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LED Colour Temperature and its Effect on the Growth of Hydroponic Lettuce Seedlings

Justin Shaw

Previous research has shown that differences in light quality can have profound effects on the growth of hydroponic lettuce. This experiment attempts to determine the correlation between the colour temperature of LED grow lights and the growth of hydroponic lettuce. Initially, this study exposed a total of 252 Butterhead lettuce seedlings to various temperatures of white LED lights to determine if there was any correlation between the warmth of light emitted and the growth of lettuce seedlings. Growth was measured in four variables: height, number of leaves, wet mass, and dry mass. When harvested at 28 days, the results suggest that there is a statistically significant difference between plants grown under 3,000K and 6,000K conditions, with results showing as much as a 232% increase in growth for plants grown under 6,000K lights.

Keywords: Colour Temperature, LED, Hydroponics, Butterhead Lettuce

Introduction

By the year 2050, the United Nations projects that the global population will exceed 9.7 billion people, the majority of whom will be moving into cities, taking up a more Western diet (United Nations, 2017). Current agricultural outputs would thus be insufficient to feed the world without an estimated 60% increase in global food production by 2050 (Alexandratos and Bruinsma, 2012; Despommier 2009; Godfrey et al., 2010; Ray et al., 2013). To put this in perspective, meeting those projections would require growing more food in the next ten years than has ever been grown in the course of human history (Bourne, 2015). Historically, there are two main ways to increase the total agricultural output (Thornton, 2012; Tilman et al., 2001):

- develop more new land, or
- increase the efficiency of current agricultural practices.

To meet these goals by exclusively developing more new land would require a land mass the size of Brazil (Despommier, 2012). According to a NASA-funded Stanford researcher, the vast majority of new agricultural land developed in the past decade came from the unsustainable deforestation of rainforests in developing countries (Gibbs et al., 2010). Even without the harmful environmental side-effects of deforestation, current agricultural development is nowhere close to the scale that would be necessary to support a 60% increase in global food production. Therefore, the first method of increasing agricultural output by developing more farmland is unfeasible. Unfortunately, various environmental factors (such as global warming and water scarcity) have restricted the efficiency of agricultural production and already pose harmful environmental side effects, making the second method unlikely to be effective (Alexandratos and Bruinsma, 2012; Godfray et al., 2010; Ray et al., 2013). For instance, according to a paper published in the journal

Science, it is projected that over the next decade pesticide usage will increase threefold, which would push many coastal marine zones past the point of no return (Tilman et al., 2001). This is because agricultural pesticide runoff creates an abundance of nitrogen in rivers and streams, feeding algae which consume all of the dissolved oxygen in an area. These areas are called a dead-zones because there is no dissolved oxygen in the water, making it ecologically 'dead' or incapable of supporting complex life. The use of chemical pesticides along the Mississippi River has created a large dead-zone in the Gulf of Mexico the size of a small state (Diaz and Rosenberg, 2008; Tilman et al., 2001). Given the increasing frequency of droughts, water usage is also a large concern given that agriculture accounts for about 70% of all freshwater usage in the United States (Barbosa et al., 2015; Winter et al. 2017). For these reasons, increasing the efficiency of current agricultural practices is becoming more and more difficult. Some argue that these kinds of Malthusian doomsday predictions have always been predicted and have never come true; however, the methods that were effective for farmers yesterday are ineffective today (Godfrey et al., 2010; Thornton, 2012; Tilman et al., 2001). To feed the growing global population without sacrificing the health of our planet, a radically new way of growing food is necessary.

Literature Review

Hydroponics

The use of hydroponic farming has the potential to radically change the way food is grown. Hydroponic technology was first deployed in World War II to provide the US Armed Forces with fresh fruit and vegetables in the desolate, and often barren islands of the Pacific. The technology sustained American troops in their victorious island-hopping campaign across the Pacific as it could grow large quantities of food without taking up a large footprint on each island (Jones Jr., 1982).

Hydroponic farming is an efficient way of producing enough food to meet the growing needs of growing global populations. Hydroponic systems do not need soil, can use up to 11 times less water for the same crop, and can be grown year-round (Barbosa et al., 2015; Winter et al., 2017). Most soil-based growers harvest their crops at most three times per year, but hydroponic plant factories can harvest up to 22 times per year in a fraction of the space (Despommier, 2013; Fischetti, 2008). In a hydroponics system, plants are cultivated in a solution that contains all the nutrients needed for plant growth instead of soil. This means they can be grown indoors which effectively eliminates the need for chemical pesticides, herbicides, or fungicides that are used in traditional outdoor agriculture. Additionally, this allows the farmer to stack multiple tiers of plants, which increases the density of plants that can be grown in a given area. There are many different types of hydroponic systems, each being specialized to a specific set of objectives and constraints. Regardless of the system used, the most common way to germinate seeds is with an expanded rock fiber called rockwool. This report will focus on the colour temperature of LED lights and how they affect the germination of seeds grown in rockwool. Because the nursery conditions are generally the same for each of the different types of systems described below, the results of this paper can easily be applied to all systems described below (Both, 1998).

Nutrient Film Technique. The Nutrient Film Technique (NFT) cycles nutrients past exposed roots via a pump (Figure 1). NFT systems are generally the least expensive hydroponic systems to purchase and operate because when the water is running continuously, it oxygenates itself. In other systems, where the water is not cycled, the use of an air pump must be implemented to oxygenate the solution. Lack of proper oxygenation can lead to negative crop yields (Both, 1998). The NFT system is also ideal for urban areas that have footprint constraints. The end of one tube can be connected to the beginning of another and the whole system can be stacked several layers high, creating a dense agricultural environment that decreases the farm's footprint and saves money (Both, 1998; de-Anda and Shear, 2017).

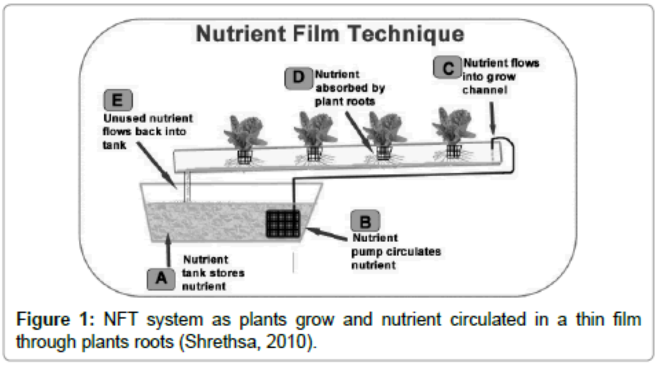

Figure 1: NFT systems cycle nutrients past exposed roots via a pump (Mchunu et al., 2017).

Deep Water Culture. Another type of system, called Deep Water Culture (DWC), uses a nutrient solution in which roots are submerged. As the water level decreases, due to plant metabolism and evaporation, more of the roots are exposed to the air which increases oxygenation to the roots as they mature. However, the use of this system still requires an oxygenator for best results. This system is best for areas with ample amounts of natural sunlight and open space as it would be difficult to scale up this setup in an urban environment without the ability to stack multiple layers (Both, 1998; deAnda and Shear, 2017).

Floating Raft Culture. A variation on the DWC method, Floating Raft Culture (FRC) uses a floating raft which holds the plants above the reservoir (Figure 2). This method is very common in commercial hydroponic systems where space and light are not issues.

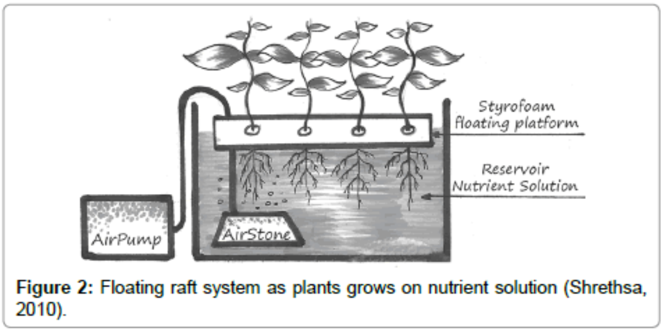

Figure 2: FRC uses a raft which holds the plants above the reservoir (Mchunu et al., 2017).

Aquaponics. Unlike the other methods, an Aquaponics system is not about the structural design of the farm; rather it is about the nutrients that are delivered to the plant. In aquaponics, plant nutrients are provided by fish (Figure 3). The result is an artificial micro-ecosystem: the fish produce organic compounds that are vital to plant growth and the plants absorb organic compounds which also cleans the water for the fish. In all of these systems, it is not uncommon to see the nutrient solution be substituted for an aquaponics system.

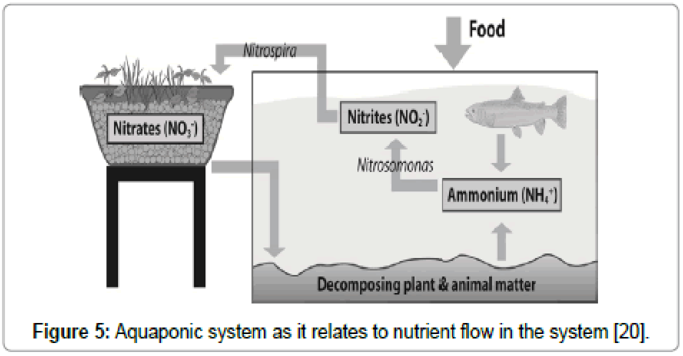

Figure 3: In Aquaponics, plant nutrients are provided by fish (FAO, 2014).

Aeroponics. In addition to hydroponics, many other systems have been developed as an alternative to traditional agriculture. One example is aeroponics where nutrients are taken from a reservoir and sprayed out of a fine nozzle at exposed roots. Aeroponics systems are great for high density urban areas because they can produce a lot of fresh fruit and vegetables in a small space. This misting method can be stacked on top of itself, which increases food production density similar to the NFT method. In many plant factories, this method is common because everything can be automated. Additionally, the quality of crops coming out of these high-tech plant factories has the potential to be greater than traditional agriculture because farmers can customize each aspect of the internal environment (like CO2 content or humidity) to specific tastes or preferences.

Research Objective

In response to the growing dangers of industrial agriculture, hydroponics offers a viable alternative that is capable of meeting targets for future demands at a fraction of the cost (Barbosa et al., 2015; deAnda and Shear, 2017; Winter et al., 2017). However, the efficiency of current hydroponic technology is not able to meet those targets. Therefore, the objective of this experiment is to examine the effects of colour temperature on the growth of Butterhead lettuce seedlings in a simulated hydroponic environment.

Photobiology

It is generally accepted that plants grow best when the majority of emitted light is in the red and blue (RB) spectrum (Folta and Maruhnich, 2007; Lee et al., 2014; Su et al., 2014; Wang et al., 2015). Small quantities of other wavelengths have also been proven beneficial for plant metabolism (Smith et al., 2017). This is because the photoreceptors (a cell protein that absorbs light) absorb red and blue photons (particles of light) more efficiently than other wavelengths. Competing studies have also contested whether or not the use of green light is effective for plant growth (Folta and Maruhnich, 2007; Kim et al., 2004; Smith et al., 2017). For instance, new research has shown that green light may also play a role in the creation of specific plant proteins that aid in growth (Kim et al., 2004; Smith et al., 2017). Other research shows that this light might not correlate into measurable plant development (Su et al., 2014). In general, using red and blue Light Emitting Diodes (LEDs) has been shown to be more efficient that only using white (Lee et al., 2014). Additional studies show that the use of far-red (the region between red and infra-red) lighting can enhance plant flowering (Deitzer et al., 1979).

This experiment used three different colour temperatures of light (3,000K through 6,000K) that vary in the proportion of red light to blue light. Each of the lights is technically ‘white’ so it contains all wavelengths of colours, but in general the higher the colour temperature the bluer the light. Therefore, the 3,000K light has the highest proportion of red photons and the 6,000K light has the highest proportion of blue photons.

In addition to the colour of light, the type of bulb is also important in horticultural research. Recent studies with new LEDs have shown that LEDs can be more energy efficient than the industry-standard Philips T5 High Output Compact Fluorescent Light (Reineke et al., 2009). Organic LEDs (OLEDs) are even more efficient but have not been tested on plant growth.

Plants perceive light differently than humans. While the range of light plants can absorb is roughly the same as the visible spectrum in humans, the efficiency (the ratio of the quantity absorbed by the cell to the quantity of light that hits the cell) at which they absorb each wavelength is vastly different. The spectrum of light available for plants is called photosynthetically active radiation (PAR). This describes the range of wavelengths of light from about 400nm to 700nm. There are two common ways of measuring the brightness of light in the PAR spectrum, either by ‘weighing’ all photons in the spectrum equally, called photosynthetic photon flux (PPF), or by giving a weight to certain photons based on the plant’s ability to absorb that wavelength, called yield photon flux (YPF). Generally speaking, red photons are easier to absorb, due to their lower energy, thus resulting in about 20% to 30% more photosynthetic activity than a blue photon (McCree, 1971). Because you have to know the specific frequency of the light source before you can weight the wavelengths, YPF is harder to measure than PPF.

Another difference between plant and human light perception is how each perceives brightness. The human retina uses a logarithmic scale when sensing light. This means going from one to two light sources would have the same effect as from 50 to 100 light sources. However, plants are linear in their perception of light; the difference between one light and two is equivalent to the difference between 50 and 51. This means that controlling the brightness level in lights is crucial. To measure brightness, Biologists describe the density of photons hitting a given surface area every second, photosynthetic photon flux density (PPFD). PPFD will be discussed more in relation to Photoperiodism (section 3.3).

According to Dr. Toyoki Kozai, Professor Emeritus and Chief Director of the Japan Plant Factory Association Center for Environment, Health, and Field Sciences at Chiba University, due to an insufficient research base on the topic, “there should be more room for improving the [lighting use efficiency] of [closed plant production systems]” (Kozai, 2013). While there is a surplus of knowledge about the differences in efficiencies between growing methods and solution contents, and wavelength of various lighting systems, more research needs to be done on the colour temperature of indoor hydroponic lighting systems (Kozai, 2013; Reineke et al., 2009). "Lighting Use Efficiency" is one of the most vital, yet underdeveloped aspects of plant factories. This paper aims to fill that gap by evaluating the varying 'efficiencies' of different colour temperatures of LED lights.

Butterhead Lettuce

Butterhead lettuce is the most widely used crop in research-based hydroponics as it grows relatively quickly (Barbosa et al., 2015; Brechner and Both, 2013; Jones, 2005; Ryder, 1999; Tyson et al., 2013). Lettuce grows best in cooler climates and is well documented in research-related studies of hydroponics (Dufault et al., 2009; Fischetti, 2008). Butterhead lettuce can be sold at a local farmer's market for a profit to help subsidize the initial costs of building a small-scale "Closed Plant Production System" (CPPS), although these systems are generally inexpensive (Becraft, 2017; Brechner and Both, 2013; deAnda and Shear, 2017; Jones, 2005).

Methods

In order to determine if various colour temperatures of LED lights will have any effect on the growth of lettuce, this experiment developed a quantitative experimental approach that closely modelled common commercial hydroponic germination techniques to measure the growth of lettuce seedlings in a hydroponic simulation. This study germinated a total of 252 Butterhead lettuce seeds in hyper-absorbent expanded rock-fiber cubes (Rockwool) in 3 different chambers each with a different colour temperature of light. Rockwool is the most common growth medium for both commercial and laboratory-oriented growers as it closely models traditional soil-based growing while absorbing a large volume of water for its size. Two seeds per rockwool cube were planted in each of the three chambers, grown over the course of two growing periods. A scaled down version of a Closed Plant Production System (CPPS), and utilized a standard 11- by 22-inch gardening tray and humidity dome, all enclosed by identical rigid white containers. The humidity dome is a standard-fit transparent dome which serves two functions:

- it increases the humidity inside the enclosure which aids the growth of lettuce seedlings,
- it protects the LED lights from water damage.

The interior of each chamber was painted white to reflect as much light as possible, which increases the efficiency of the LEDs dramatically. In each of the two growing periods, 21 rockwool cubes (42 seeds) were soaked in a nutrient-rich bath for 2 hours and then placed in each of the three chambers. Rockwool cubes can hold water for a matter of weeks before drying out, but nutrient levels may vary over that time. Excessive watering can lead to nutrient buildup and can harm vital plant functions, so nutrients were replenished by spraying each chamber with a nutrient solution every three days. After the standard growth period of 28 days (after planting), various measurements were taken (described in section 3.6).

Crop Selection

This paper uses Butterhead lettuce as a test crop as it grows relatively fast, is compact, and is supported by a large base of past research. The large base of literature surrounding Butterhead lettuce means this paper has direct and pragmatic implications for both commercial hydroponic growers, and academic researchers alike as they incubate their own lettuce seedlings and are questioning the relationship between colour temperature and plant growth as a means of improving the efficiency of plant production.

Nutrients

In hydroponic conditions, all of the nutrients needed for plant growth are dissolved into a solution to which the roots are exposed. This type of setup is advantageous because the nutrients available to the plant can be more accurately controlled. In general, plants need two categories of nutrients: micronutrients and macronutrients. This paper utilizes a discipline-standard mix of Masterblend™ 4-18-38, Calcium Nitrate, and Magnesium Sulfate. The numbers 4–18–38 in the fertilizer naming system stand for the relative abundance of Nitrogen, Phosphorous, and Potassium (NPK). For example, this experiment used a formula with 4% Nitrogen, 18% Phosphorous, and 38% Potassium by volume. The combination of these ingredients sufficiently satisfies both the macro- and micronutrient requirements of the plants. The specific ratio between these chemicals is very important as a lack of nutrients may lead to visual deficiencies. However, a more in-depth justification for each of the nutrients is beyond the scope of this research paper.

Photoperiodism

Past research has shown that plants need to spend specific amounts of time in both light and darkness. The photoperiod of this experiment is tuned precisely with that of developing lettuce seedlings; 18 hours of light and 6 hours of dark. The use of a digital 24-hour timer ensures that all of the trials get the same amount of light. Although this model attempts to equalize the amount of light that hits each plant's leaves, differences in the PPFD output of the lights themselves may also limit the consistency of the light absorption of the plants. This is to say that some lights may be fractionally 'brighter' than others which may influence data. This can not be corrected for as the difference in PPFD between colour temperatures is an intrinsic property of each light, and should be considered as such when evaluating the data processes.

LED Strips

Due to both cost and space constraints, the use of a high density and relatively low-cost lighting was essential. For this reason, LED light strips were the best choice because they output a lot of light relative to their size, were easily attachable to the interior of each box, and could be wired together and supplied by a standard computer power supply unit (PSU) which was repurposed for this experiment.

Colour Temperature

The manufacturer of the LED light strips does not provide strips in the 4,000 Kelvin (K) range. This is most likely because the 4,000 K phosphor is too expensive to be profitable for the company. While this limitation is unfortunate, having three sample points at 3000K, 5000K, and 6000K was sufficient to demonstrate a correlation between colour temperature and the various methods of measuring growth (described in section 3.6, below).

Dimensions of 'Growth'

In general, the metrics for measuring plant growth vary widely based on the objective of the research. However, it is typical to include at least three different quantitative measures so as to get a wide breadth of data about each plant in order to tell a complete story. While no individual measurement fully explains the status of the plant, a combination of these three perspectives can give a more detailed picture of how each plant grew under the various conditions. The following three measurements were the most common way of measuring plant growth in academic biological research.

Height. Height (the distance from the base of the plant at the surface of the rockwool to the tip of the longest leaf) can have various implications in biological terms. In general, a large height value can imply that the plant grew fully and prospered in the given conditions. From an evolutionary standpoint, a taller plant is favoured over a small plant as tall plants have easier access to sunlight than do plants of smaller stature. However, that is not always the case. 'Bolting' is a term used to describe a plant that does not have adequate light and thus grows thin and tall in an attempt to reach light. This is a potential drawback of this method of measurement however, in combination with other measures, the height of a plant is an integral aspect of its overall growth.

Number of Leaves. The number of leaves can have multiple implications with respect to plant growth. It is widely agreed that the more leaves a plant has, the healthier its growth is. Growing a new leaf requires a lot of energy that the plant must spend and thus is a good indicator of its overall stage of growth. However, the number of leaves does not describe the health or size of those leaves, so while a plant may have a large number of leaves, they might all be small, discoloured, or misshapen.

Biomass. This paper utilizes two ways of finding the mass of each plant: wet mass and dry mass. Whereas the wet mass is the mass of the plant as grown in the chamber (including the water inside the plant), the dry mass is the mass of the plant devoid of water (by evaporating water out of the plant). This paper used a standard convection oven set to 100 degrees Fahrenheit to dry the plants over a period of 4 hours, after which the plants were cooled down and their mass was taken. For both the wet and dry mass, only the average mass was recorded because the scale was inaccurate at lower masses. The mass of all plants was taken simultaneously and the data (Table 3 and 4) represent the average. The dry mass shows the actual mass of organic matter that was grown in the process of creating the plant. This is important because it serves to show how much 'growth' the plant ended up doing via the net change in organic matter that was created by the plant. Additionally, wet mass is an important statistic as it shows the absorption of water (and therefore nutrients) by a plant. If a plant's wet mass is not significantly greater than its dry mass, the plant failed to absorb water from the rockwool which would lead to negative growth yields. In hydroponics, where all the nutrients are dissolved in a solution, different wet mass values may indicate different absorption rates as a result of the colour temperature. Therefore, analysis of both the wet and dry masses will provide a more complete picture of the true growth of the plant, especially when such plant is grown in hydroponic conditions.

Results

Height (cm)	3000K	5000K	6000K
Average	9.4	13.1	13.2
Standard Deviation	4.2	4.2	4.7

Table I. Height of seedlings after 28 days of growth in a controlled-environment chamber under various colour temperatures of LED lights.

Note: This table shows the height (in centimetres) of each seedling grown under three different colour temperatures of LED strip lights; 3000K, 5000K, and 6000K. Notably, there is nearly no difference between the heights of 5000K and 6000K plants. Both the 5000K and 6000K chambers had plants that grew very tall and sturdy (13.1 and 13.2cm, respectively), compared to 9.4cm for 3000K. Overall, the data is strongly correlated with a linear fit as the Pearson correlation coefficient (R2 = 0.901).

# of leaves	3,000 K	5,000 K	6,000 K
Average	8.7	10.8	12.2
Standard Deviation	2.3	2.8	4.0

Table II. Number of leaves after 28 days of growth in a controlled-environment chamber under various colour temperatures of LED lights.

Note: The data in this table shows the average number of leaves on each plant under each of the three different colour temperatures of LED lights (3,000, 5000K, and 6,000 Kelvin). In general the average number of leaves increases as the colour temperature increases. There is a notable gap between the 3000K and 5000K plant average (8.7 versus 10.8 leaves). This difference is less notable between 5000K and 6000K (10.8 versus 12.2 leaves). This relationship is almost perfectly linear with a remarkably high Pearson correlation coefficient (R2 = 0.996).

Average Mass (g)	3,000 K	5,000 K	6,000 K
Wet Mass	3.1	5.7	18.9
Dry Mass	3.0	4.9	12.3

Table III. Wet and dry masses of seedlings after 28 days of growth in a controlled-environment chamber under various colour temperatures of LED lights.

Note: This table describes the wet mass and dry mass of each plant 28 DAP. As shown above, both the average wet mass and dry mass of the plants increases with increasing colour temperature. There is a notable lack of change between the wet and dry masses of the 3000K chamber (3.1g wet versus 3.0g dry) because the plants grown in this chamber had trouble absorbing water. The rockwool was constantly dry but for the sake of reliability no extra water was given. The correlation was moderately strong (Wet Mass R2 = 0.718, Dry Mass R2 = 0.754).

Discussion

Germination Rates

Throughout the course of this paper, the germination rates between different colour temperatures varied substantially. For example, of the seedlings initially fertilized in the 3000K chamber (two seeds per Rockwool cube), less than 30% germinated. Contrastingly, a larger percentage of the seeds in the 6000K chamber germinated (67% germination rate). This has two main implications. First, the sample size representing 3,000 K plants is smaller than the other two which may vary they validity of the data slightly. Second, the difference in germination rates may be correlated with the difference in colour temperature. However, further research must be done in this area in order to determine the underlying factor causing this significant discrepancy of germination rates between colour temperatures as the results from this experiment are insufficient to describe this relationship with any certainty.

Experimental Constraints

While there was enough time to replicate the initial trial, some accuracy was lost due to the time and space constraints of this experiment. A lack of room inside the chamber meant there was a smaller-than-optimal carrying capacity for each enclosure. The larger plants dominated the enclosures and blocked light from reaching the smaller plants. This was nearly made up for by repeated trials; however, further research may find it best to use larger chambers for conducting this type of research to prevent crowding. The culmination of these issues was that each trial was stopped short of a full growing period (40-50 DAP) to allow room for the next trial, which slightly decreased the validity of the data. This decrease in growth duration ended up being inconsequential as after 28 days of growing there were significant and measurable differences between groups. Future research should look to optimize the length of the growth period of each trial with oversized enclosures.

Conclusion

Results

The results of this paper have profound implications as to the viability of hydroponics to act as an alternative to traditional agricultural practices. Traditional hydroponic intuition would point toward the low colour temperature light as having the best output as they have the greatest red-to-blue light ratio. However, the results of this paper points in the opposite direction, that the cooler light (highest colour temperature) was best for plant growth.

This experiment found that colour temperature was strongly correlated (R2 of 0.901) with the height of a plant grown in hydroponic conditions (ranging from an average of 9.4cm to 13.2cm in height). This trend was consistent across all temperatures of light and was justified by multiple trials of over 250 individual seeds.

Additionally, the number of leaves on each plant was very strongly correlated (R2 of 0.996) to an increase in colour temperature (averaging 8.7 to 12.2 leaves). Although the standard deviation increased dramatically for the 6000K enclosure, this can be attributed solely to the lack of space in the enclosure. The large plants completely dominated the 6000K enclosure which meant that the smaller plants were too small to thrive.

Perhaps most impressive, the average wet mass of the plants grown under 6000K LEDs was 232% higher than that of the 5000K plants and the dry mass saw similar improvements. While there is only a moderate linear correlation between a plant's biomass and colour temperature, it is possible that a quadratic or even exponential fit may be a more appropriate fit for the data.

This research orients itself in opposition to traditional hydroponic intuition, creating a new understanding of the relationship between the colour of light and horticultural growth. Our results suggest that higher colour temperatures are conducive to greater growth in plants.

Implications

The objective of this paper was to find and optimize the best growing conditions for Butterhead lettuce using only differences in the colour temperature of LED lights. Against conventional intuition, the results of this paper suggest that a higher colour temperature (cooler light) is strongly correlated with both the number of leaves (R2 was 0.996) and height (R2 was 0.901) and moderately correlated with the wet (R2 was 0.718) and dry masses (R2 was 0.754). This has tremendous implications for hydroponic researchers and commercial growers alike as the results of this paper can be directly translated into optimizing the lighting conditions for commercial hydroponic farms, especially in states like California where Butterhead lettuce is commonly grown hydroponically. To that end, hydroponic growers of all backgrounds, whether growing in a high-tech lab or in an abandoned warehouse in the inner city, should look to use higher colour temperature lights to grow their lettuce.

Looking Forward

While past research has a primary focus on the biochemical properties of hydroponics, this paper examines the difference that the colour temperature of LED lights can have on the overall growth of hydroponically-grown Butterhead lettuce. Even among photo-biological research, there is a strong need for more research on the biological application of new LED technology including colour temperature, colour-programmable, and even organic-LED (OLED) lighting technology.

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