Photosynthetic Absorption Spectra and Tomato Plant Growth Rates

Final Report

Katie Whitcomb

Faculty Adviser
Dr. David Gore

Physics, Computer Science, and Engineering
Christopher Newport University
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Contents

1 **Abstract** 2

2 **Introduction** 2

3 **Theory** 4

4 **Methods** 5

5 **Data** 7

6 **Discussion and Conclusion** 13

7 **References** 16

1 Abstract

Adenosine Triphosphate (ATP) is essential to life in both plants and animals. For plants, ATP is the primary form of chemical energy. Most ATP is produced through photosynthesis. For photosynthesis to take place, light must transfer its energy to the chlorophyll molecule, which turns the energy into ATP, thus allowing the plant to grow. Energy transfer efficiency is dependent on the wavelength of the light and the pigments found in the plant. Pigments are more likely to absorb certain wavelengths over others. Pigment absorption has a direct impact on the rate of photosynthesis. This project aims to experimentally verify the photosynthetic absorption spectra by observing the effect of light source wavelength on the relative growth rates of tomato plants. Results of this experiment are inconclusive. There is not enough data to support any relationship between the proposed absorption spectra and tomato plant growth rates. Suggestions for further experimentation include expanding the scope of the experiment by adding in more light sources and more data points for each light source.

2 Introduction

Optimizing plant growth is vital. When the demand for food exceeds the supply, the cost increases. Indoor gardening is a solution, but to efficiently use power, reduce cost, increase plant growth, and increase supply, an optimized light source is necessary.

To experimentally determine the most effective light, plant growth rate measurements are compared to the total energy calculations. Tomato plants were chosen because they are able to grow in confined spaces and they grow quickly, which fits the time and space constraints of this project. The plants were grown under isolated light sources. There were six different light sources: red, green, blue, white, yellow and magenta. Light absorbency is the probability that pigments, found in the chlorophyll of a plant, will accept the photons from a specific light source and use their energy for photosynthesis. This must be considered when determining the ideal light source. Pigments found in the chlorophyll of tomato plants are more likely to absorb certain wavelengths than others. To predict which plants will experience more growth, the absorbency of each light wavelength is used. Based on the photosynthetic absorption spectra (Figure 1), blue light has the highest absorption value by a factor of 6, then red light and green light have relatively the same absorption factor.

The LED lights used in this project only have red, green, and blue lights. While they were not ideal due to their limited variability, they fit the budget and functionality of the project better than any other product available. As a result, white light was composed of red, green, and blue light; yellow light was red and green light; magenta

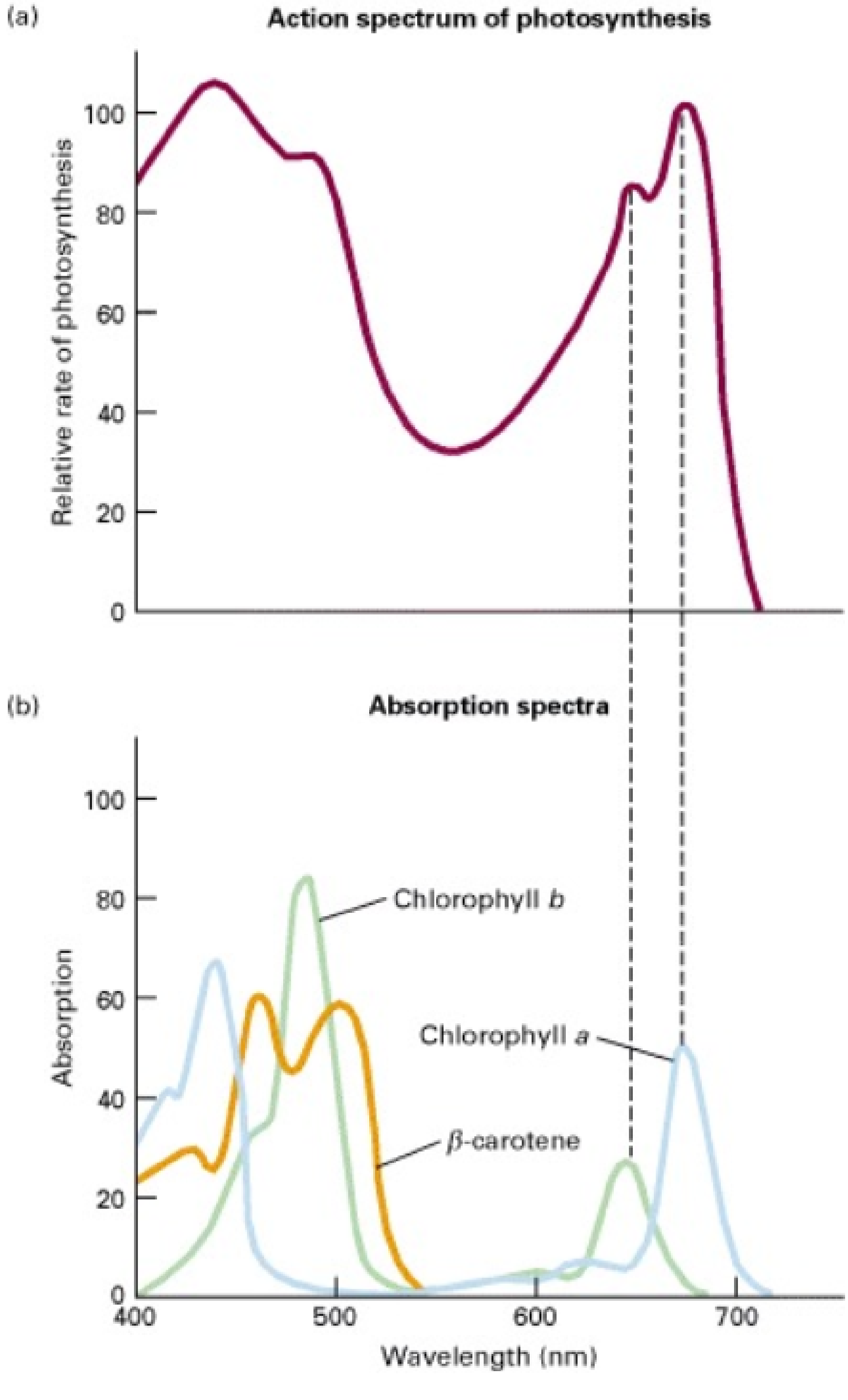

Figure 1: Photosynthetic Absorption Spectra

light was red and blue light. The absorption value of these lights was a combination of the absorption values of the individual LEDs used to make up the light source.

3 Theory

Light deposits energy when it interacts with matter. The amount of energy in a light source is inversely related to the wavelength of the light. Energy contained in one photon of light can be described by the equation:

$$E = \frac{hc}{\lambda} \tag{1}$$

where h is Planck's constant (6.63×10^{-34} Js), c is the speed of light (3×10^8 m/s), and λ is the light source's wavelength.

Not all energy from the light is accepted equally by the plant due to the pigments found in chlorophyll. There are three major photosynthetic pigments: chlorophyll α, chlorophyll β, and β-carotene. A graph of the absorption spectra of these pigments are found in Figure 1. Part (a) of the figure is a graph of the rate of photosynthesis based on the absorption spectra of the different pigments. Based on this model, light sources with wavelengths between 400 - 500 nm and 650 - 700 nm should optimize energy transfer to the plants.

To analyze plant growth rate, a measurement of the total energy available to the plant will be determined. This requires a calculation of the number of photons, N, multiplied by the energy, E, of a photon. The equation is the following:

$$\text{Total Energy} = NE = IA \tag{2}$$

where I is the measured irradiance (in W/m^2) and A is the surface area of the plant. This was compared to measured growth which can be used to compute the relative absorption of energy.

For irradance measurements, a light meter was used which had units of candles per foot squared. Spectral luminance must be converted using the standard luminosity curve (Figure 2). Unit conversion is described in Equation 3

$$Luminous flux = 680 \times y \times \phi(\lambda) \tag{3}$$

where y is the normalized intensity (the value on the y axis of Figure 2), λ is the wavelength, and $\phi(\lambda)$ is the spectral luminance of the wavelength. To convert luminous flux to watts per meter squared, it is multiplied by 0.0162 $\frac{ft^2W}{m^2cd}$. After irradiance was found, it was multiplied by the surface area of the plant to calculate the total energy available.

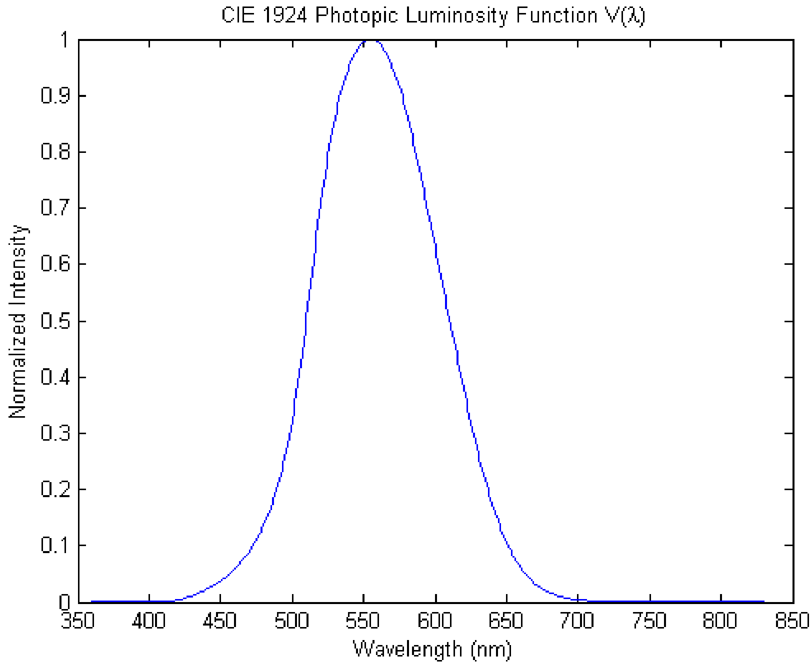

Figure 2: Standard Luminosity Curve

For combination lights, the irradiances of the individual wavelengths (red, green, or blue) were added together and multiplied by the surface area. For example, the total energy calculation for white light can be shown by Equation 4.

$$TotalEnergy = A(I_{red} + I_{green} + I_{blue}) \tag{4}$$

Then, to find the theoretically absorbed energy, the light source irradiance was multiplied by its absorption value, α. For example, the predicted absorbed energy for white light is represented by

$$AbsorbedEnergy = A(\alpha_{red}I_{red} + \alpha_{green}I_{green} + \alpha_{blue}I_{blue}) \tag{5}$$

The absorbed energy calculations should agree with the average growth rates.

4 Methods

This experiment requires light sources, plant care, and data measurement. To analyze plant growth under a specific light source, all outside light must be removed. Boxes were constructed out of cardboard to block out unwanted light. The boxes

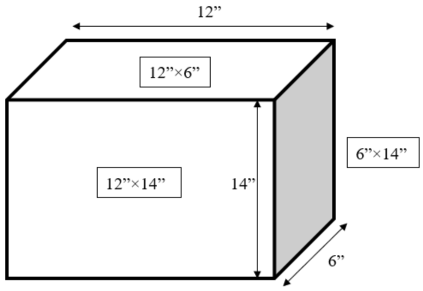

Figure 3: Box dimensions

had dimensions of 12”×6”×14” (Figure 3). Box height was chosen to accommodate the maximum expected height of the plants. Each group of 10 plants, ordered in two rows of five plants, had their own light source. Since the pots for the plants are 2”×2”, the width of the box had to be at least 4 inches and the length had to be at least 10 inches. The bottom of the boxes were open, so they can be placed over the plants. After the box was constructed, 3 LED light strips (powered by USB ports) were attached to the top of the box, parallel to the 12-inch edge of the top of the box, and spaced 1.5 inches apart.

Tomato plants were chosen because of their fast growth rates and ability to be grown in small pots. This fits both the time and space constraints of this project. It takes around 6 – 8 weeks for tomato plants to grow 8 – 10 inches from a seedling.

The experiment was concluded before tomatoes start to form because, if some tomatoes fall off the plant, the mass of the plant will change. Therefore, because tomatoes begin to form fruit after 50 days, the initial projected duration of the project was 50 days. Plants did not grow as quickly as predicted and the project was extended.

Prior to the start of the experiment, a test-run was done to determine how much water would be required. The test-run plants were grown in the sunlight with five different watering amounts. There were five pots and two seeds per pot. Every three days the plants were watered and both plants in each pot grew. Because it was found that any amount would be sufficient for growing the plants, measurement restrictions decided which amount of water to use. The experimental time interval between watering was every four days, and since 5 ml of water left the soil completely dry after 3 days, 7.4 ml was chosen because the soil would be dry enough so when the plants were weighed, no water would contribute to the weight. The experiment then began with those watering parameters.

At first, several plants under the red, green, blue were growing. However, after about two weeks, they started withering away and dying. To try and prevent further death, the interval between watering was decreased from four days to three days, and was then further decreased to every other day. This lasted for a week, but the plants began retaining the water quickly and excess water began seeping from the holes in the bottom of the pot, so the interval was returned to every 3 days.

To calculate the energy available to the plants, as described by Equations 1 and 2 in the theory section, irradiance, plant surface area, and wavelength are needed. Wavelengths of the different light sources were determined by a digital spectrometer provided by the PCSE department. Luminance was measured using a light meter, provided by Dr. Gore, and converted into energy as described by Equations 2 and 3.

Plants were intially weighed with a mass scale, provided by CNU. Since the soil was drying out, the weights were decreasing over time. As a result, the weight of the plants in the pots were not used for analysis. The plants which were still alive at the conclusion of the experiment were weighed and the mass of the plant was divided by the amount of time it grew to get an average growth rate. Plant height was measured with a centimeter ruler. The average width and length of the leaves were also measured with a centimeter ruler. Plant surface area was approximated by multiplying the length and the widths of the leaves.

5 Data

The light source wavelength spectra are shown in Figures 4 – 9. For the white, yellow, and magenta light sources, the different wavelength peaks are assumed to be at the same intensity level even though the graph does not depict this. The optical probe used for the light spectra measurements had a small light acceptance area. Due to the size of the LEDs, it was challenging to align the light strip so that all three LED elements were exposed equally. As a result, the intensities of the different light wavelength are treated to be the same since each LED light received the same amount of power and would have the same intensity.

For energy calculations, a plot of the surface area over time was used (Figure 10). As described in Equation 2, total energy available was calculated by the surface area times the irradiance of the light source (Equation 4, Table 1). Each point on the surface area graph was multiplied by the light source's irradiance to get the total energy at each point. To calculate the total energy available, the surface area plot was fit with a polynomial. The polynomials were integrated over time, to get the total surface area exposed over time. Multiplying the surface area exposed over time by the irradiance values yielded the calculation of total energy available (Figure 11). Predicted energy absorption was calculated with the same method, but instead of it being the product of surface area and irradiance, irradiance was also multiplied by the absorption of each wavelength, described by Equation 5.

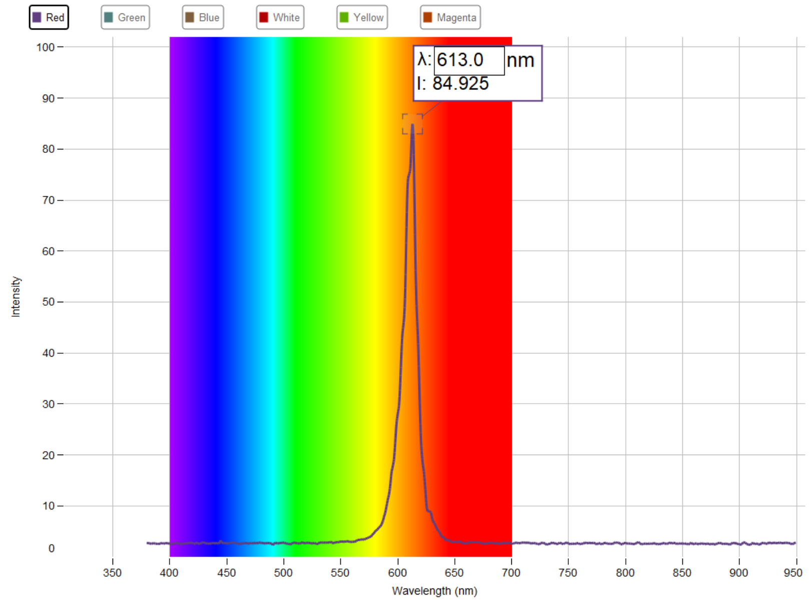

Figure 4: Red Light Spectrum

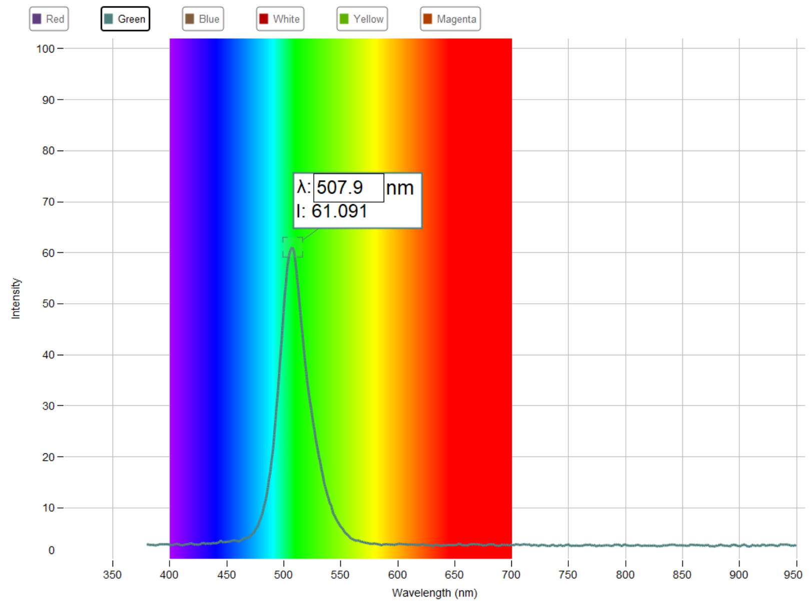

Figure 5: Green Light Spectrum

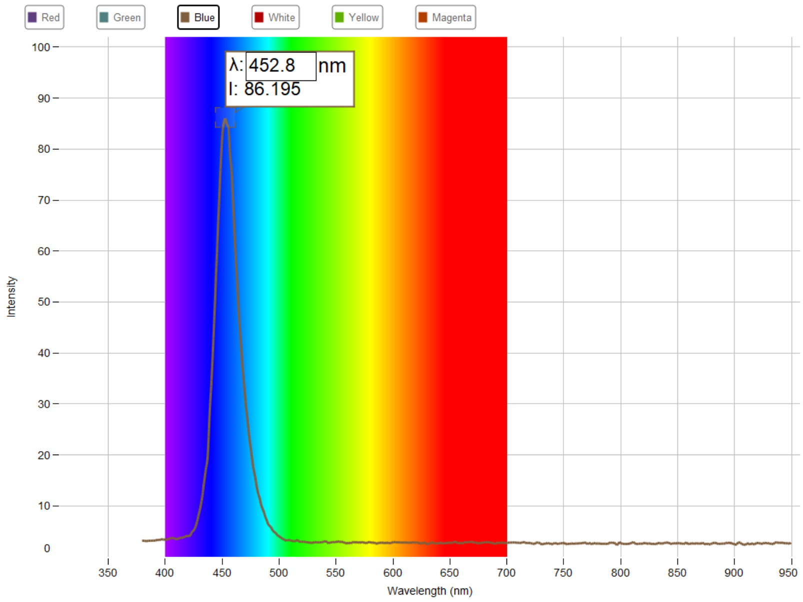

Figure 6: Blue Light Spectrum

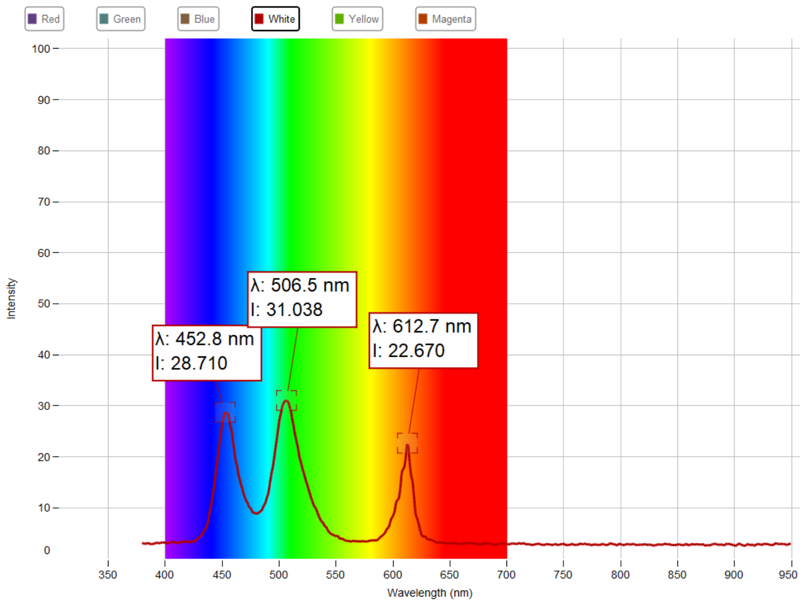

Figure 7: White Light Spectrum

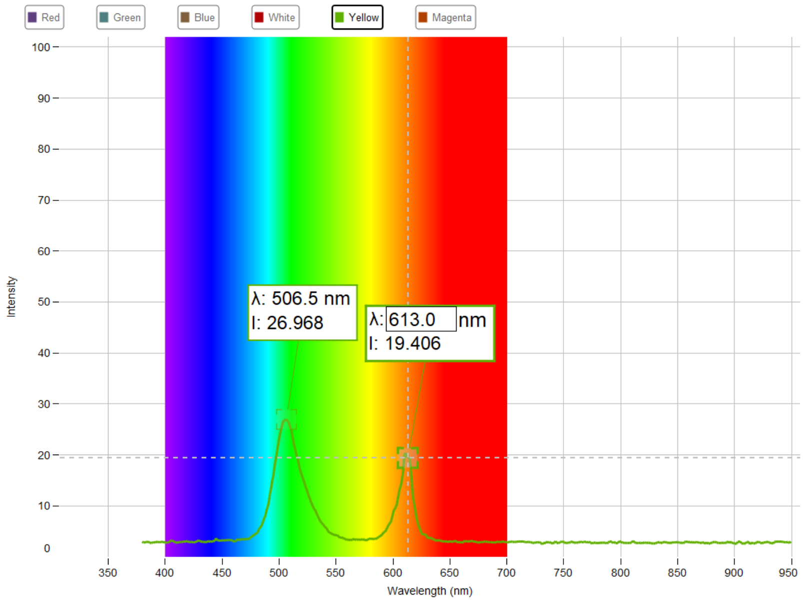

Figure 8: Yellow Light Spectrum

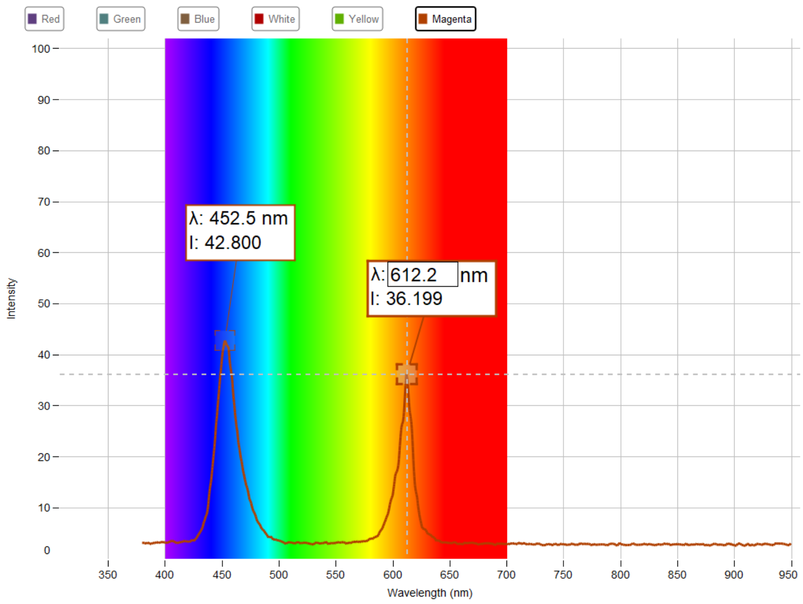

Figure 9: Magenta Light Spectrum

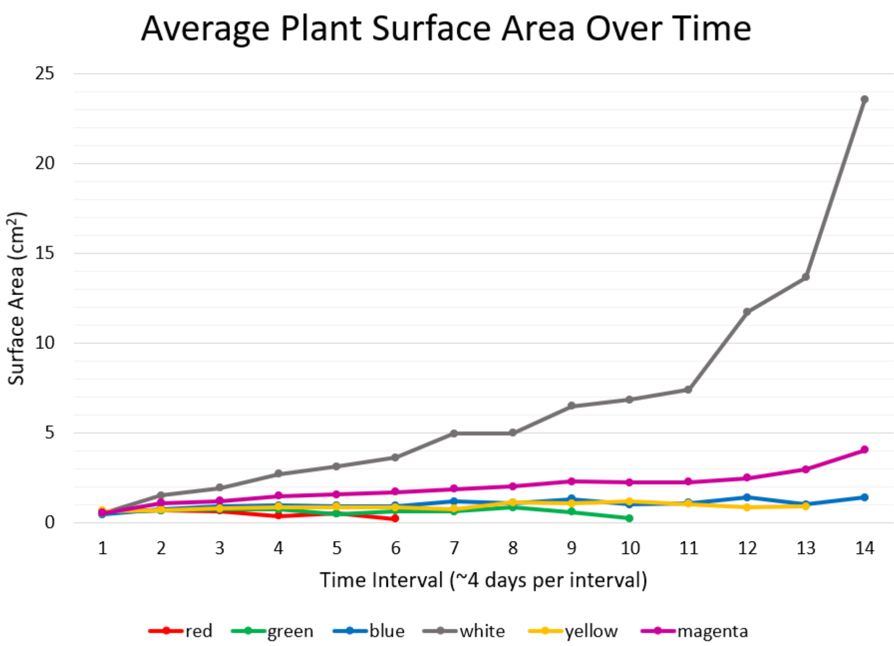

Figure 10: Surface Area Over Time

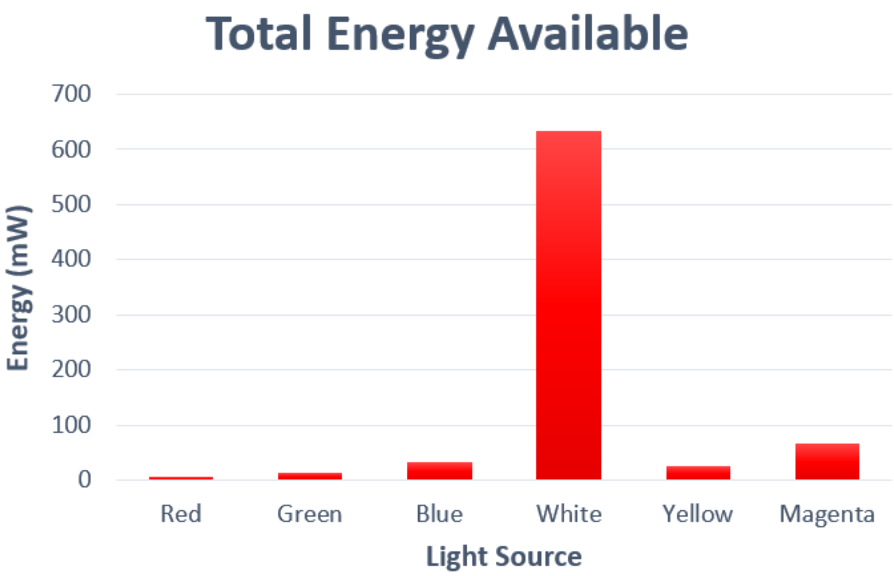

Figure 11: Total Energy Available

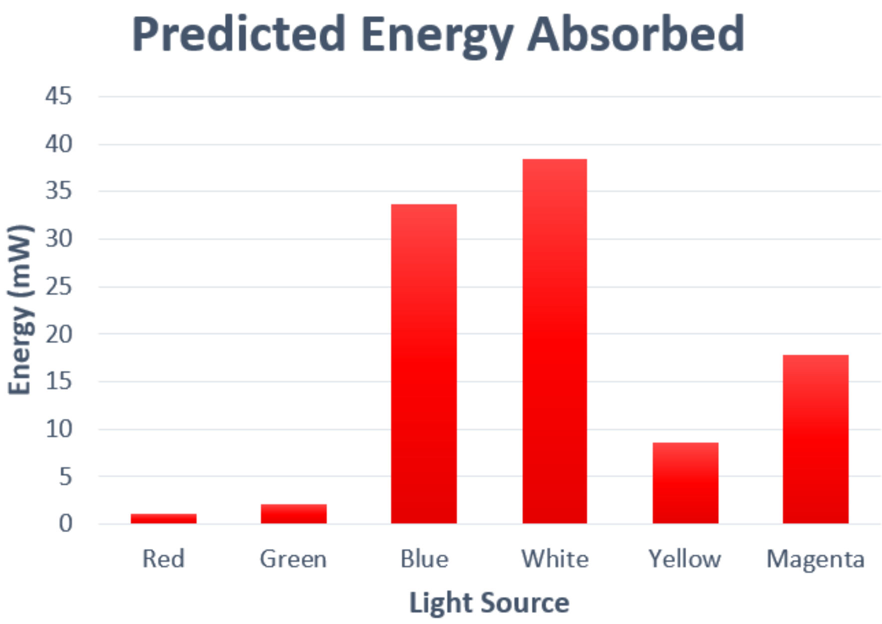

Figure 12: Predicted Energy Absorbed

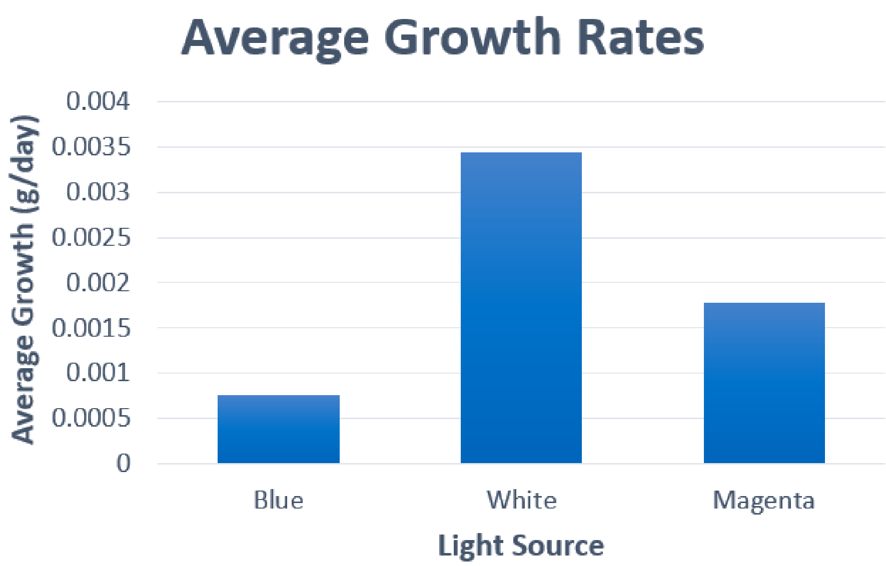

Figure 13: Average Growth

Light Source	Luminosity (cd/ft^2)	Relative Absorption
Red	3.2	0.18
Green	6.5	0.15
Blue	4.9	1

Table 1: Light Source Measurements

Light Source	Growth Rate (mg/day)	Number of Plants
Blue	0.758	1
White	3.435	5
Magenta	1.781	6

Table 2: Average Plant Growth Rates

6 Discussion and Conclusion

Based on the results, white light behaved as expected and had the highest growth rate. Blue light was supposed to have the next highest growth, but magenta was the second highest. Although the ordering does not agree, the fraction of growth experienced by the white light versus magenta light agrees with the expected fraction of energy absorbed. White light had five plants available for the growth rate calculation and magenta light had six plants available. Blue light had a lower growth rate than expected. There was only one plant used in the calculation of growth rate, which is not an accurate representation of the blue light source growth rate. None of the other light sources sustained plant life until the end of the experiement. This is believed to be because the light sources did not provide enough energy for the plants to continue prolonged periods of growth. From what we can tell, the data agrees with the proposed model, but due to the lack of germination success, summarized in Figure 14, there was not enough data to make a definite conclusion about the validity of the proposed absorption spectra. The predicted energy absorption values were meant to be compared to relative growth rates, but as shown in Figure 13, only three light sources sustained plant life until the end of the experiment. Of those three light sources, only two light sources had more than one plant to calculate the average growth rates, as indicated in Table 2.

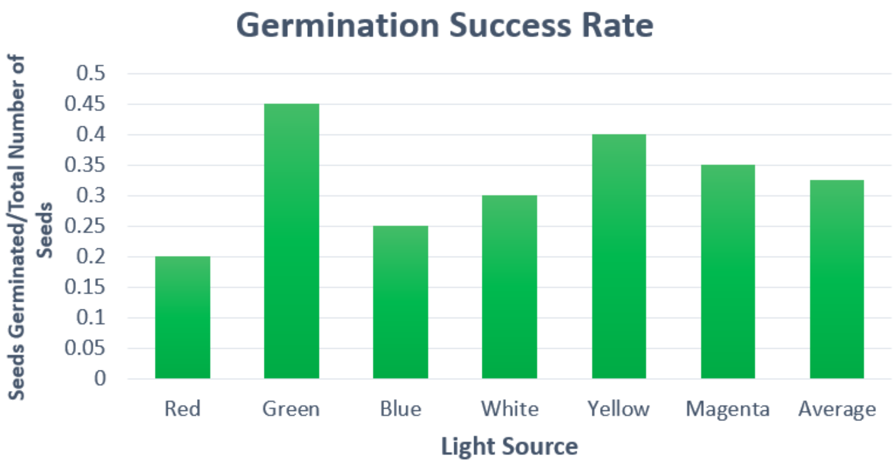

Figure 14: Germination Efficiency

To improve data collection, various aspects of this project can be improved upon. The trial run was small in scope and was not an accurate representation of the experimental plant care. After the trial was completed, the time interval between watering was changed. When the interval was changed, a second test run should have been preformed to see how the change might affect growth or germination.

Initially, plants were supposed to be weighed over time. As a result, there had the be a large interval between watering so plant weight did not include excess water found in the soil. After taking weight measurements for a few weeks, the weight was found to be decreasing. This was a result of the soil containing moisture when the plants were first potted, but drying out over time. Plant weight measurements over time was no longer deemed to be a viable way to track growth. Without the concern over excess water, the time between watering plants did not have to be as long. Ideally, the plants should have been measured and watered daily. Unfortunately, due to time availability and scheduling, this was not an option.

To increase data quality, more than 10 plants should have been grown under each light source. Even with the space constraint, at least 20 plants per light source could have been accommodated. For each pot, more seeds should have been planted to increase the likelihood of a plant growing in each pot. This, along with the shorter watering time interval, could have helped determine if the red, green, and blue plants died because lack of water or if the light source was not enough to support plant life.

In addition to improving plant care and data quality, the scope of the project could be expanded. Due to the light source used in this project, only three wavelengths could be tested. These wavelengths were random and did not highlight the different key areas of the absorption spectra. While the blue light was in a key part of the spectra, highlighting a maximum value, red and green lights both highlighted the same minimum. If another wavelength could have been tested, there is a second maximum at around 650 nm. This would have been beneficial for comparing the relative maximums. Also, it would have created a more robust analysis of the light spectrum absorption levels.

7 References

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