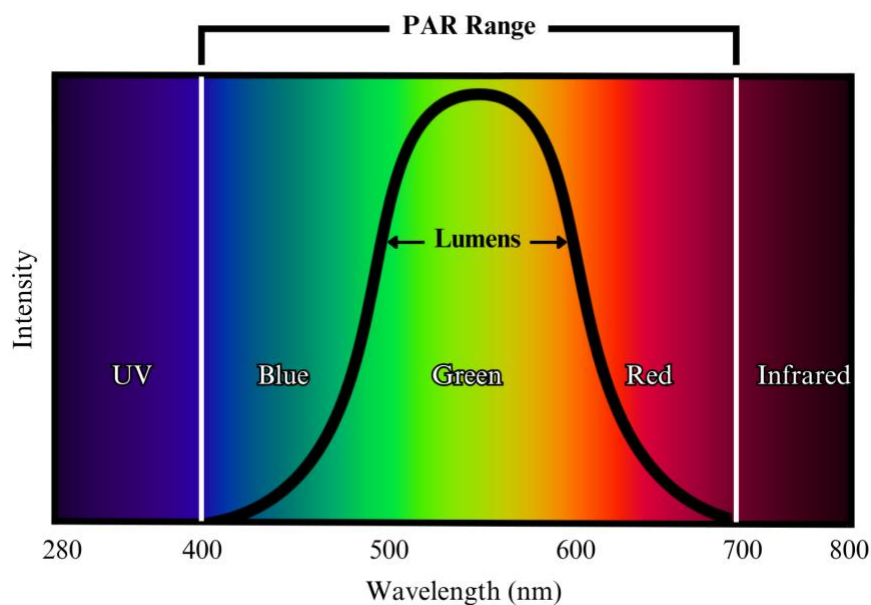


Figure 2 - Illuminance vs PAR

Quantum meters measure PPFD within the PAR range of 400nm to 700nm. This range corresponds with the light spectrum plants use during the photosynthesis process. The units for PPFD are $\mu\text{moles}/(\text{m}^2 \cdot \text{sec})$, which is what a quantum meter is designed to measure (Nexsel Tech, 2023). Another way to measure PPFD is through a spectroradiometer. This device provides the same measurements, but through a different, more precise, method. Spectroradiometers use a prism to distribute the incoming wavelengths instead of filtering the wavelengths like a quantum sensor does. Since these devices measure the wavelengths intensity, they are also used to track the wavelengths of color being emitted by the light source. Other major differences between a quantum sensor and a spectroradiometer are price range and accuracy. Quantum sensors are about 10 times less expensive than a spectroradiometer (Apogee Instruments Inc., 2016a). Quantum sensors have an error of around three percent when they are of the highest quality. Sometimes the less expensive quantum sensors do not include the entire

PAR range, so careful consideration of which devices to choose is needed (Krado, n.d.). A device should be chosen based on preference of accuracy or budget.

In conclusion, conducting experiments in vertical farming to determine the best lighting design for optimized plant growth necessitates a comprehensive set of equipment, including PAR meters, spectroradiometers, and illuminance meters, to accurately measure PPFD. Careful consideration of spectral responses and the use of additional tools for data collection and analysis are crucial to achieving meaningful and reliable results in the pursuit of efficient and sustainable vertical farming practices.

Chapter 5 – Layout Overview

This chapter delves into the ideal testing conditions for producing four crops: strawberries, tomatoes, peppers, and lettuce. There are a variety of environmental factors that need to be tailored for optimizing plant growth, but the only conditions considered in this report are crop layout and the lighting design. This report assumes each crop will be grown in its own environment, therefore not requiring details to be coordinated between plants.

5.1 Crop Layouts

The crop layout design is an important aspect to consider for optimal plant growth. The goal is to determine the ideal growing medium for each crop type. The contrast between soil-based and soil-less plant growth warrants consideration for each crop. Alongside different growing mediums, it is important to understand the variety of structures that should be considered for the plants to grow. This section will break down each of these specific considerations and describe what is best for each crop type.

5.1.1 Growing Mediums

To begin the considerations, hydroponics is a growing technique that can be used and does not require soil for plant growth. This technique uses water and nutrient solutions sometimes with other growing mediums (*Hydroponics* | *National Agricultural Library*, n.d.). The two main types of hydroponics are liquid and aggregate. Aggregate hydroponics is when the use of other mediums can be incorporated to provide more support to a plant's roots. Examples of other mediums include gravel, perlite, and rockwool cultures (Jensen, n.d.). The advantages of hydroponic growing are the ability to control nutrients, higher crop yield, faster growth, and

more. There are a few disadvantages including higher initial cost and needing skilled knowledge for proper operation (Dunn & Shrestha, 2017).

Aeroponics and aquaponics use the ideas of hydroponics in diverse ways. Aeroponics is the use of mist or fog to deliver nutrients and oxygen to plant roots (Dunn & Shrestha, 2017). Aquaponics uses hydroponics in combination with fish farming. This system creates a symbiotic relationship between fish and plants (*How Can You Grow a Variety of Crops Using Vertical Farming Techniques?*, n.d.).

On the other hand, soil-based growing techniques are the traditional form of growth for crop production. Since this type of system is widely used, it is easier for farmers to understand the processes for growth. The advantage of soil-based systems is the ability to retain nutrients in the soil. However, the downside is the amount of water needed to hydrate the plant is high in comparison to hydroponics (Boekhout, 2023). Typically, hydroponic growing systems are used since it is easiest to implement in a vertical farm. However, soil-based vertical farming systems are becoming more common throughout the world.

Choosing the appropriate growing medium for plants involves considering several factors, including personal environments and the ability to select a system. While the following methods are common suggestions based on research, it is important to recognize that there is no universal solution for every situation. A traditional soil-based system is effective, but alternative methods may be a better choice in vertical farming to combat space restraints. Strawberries are studied mostly in aggregate hydroponics with perlite and other mixtures for premium fertilizer (Wortman et al., 2016). Lettuce has been assessed in hydroponic and aeroponic systems. Lettuce is extremely versatile when it comes to where it desires to grow. There have been many systems for lettuce in liquid and aggregate hydroponics (Awalina et al., 2022; Sandoya et al., n.d.).

Peppers and tomatoes tend to use aggregate hydroponics as well. Due to the height and weight of tomato and pepper plants, the addition of a variety of aggregate provides needed support to the plant's root system. The commonly used aggregate for these systems is rock wool, clay balls, and more (ABC Science, 2020; Jensen, n.d.).

5.1.2 Structure

There are a variety of different structures that are feasible in an indoor environment for crop production. A vertical farm yields crops to be cultivated in a more vertical fashion, but there are three main ideas for the vertical solution: stacked trays/layers, vertical towers, and green walls. Each of these types have benefits and the choice is dependent on the building layout and the owner's desires. Owners have a variety of different spaces they want to occupy for vertical farming, including shipping containers, which will be considered for the proposed experiment outlined in this report.

A stacked layer design incorporates multiple horizontal beds with vertical stacking. There are a few separate ways this can be utilized: rotating beds, A-frames, multi-floor towers, balconies, and more. Figure 3 shows the assorted options that fall into this category. Figure 3 (a) shows a standard stacked system, where plant beds are stacked in a designated height interval. Farmers can stack as many as they can fit or would like, but an important consideration includes how growers will access the plants once stacked since ladders have limitations (Beacham et al., 2019). Figure 3 (b) depicts the concept of rotating stacked beds, and these applications can be a broad range of sizes. Rotating beds allow for ease of access for farmers to work on the beds. This application is on the more expensive side but can prove to be more accessible. Figure 3 (c) shows A-frame stacked beds which is another form of a standard stacked system, used in a comparable

way. A-frame setups allow for a different ease of access. Since the beds are offset, the lighting needed is lessened due to the reduction of shadows. This type of system is also easily assembled in a variety of sizes. However, A-frames do require more space to be taken up in their horizontal footprint.

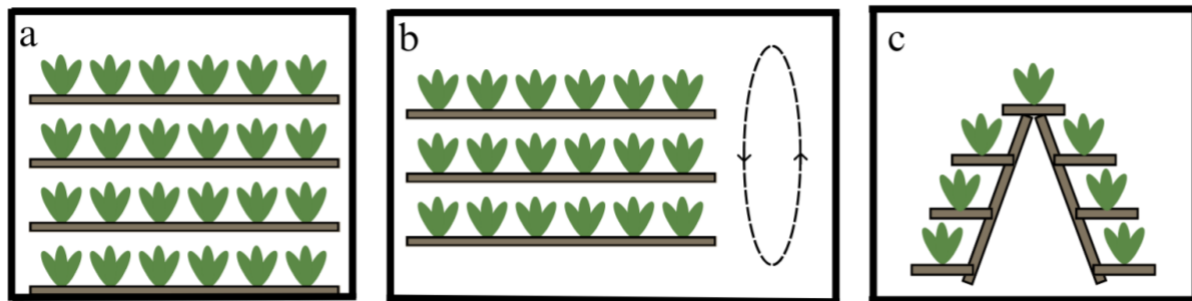


Figure 3 - Stacked Structural Design

Green walls are another structure that can be used for vertical farming applications; these provide aesthetic appeal while also serving as functional farming space. Figure 4, shows an example of green wall structures for farms. Walls can utilize hydroponics or soil-based designs. They can be incorporated outside and inside, and historically have not been used for crop production (*Increasing Energy Efficiency: Residential Green Walls* | *Asla.Org*, n.d.). For fruit-producing crops, a wall technique would not be as ideal since the roots of the plants are horizontal to the gravitational pull on the growing fruits. Instead, a wall structure works best for growing herbs and spices.

Depiction (d) shows multi-floor towers, which are also known as sky farms. This system type is integrated into high-rise buildings. This is a design solution for large-scale crop production, where automated systems are integrated into the build. Each floor of the building has its own crops, so this solution can host a variety of different crop types that each may require

different lighting. Lastly, (e) shows the use of balconies, which can be used in an equivalent way to a stacked system or green walls. These systems tend to be used either for more aesthetic purposes, since they are not as large of an area, or for small home farms as desired.

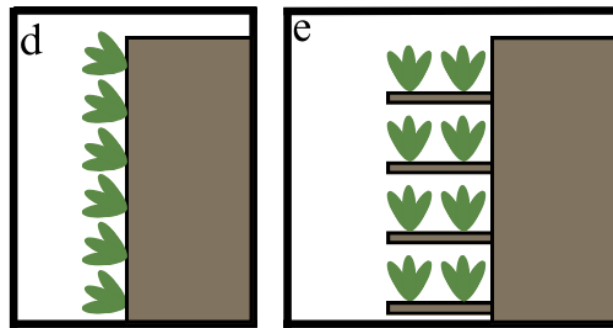


Figure 4 - Green Wall Designs

Lastly, vertical tower farms represent one of the most common and efficient structures for vertical farming. Towers typically consist of multiple trays or levels stacked and use hydroponic or aeroponic systems without soil. Figure 5 provides a visual representation of a tower application where each tier holds a select number of plants that are able to be cultivated in a space-efficient manner. These towers do not require a specific location, so they can be implemented anywhere.

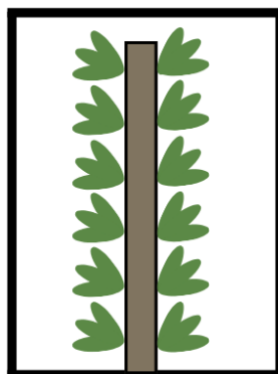


Figure 5 - Vertical Tower Design

The various structural frames and designs in vertical farming address the special challenges of being able to cater to a farmer's preferences and spatial constraints. The three primary solutions are stacked trays, green walls, and vertical towers, each with distinct advantages depending on the context and desired outcomes. The final choice of which structure to implement depends on factors like space, desired crops, cost considerations, and specific function requirements. In this report, a stacked tray/planter design has been selected for implementation in this proposed experiment process.

5.2 Light Sources

Lighting is the most important consideration for controlled environment vertical farming. This section will focus on the implementation of lighting in vertical farms including what type of sources are useful, where light should be implemented, and how to select a luminaire. Lighting in controlled environments is the only source of energy for photosynthesis since there is no access to sunlight. Electric lighting can provide a tailored light spectrum throughout a plant's growth and is essential in these environments. Implementing appropriate lighting involves strategic placement to allow for an ideal environment for plant cultivation.

Throughout history, a variety of different light sources have been used for plant cultivation. For example, fluorescent and high-intensity discharge (HID) lamps were commonly used before the invention of light emitting diodes (LEDs). LEDs are the preferred choice today for indoor crop cultivation. This choice is due to their energy efficiency, longevity, and ability to select specific wavelengths to emit. A full spectrum LED includes PAR wavelengths (red to violet) (*NEW Horticulture Lighting*, n.d.). Far-red Spectrum LEDs include PAR plus ultra-violet

and far-red wavelengths. A full-spectrum LED includes the required wavelengths necessary in photosynthesis, so the addition of far-red (FR) and ultra-violet (UV) will need to be specified to determine which kind of luminaire to use. A farmer can suffice with just the implementation of full spectrum, whereas researchers should consider whether their experiment needs UV or FR. Overall, LEDs have a broad range of customizability and can align with the desire to customize the duration, intensity, and color for each crop.

Efficient placement of luminaires for a vertical farm is crucial to ensure each plant receives a uniform illuminance of light. The structure and layout of crops is an essential factor in determining where lights should be placed. For example, the lighting required for a stacked system is vastly different than the lighting design for a green wall. Since this report is limiting its analysis to the use of stacked systems, the lighting design will only consider this specific layout. Stacked structures can provide light from above since luminaires can be affixed to the underside of the planter above. Each luminaire has its own distribution based on the manufacturer's data provided. Uniform light distribution is imperative to mitigate issues of shading and to ensure consistent levels for growth and development (IES Horticultural Lighting Committee, 2021). Figure 6 shows an ideal cross-section lighting layout for a stacked crop design. An overlap of the lighting distribution allows for an even coverage of PPFD to be distributed to each crop.

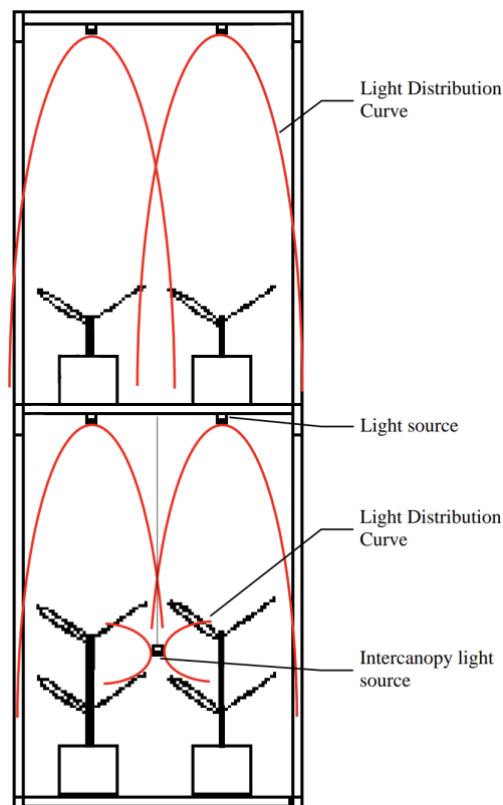


Figure 6 - Overhead Lighting Design Layout

A key strategy to incorporate specific crop species is inter-canopy lighting. Inter-canopy lighting is the addition of luminaires in the middle of a growing crop. Figure 6 incorporates inter-canopy lighting in the lower section where the lights are suspended. Inter-canopy lighting works best for taller crops like tomatoes and peppers. When tall plants like these are growing, their leaves begin to shade themselves from growing further down toward the soil. The ability to incorporate inter-canopy luminaires allows for increased uniformity for each crop.

This section emphasizes lighting's crucial role in vertical farming, focusing on LED technology's superiority due to energy efficiency and customizable attributes. Their adaptability in adjusting light duration, intensity, and color provides tailored solutions for a diverse array of crop species. Strategic fixture placement is vital in stacked systems, ensuring even light

distribution across tiers for optimal growth. An innovative approach includes inter-canopy lighting, beneficial for taller crops, preventing self-shading, and promotes uniform growth. Overall, the versatility of LEDs and their strategic placement enhance vertical farming efficiency, positively impacting both crop yield and quality.

Chapter 6 – Experimental Design

This section will incorporate the design considerations from Chapters 4 & 5 to determine what should be evaluated in an experiment for accommodating four crop options: lettuce, tomatoes, strawberries, and peppers. In this report, the focus is to lay out the necessary processes that should be considered for a controlled environment experiment. The location of this experiment is based on utilizing a shipping container as the enclosure to provide a protected interior environment. An advantage to selecting a portable shipping container instead of a building is that it can be placed anywhere since all of the needs from the plants will be supplemented from alternative resources.

There are a variety of items that need to be assumed from an agricultural aspect. To begin, the shipping container is assumed to be a typical 40-foot container. A 40-foot container has an 8-foot width and a 9.5-foot height. Inside, the structural design for growing the plants will be a stacked system with four different layers, as shown in Figure 7 - Section View of Stacked Design. Since there are different crops for consideration, the stacked design would allow for each stack to focus on a singular crop without having the light interfere with the crops on the other levels. This report will assume HVAC conditions within the shipping container have been previously researched and that these conditions have been implemented to facilitate optimum plant growth. For the specific plants themselves, the lighting design outcomes examine the fruiting and growth stage of the plant and will not consider the germination phase of the plant. Therefore, for the hypotheses outlined, only mature plants will be taken into consideration. The tracking of plant growth will be determined by an agriculturalist and will not be outlined in this report. These assumptions are necessary to provide adequate hypotheses for a crop production experiment that focuses on understanding how lighting design impacts plant growth.

6.1 – Lighting Layout

To allow for even lighting on the plants, careful consideration is needed to determine a symmetric light distribution design. To begin this consideration, the height between the light source and the plants needs to be determined based on estimated plant growth. Figure 7 shows the proposed stacked design where each crop can have its own shelf where the lighting from other crops will not affect each other. The shelves can be adjusted based on plant height, so the pepper and tomato plants would require more height between shelves whereas that is not needed for strawberries and lettuce. This design will be looking into direct luminaires, with a wider throw to allow for more uniform distribution. In Figure 8, the distribution shown represents a sort of oval design to allow for both direct down lighting and angular light and minimize shading from each plant.

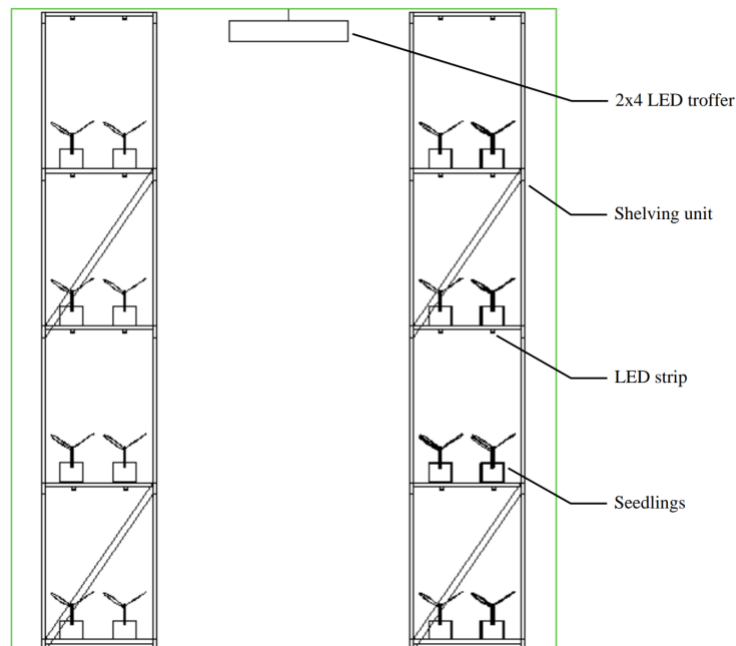


Figure 7 - Section View of Stacked Design

To be able to vary the lighting for the experiment, an electronic control system will be implemented. There are a variety of control systems that exist from an assortment of manufacturers. A typical control schematic would have the lights connected to the control system, which is then connected to a computer enabling customization as needed. A control system allows for shifts in wavelengths, intensity, and duration (Philips lighting, 2022). Figure 8 shows a floor plan of the proposed storage container where the luminaires and measurement sensors are laid out. Each of these is connected to both the control system and data collection system. The data collection system allows researchers to refer back to the information obtained as they continue the experiment. The quantum sensors implemented into the design track the actual light attributes given off from the luminaires which allows researchers to track more accurate data.

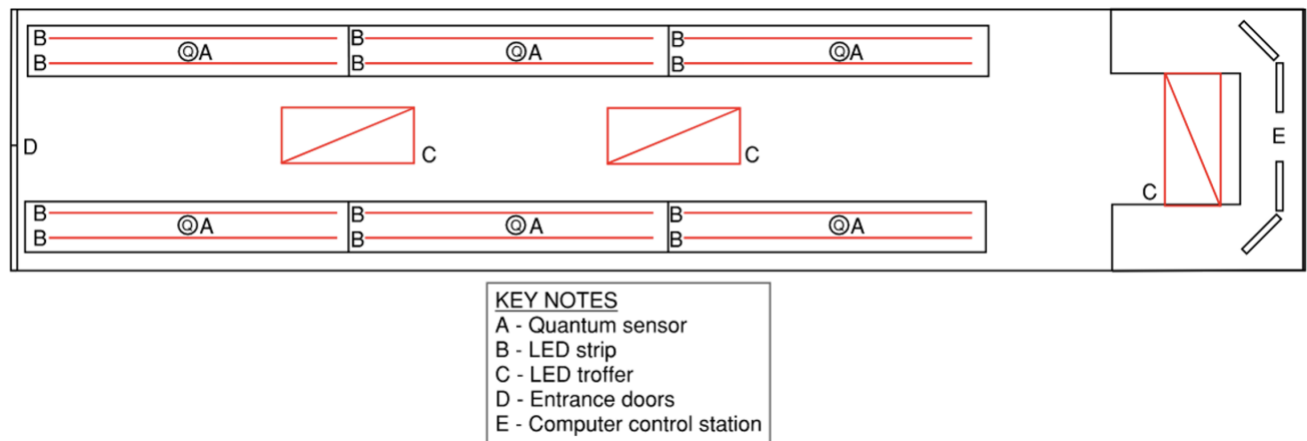


Figure 8 – Floor Plan

The storage container is a typical 40ft container to allow for the shelving along the sides and a work area for researchers to use, depicted in Figure 10. The storage container can be

modified to add an additional door or be adapted further as needed. This report will assume the storage container has no modifications, so there is a single entrance at one end. Figure 9 provides a look into the containers interior as viewed from the two main double doors at the end.

Researchers can enter and have immediate access to the shelving space used for growing the crops. There are 2x4 troffers mounted to the storage unit that can be used to provide general, utility lighting which will not be used while the experiment is in progress but can be used for set up and take down. The singular troffer over the desk will be controlled separately from the other troffers to allow for lighting over the desk when in use. Task lighting on the desk can be implemented as well.

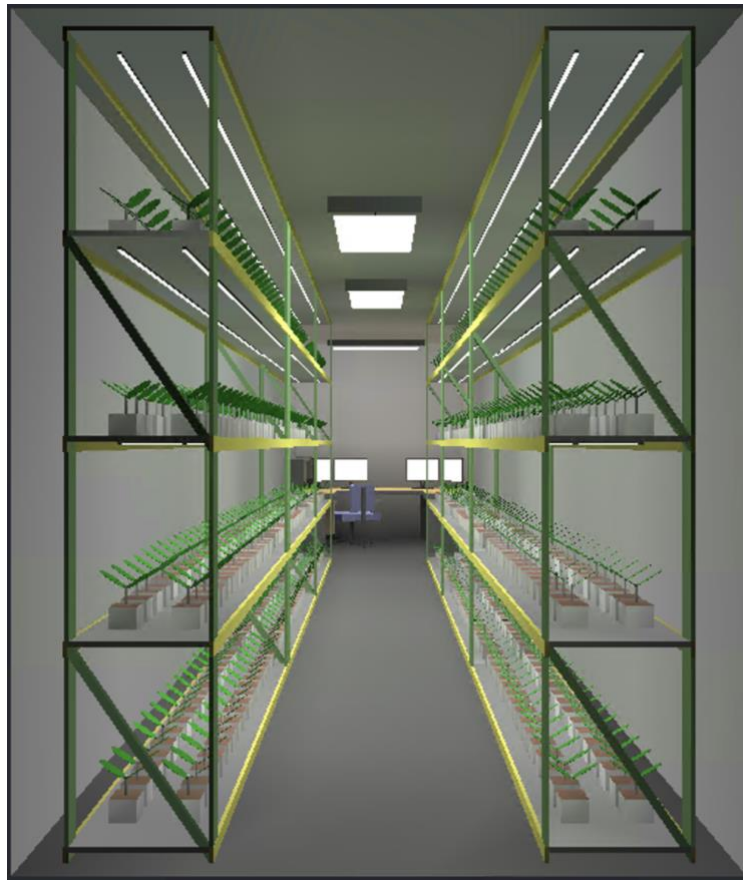


Figure 9 - Section View

The luminaires on each shelf will be attached to the bottom side of the shelf above it. Two luminaires are shown per shelf so there are even distributions of light throughout the plants as they grow. Figure 10 shows two views of the storage space to allow for a further understanding of the layout. The storage space is a compact, yet efficient method of vertical farming with numerous options for layout. Depending on storage container specifics and intended crops, the proposed layout can be adjusted as needed.



Figure 10 - 3D View

6.2 – Hypotheses

To determine a hypothesis for a plant growth experiment there are many items that can be tested. This report aims to outline an experiment for testing different lighting conditions to solidify an optimum lighting design that promotes an ideal crop production. Many considerations were evaluated to figure out the best way to outline this experiment. The original intent was to formulate a month-by-month outline; however, after thinking through each topic and how it should be tested, there was a concern that in a month-to-month format there would not be enough

time to determine outcomes for each. This report will assume the researcher will determine which aspect they want to evaluate and use the following information to formulate a proper experiment.

For each crop, a table has been formulated that will outline various hypotheses. The three main criteria; intensity, duration, and color are laid out and have base criterion determined for each crop discussed in section 4.1 Defining Crops. Each main criterion is then shifted to increase and decrease with a hypothesis of what should occur when assessed. The PAR test (color test) is broken down into three different wavelengths: red, green, and blue. After referring to various researchers' reports, PAR is denoted by a percentage of each wavelength where 100 percent is the intensity value (PPFD) outlined. The three tests focus on a specific color and its effect on crop production, therefore when the percentage of PAR for that color is shifted, an equal distribution of the other two colors is shifted accordingly.

Table 5 - Lettuce PPFD Experimental Values

Lettuce	Shift	PPFD	PAR	Photoperiod
PPFD Test	Base	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	16 hr
	Raise	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	16 hr
	Lower	50 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	16 hr
Hypothesis	If the base values are used to grow lettuce, then the plants will grow the best because the values are ideal.			
	If the plants are grown under an increased intensity, then the growth will be similar to the base except with tip burn because the plant will become stressed.			
	If the intensity is lowered to grow the plant, then the growth will be underdeveloped because they cannot obtain enough nutrients.			

Each crop will have three designated tables for each criterion researched. Table 5 outlines the values of PPFD for lettuce that should be considered in an experimental application. The baseline constant values were determined through comparing similar experimental studies and

finding what values produced ideal production. After specifying an appropriate baseline value, the overall hypotheses were concluded for each test where the base value is predicted to produce the ideal scenario; raising the intensity would be too much for the plant and lowering them would not be enough. The hypothesis about increasing the intensity mentions tip burn as a result. Tip burn is a physiological effect on plants where the leaves will turn brown, due to lack of water intake from high intensity (Department of Jobs, 2021).

Table 6 - Lettuce PAR Experimental Values

Lettuce	Shift	PPFD	PAR	Photoperiod
PAR Test	Base Red	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R , 10% G , 20% B	16 hr
	Raise Red	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R , 5% G , 15% B	16 hr
	Lower Red	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	60% R , 15% G , 25% B	16 hr
	Base Green	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	16 hr
	Raise Green	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	65% R, 20% G , 15% B	16 hr
	Lower Green	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	75% R, 0% G , 25% B	16 hr
	Base Blue	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	16 hr
	Raise Blue	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	65% R, 5% G , 30% B	16 hr
	Lower Blue	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	75% R, 15% G , 10% B	16 hr
Hypothesis	If the red lighting is shifted, then the leaf size and leaf pigment will be affected because red wavelengths directly correspond to chlorophyll absorption.			
	If green wavelengths are shifted, then leaf growth and color will also be affected because green lighting penetrates the plant deeper than red or blue.			
	If blue exposure increases, then the leaves will be vibrant and slim, but if blue decreases then the leaves will be dull because lettuce is more sensitive to blue light.			

The PAR table for lettuce, Table 6, is categorized into red, green, and blue wavelengths being hypothesized independently. Lettuce desires a higher percentage of red lighting over green or blue which was taken into consideration for the base values. Shifting red lighting will affect the value of lighting the chlorophyll will absorb. The ability for chlorophyll to intake these wavelengths vary the available nutrients provided to the plant for growth. The shifts in these

wavelength combinations as shown in Table 6 are subtle, so further exploration into color combinations can be researched using more pronounced variations.

Table 7 - Lettuce Photoperiod Experimental Values

Lettuce	Shift	PPFD	PAR	Photoperiod
Photoperiod Test	Base	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	16 hr
	Raise	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	20 hr
	Lower	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R, 10% G , 20% B	12 hr
Hypothesis	If the base values are used to grow lettuce, then the plants will grow the best because the values are ideal.			
	If the plants experience longer exposure to light, then the crop will bolt and create a bitter tasting lettuce because it will become over grown.			
	If there is a shorter light exposure, then the plant will become underdeveloped because it will not have the access to the nutrients it needs.			

The last criterion researched for lettuce is photoperiod in Table 7. The duration of lighting is an important attribute for lettuce since it is a long-day plant. However, raising the duration will still have undesirable results like making the crop bolt, which means it will grow vertically instead of flourishing its leaves. Bolting also means the crop will change its taste, making it more bitter. Inversely, not allowing lettuce enough sunlight will deprive the photosynthesis process, causing it to be underdeveloped.

Table 8 - Tomato PPFD Experimental Values

Tomato	Shift	PPFD	PAR	Photoperiod
PPFD Test	Base	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	14 hr
	Raise	500 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	14 hr
	Lower	200 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	14 hr
Hypothesis	If the base values are used to grow tomatoes, then the plants will grow the best because the values are ideal.			
	If the intensity is increased, then the fruit grown will experience "sun-scaling" because the fruit is experience too high of an intensity.			
	If the intensity is decreased, then the plant will be less developed overall and will lack in fruiting because the plant will not get enough nutrients.			

The following tables will focus on the outcomes for tomatoes. Table 8 shows the experimental PPFD values to be considered. When increasing the intensity for tomatoes there is the risk of causing sun-scaling to occur on the fruit. Sun-scaling is when the light intensity scalds the tomato causing the outward appearance to be affected however, it is not otherwise harmful. A decreased PPFD can impact the photosynthesis processes of the plant.

Table 9 - Tomato PAR Experimental Values

Tomato	Shift	PPFD	PAR	Photoperiod
PAR Test	Base Red	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R , 5% G, 15% B	14 hr
	Raise Red	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R , 0% G, 10% B	14 hr
	Lower Red	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	70% R , 10% G, 20% B	14 hr
	Base Green	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G , 15% B	14 hr
	Raise Green	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	75% R, 15% G , 10% B	14 hr
	Lower Green	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	82% R, 1% G , 17% B	14 hr
	Base Blue	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	14 hr
	Raise Blue	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	75% R, 0% G, 25% B	14 hr
	Lower Blue	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	85% R, 10% G, 5% B	14 hr
Hypothesis	If red lighting is increased, then the plant will elongate and have thin leaves, but if decreased, then the fruit will be small and less vibrantly colored because of the shade avoidance syndrome.			
	If green is increased then the leaf area and overall height will increase, but if green decreases, then the leaf and fruit sizes will decrease due to lack of nutrients.			
	If blue wavelengths increase, then there will be decreased fruit and leaf size, but if decreased the fruit will have low carotenoids and antioxidance because the wavelengths experienced are unbalanced.			

Table 9 outlines the PAR hypotheses, classified into red, green, and blue. Tomatoes prefer a higher ratio of red lighting, which can be seen in the constant values. Shifts in red lighting can not only affect the color of the fruit produced, but an excess of red lighting can mimic shade avoidance syndrome. When this is the case, the plant will elongate trying to reach past the shadow it is being blocked by even if in these instances there is no shadow.

Table 10 - Tomato Photoperiod Experimental Values

Tomato	Shift	PPFD	PAR	Photoperiod
Photoperiod Test	Base	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	14 hr
	Raise	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	18 hr
	Lower	350 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R, 5% G, 15% B	10 hr
Hypothesis	If the base values are used to grow tomatoes, then the plants will grow the best because the values are ideal.			
	If the exposure increases, then the leaves will experience chlorosis and have an increase in biomass because the plant is experiencing too much lighting causing it to become stressed.			
	If there is a lower exposure of light, then the plant will experience stem elongation because of the shade avoidance syndrome.			

Photoperiod is the last criterion for tomatoes, shown in Table 10. Since tomatoes are neutral-day plants, the duration of lighting does not affect their fruiting or flower processes, so only the photosynthesis process will be affected. If a crop is exposed to lighting for too long there is a possibility of overwhelming the photosynthesis rate, in turn slowing down and causing stress to the plant. For tomatoes, if the exposure is decreased, stem elongation is possible from shade avoidance syndrome.

Table 11 - Strawberry PPFD Experimental Values

Strawberry	Shift	PPFD	PAR	Photoperiod
PPFD Test	Base	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
	Raise	500 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
	Lower	100 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
Hypothesis	If the base values are used to grow strawberries, then the plants will grow the best because the values are ideal.			
	If the intensity increases, then the fruit size will be smaller and have a less vibrant color because the plant will experience far more light than needed.			
	If the intensity is decreased, then the fruit will be deformed and decrease in yield because the plant will not get enough nutrients to form fruit correctly.			

Next, the strawberries' experimental values will be considered. Table 11 presents the PPFD values for strawberries and their corresponding hypotheses. The intensity can have a variety of impacts on strawberry growth, such as fruit formation, color, and yield. A lower intensity will slow the photosynthesis process leading to deformed fruits and fewer fruits overall. However too high of intensity can impact the color vibrancy of the fruits.

Table 12 - Strawberry PAR Experimental Values

Strawberry	Shift	PPFD	PAR	Photoperiod
PAR Test	Base Red	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
	Raise Red	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	25% R, 0% G, 75% B	12 hr
	Lower Red	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	5% R, 10% G, 85% B	12 hr
	Base Green	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
	Raise Green	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	10% R, 15% G, 75% B	12 hr
	Lower Green	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	17% R, 1% G, 84% B	12 hr
	Base Blue	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
	Raise Blue	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	10% R, 0% G, 90% B	12 hr
	Lower Blue	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	20% R, 10% G, 70% B	12 hr
Hypothesis	If the red is increased, then the plant will have stem elongation, increased leaf area, and smaller fruit sizes, but if decreased, then faster yield but smaller fruit sizes because of shade avoidance syndrome.			
	If green lighting is increased, then there will be a slower yield and small fruits, but if decreased, then richer fruit pigment and smaller leaf sizes because of lack of nutrients.			
	If blue is increased, then there will be lower chlorophyll and smaller leaves, but if decreased, then there will be stem elongation and smaller fruit sizes because the plant will not be able to create enough nutrients.			

The PAR test focuses on the three different wavelengths in Table 12. If there is a shift in how much red lighting there is, then the fruit size and plant size will be affected based on the ideas of shade avoidance syndrome. A shift in the green light spectrum will impact fruit size, as well as fruit pigment and leaf size due to impacts on photosynthesis. Lastly, if there is a shift in

how much blue wavelength is given, then the leaf and fruit size will change, as well as the crop size overall.

Table 13 - Strawberry Photoperiod Experimental Values

Strawberry	Shift	PPFD	PAR	Photoperiod
Photoperiod Test	Base	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	12 hr
	Raise	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	16 hr
	Lower	300 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	15% R, 5% G, 80% B	8 hr
Hypothesis	If the base values are used to grow strawberries, then the plants will grow the best because the values are ideal.			
	If the duration increases, then the fruit will stop producing because strawberries are short-day plants and will only fruit when the days are shorter.			
	If there is a decrease in duration, then there will be minimal flowering and smaller fruit sizes because the fruit will not obtain enough light to grow.			

The last test for strawberries is to compare the photoperiod, which can be seen in Table 13. Since strawberries are short-day plants, duration is a key component to determine when fruiting and growth will occur. If the photoperiod is increased to 16 hours, then the fruit yield will decrease due to a decline in production. If the day-length is minimized to 8 hours, then the plant will have limited flowering yielding less fruit production and the fruit will be smaller in size.

Table 14 - Pepper PPFD Experimental Values

Pepper	Shift	PPFD	PAR	Photoperiod
PPFD Test	Base	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	20 hr
	Raise	650 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	20 hr
	Lower	250 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	20 hr
Hypothesis	If the base values are used to grow peppers, then the plants will grow the best because the values are ideal.			
	If the intensity increases, then pepper production will be inhibited because the photosynthesis decreases due to the plant being overwhelmed and stressed.			
	If there is a decrease in intensity, then there will be less growth with thin leaves and smaller peppers because photosynthesis will drop not providing the plant with nutrients it needs.			

The last crop in this research is sweet peppers where Table 14 defines the experimental PPFD values. If the intensity is raised to 650 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$, then there will be a limitation of pepper production due to a reduction in the rate of photosynthesis from overworking. If the intensity decreases to 250 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$, then the plant will have less growth with thin leaves and smaller sized peppers.

Table 15 - Pepper PAR Experimental Values

Pepper	Shift	PPFD	PAR	Photoperiod
PAR Test	Base Red	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R , 5% G, 5% B	20 hr
	Raise Red	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	94% R , 1% G, 1% B	20 hr
	Lower Red	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	80% R , 10% G, 10% B	20 hr
	Base Green	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G , 5% B	20 hr
	Raise Green	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	85% R, 15% G , 0% B	20 hr
	Lower Green	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	92% R, 1% G , 7% B	20 hr
	Base Blue	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	20 hr
	Raise Blue	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	85% R, 0% G, 15% B	20 hr
	Lower Blue	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	92% R, 7% G, 1% B	20 hr
Hypothesis	If red wavelengths are increased, then the plant height will increase, but if red is decreased, then the peppers produced will be smaller because of the shade avoidance syndrome.			
	If green is increased, then leaf area will increase and the stem will be elongated, but if decreased, then there will be higher plant biomass because green is able to penetrate into the plant deeper.			
	If blue lighting is increased, then there will be an increase in leaf area, carotenoids, and antioxidants, but if decreased, then lower carotenoids and antioxidants because the wavelength balance is off.			

Table 15 shows the PAR tests with their three categories: red, green, and blue. A shift in red wavelength affects plant height, so if decreased, there will be stem elongations from shade avoidance syndrome. If the green wavelength is changed, then leaf area and plant height are impacted since green lighting penetrates into the plant deeper than either red or blue. Lastly, if the blue wavelength is shifted to be more or less, then the change will impact the color and leaf area of the plant.

Table 16 - Pepper Photoperiod Experimental Values

Pepper	Shift	PPFD	PAR	Photoperiod
Photoperiod Test	Base	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	20 hr
	Raise	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	24 hr
	Lower	400 $\mu\text{moles}/(\text{m}^2\cdot\text{sec})$	90% R, 5% G, 5% B	16 hr
Hypothesis	If the base values are used to grow peppers, then the plants will grow the best because the values are ideal.			
	If the duration of light exposure increases, then the plants fruit will decrease in size and leaves will experience chlorosis because the plant is stressed due to too much lighting.			
	If the duration decreases, then the plant will experience stem elongation and smaller fruit production because the plant will experience shade avoidance syndrome.			

The final test values for peppers are for photoperiod in Table 16. If the photoperiod is increased to 24 hours, then the plant will decrease in fruit size and the leaves will experience chlorosis. This effect will occur since the plant will become limited in its photosynthetic process. Inversely, if the plant photoperiod is decreased to 16 hours, then the plant will experience shade avoidance syndrome and have stem elongation.

The content presented in this chapter outlines the design considerations and experimental parameters of vertical farming for the optimal cultivation of four crops: lettuce, tomatoes, strawberries, and peppers. The goal achieved was to outline a structured approach for a controlled environment experiment in vertical farming. The assumption of using a modified shipping container allowed for detailed designs in lighting layout and control schemes. The proposed stacked structure of plant beds ensures individualized light exposures for each crop and is complemented by the implementation of sensors for accurate data tracking. Each crop is divided into formulated hypotheses for altering lighting conditions to allow for future experimentation. These hypotheses expressed anticipated outcomes to guide researchers in determining optimal growing parameters. These hypotheses can be expanded upon, and combinations can be shifted as desired. Overall, this chapter signifies how the management of

precise electric lighting is crucial in achieving optimal growth and yield for further advancements in vertical farming.

Chapter 7 – Conclusions and Future Considerations

The consideration of controlled environments for vertical farming is an important aspect to allow for further expansion of crop production in the world. The lighting design considerations in a controlled environment are crucial to promote optimal crop growth. This report focuses on those considerations and outlines a way to show a proposed design that allows for optimized crop production in a vertical farm application.

There are key terminologies that need consideration when it comes to experimenting with lighting for horticulture. Photosynthetic active radiation describes the wavelengths plants are affected by and needs to be understood to allow for determining proper wavelength combinations that promote photosynthesis. Photosynthetic photon flux density (PPFD) refers to the intensity of the light given off from each light. This unit is different in comparison to what humans experience because footcandles and lux are a human perception which is not beneficial for plants. Lastly, the duration of each light exposure for each plant is its photoperiod. The ideal photoperiod depends on whether the plant is classified as a long, short, or neutral-day plant.

Determining what crops work best in a controlled environment is imperative, especially for testing and experimentation. Taller crops like corn or wheat are not suitable for these spaces since they require extensive vertical space that would be beyond the typical vertical planter bed intervals seen in controlled environments. In the future, perhaps these crops can be considered, but since this idea needs further analysis, smaller crops like lettuce and strawberries are ideal candidates for vertical farming implementation. This report also focuses on tomatoes and peppers, which are considered to be small to medium height plants. Each of these crops desires different lighting attributes for optimized growth. These light attributes can be measured via two sensor types: quantum sensors and spectroradiometers. Quantum sensors are less expensive but

are also less accurate. The choice of what sensor to use can be determined should be based on what application is needed and the available procurement budget. The selection of a light source should be considered in combination with the selected sensor types as well. There are light sources specific to horticulture that can properly provide the required PAR range or the PBAR range.

Lastly, this report focuses on proposing hypotheses for different outcomes based on the three main characteristics: intensity, duration, and color. Fruit production is very dependent on these characteristics, and overall photosynthesis can be affected by changes in these attributes. Although this research only focuses on specific crops and their outcomes, the ideas presented can be adapted for applications in growing other crops by hypothesizing how their growth may be affected by targeted lighting adjustments. Since this report focuses on outlining possible outcomes, the experimentation of these hypotheses should be considered as a next step to further investigate this topic. Other advances to evaluate in this area should include further exploration into optimizing crop production in controlled vertical farming environments by examining how lighting design and structure layout could be varied with other crop not discussed in this report. Advancements in vertical farming research will allow for the much-needed capability of local, year-round crop production. Enabling urban communities to implement more vertical farming sites, will help advance and redefine the future of sustainable food production which is necessary to help feed increasing populations world-wide.

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