Whole Plant Spectral Response Models

1st Year Progress Report

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Contents

1 Introduction

Protected cultivation has developed rapidly worldwide to meet the increasing demand for fresh vegetable and horticulture crops. Greenhouses with supplementary lighting and plant factories are the most recent phases of modern protected horticulture. Artificial lighting systems can be used to improve the quality and quantity of agricultural products. The trend towards protected horticulture has several reasons such as, growing world population meanwhile declining arable lands leads to farming in smaller fields with bigger yields, increasing food demand, urbanisation problems which create overpopulated cities, food security issues, increased pesticide and chemical usage in agriculture, water scarcity, fluctuating yield over the year but meanwhile the markets demand towards all year round production[1,2]. Optimisation of LED lighting systems has great significance for modern agriculture, as supplementary lighting in greenhouses or sole light source in plant factories.

Light is the sole energy source for photosynthesis and main factor that shapes plant growth and development. For each plant and each developmental stage, light requirements varies, and this fact gives emphasis on research for light recipes to manipulate the growth of desired species and manipulation of any stage of growth to reach the target yield and quality. Development of solid state light sources gave great opportunity to experiment and optimise the light spectrum for plant growth, from effectively infinite spectrum possibilities which LEDs have enabled. Among the related literature, red, blue and compound white light are accepted as highly beneficial meanwhile green, purple, yellow and orange are secondarily contributing, UV and far red lights are beneficial even though they are outside of the photosynthetic active radiation (PAR) region which is from 400nm to 700 nm in spectrum, UV-B (280-320 nm) and UV-A (320-400 nm) are important spectral components for vegetable production[2]. Light is acting on chlorophyll for photosynthesis, also it acts on cryptochrome, phototropin and the other photoreceptors after being absorbed by photosynthetic tissue. Plant growth and development are regulated by light quality, light intensity and photoperiod.

LEDs are solid-state, narrow bandwidth lighting devices that give unique opportunity to realise light quality precise managements to obtain optimal plant responses; such as morphology, yield and nutritional quality. Determination of plant light recipes and optimisation of light sources will save energy by removing the unnecessary light spectra from horticulture lighting while increasing yield and product quality.

2 Literature Review & Background

First, some of the relevant literature and background in the field of plant response to light is reviewed. This project focuses on experiments and modelling, so its important to understand the context of LEDs in plant growth, as well as to understand what is and isn't currently known about how different plants respond to different types of light.

The field has many gaps of knowledge due to the vast number of possible setups to investigate, but there still exists a significant amount of research to help build a foundation of knowledge to build on.

2.1 Lighting and LEDs

Light is required throughout the entire life-span of a plant. Plant performance is determined primarily by three important grow light parameters, these are quantity, quality and duration, all of which effect plants in different ways [3].

- **Light Quantity (Intensity) -** This parameter mainly affects the photosynthesis of plants. The energy from the light is used to induce a photochemical reaction converting carbon dioxide into carbohydrate in the chloroplasts.
- **Light Quality (Spectral Distribution) -** This refers to the spectral distribution of radiation in terms of wavelength composition of a light. Plants respond best to red and blue light with regards to photosynthesis. Spectral distribution affects more than just linear growth of plants, it influences shape and development, as well as playing an important role in the flowering process.
- **Light Duration (Photoperiod) -** The photoperiod refers to the duration of time the light works per day. This would influence the rate of growth of the plant.

The radiation received from the sun contains a continuous spectrum of light, including all visible frequencies. However, plants only absorb discrete wavelengths according to their photochemical reaction mechanisms. The most photo-synthetically active region lies between around 400 and 700nm, which is approximately the visible spectrum [4].

Due to the flexibility of LEDs in all three of the parameters described above, particularly in their wavelength specificity, they are an extremely useful tool to study the ideal lighting for any species of plant. LEDs emit in discrete wavelengths making them much narrower than other conventional sources of lighting used for plant growth. This means that LEDs have the potential to be extremely efficient and perfectly tuned to fit their purpose, but the design process is challenging. It involves choosing a discrete combination of wavelengths which match the optimum biological response of the specific plant of interest. This is an endeavour which involves vast amounts of data required, and as worldwide research accumulates, a database of light formulae can be built by which particular light recipes resonate best with particular plants.

The specific and customisable nature of LEDs also means that plants can be grown in different ways, to produce different shapes and compositions, this is interesting since aesthetics and taste can potentially be changed by LED wavelength choice. Currently, much research exists detailing LED compositions which give the best responses from plants, typically depending on the plant type [5,6]. The fact that agriculture includes a huge number of different plants makes research complex, also each plant adopts different shapes and properties throughout its lifetime, so different light environments may be optimum at different stages of a plant's life [7,8]. This coupled with the huge number of combinations of wavelength, intesity and photoperiod etc. make the field of LED plant response research extremely complex.

LEDs are also advantageous in other ways: they are compact, energy efficient, relatively durable and don't emit much heat, allowing them to be close to the plants while remaining cool, thus reducing watering and ventilation maintenance. Many of these factors add to their overall efficiency, allowing the overall energy consumption to be reduced by up to 70% relative to traditional light sources, such as fluorescent lamps, incandescent lamps, high pressure sodium (HPS) lamps and metal halide lamps, which have low electrical efficiency in comparison, since they emit many frequencies which aren't useful for plants and they also produce waste heat[9].

A recent study reported that an HPS lamp with 150W power had a similar effect on the flowering pattern of bedding plants to a 14W LED. This considerable difference in power output and efficiency shows how beneficial adoption of an LED system can be on an economical level for greenhouse growers' energy consumption [10]. In terms of installation and initial investment costs, LED systems are comparable to HPS systems, despite HPS being more established [11]. The study also notes that the lifetime of an LED fixture is up to 50,000 hours, more than twice that of the 20,000 hour HPS lifetime.

LED systems are applicable to indoor applications. Greenhouses are an important area of application for this field, thus stating the common issues arising in greenhouse growth and their relation to LEDs is useful. Greenhouses are often dense environments with vertically or otherwise close packed

Comparison	Incandescent	HID	Fluorescent	LED
Power efficiency	5%	30%	40%	60%
Utilization of radiation	low	low	low	high
Lifetime	low	medium	medium	high
Heat productivity	high	high	low	low
Spectrum Adjustment	no	no	no	yes
Price	low	medium	medium	high

Figure 1: Comparison of different lamps in protected horticulture[16].

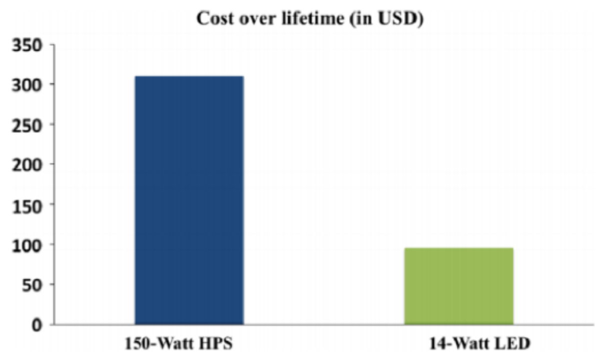

Figure 2: Lifetime cost comparison of of a 150W HPS lamp and a 14W LED[16].

plants, this means that insufficient light intensity and illumination time are common problems. Due to greenhouses often relying on natural light, seasons and weather are also an factors which can cause issues with plant growth or even crop failure[12]. Implementation of LEDs is desirable in many ways: LED systems are easy to power, can run using a DC supply, and they are energy efficient and economical. They are also sufficiently cool, such that lights can be placed closely and compactly near the plants.

LEDs are semiconductor diodes which permit current to flow in one direction only. This diode is formed by using two slightly different materials to form a PN junction. In a PN junction, the N side contains electrons, and the P side contains electron holes. When a forward voltage is applied to the PN junction, electrons move from the N side towards the P side and holes move from the P side towards the N side and combine in the depletion zone between these the PN junction. Some of these combination events radiate energy in the form of photons.

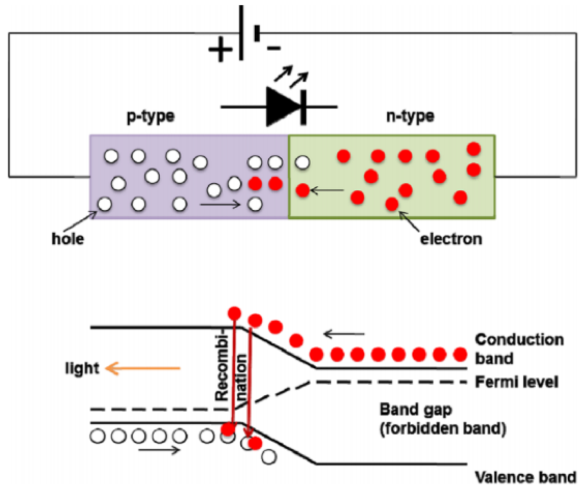

Figure 3: Schematics of light emission mechanism inside an LED chip[13]

The photon energy is approximately equal to the band gap energy (E_g). The conservation of energy from electrical to optical requires a forward voltage (V) through the LED which is equal to the band gap energy. The following equation is derived from energy conservation;

$$V = \frac{h\nu}{e} \approx \frac{E_g}{e} \tag{1}$$

There are mechanisms that cause the forward voltage to differ from the above value. For example, the diode could have series resistance causing voltage loss or energy loss due to holes. These mechanisms change the forward voltage equation of a LED. On the other hand, forward voltage has temperature dependence. The below equation shows the I-V characteristic of an ideal LED.

$$I = I_s(e^{\frac{eV-E_g}{kT}} - 1) \tag{2}$$

Where I is forward current for the LED, I_s is saturation current of LED, V is forward voltage drop of LED, k is Boltzmann constant, T is temperature, e is electron charge. Diode forward voltage is temperature dependent even if the drive current of LED is constant. Voltage drop across the diode will change. Solving the equation brings the forward voltage as a function of temperature.

In the equation below, the right side is the change of energy level with respect to temperature. As temperature increases, the energy gap of semiconductors decreases. The reason of the LED voltage change is; the recombination process becomes easier and voltage drop decreases by 2mV for each degree as the temperature rises[13].

$$V_T = \frac{kT}{e} ln\left(\frac{I}{I_s}\right) + \frac{E_g T}{e} \tag{3}$$

The graph below shows the band-gap energies and corresponding wavelengths for two major semiconductor materials used for LEDs today. InGaN (indium gallium nitride) is used for violet, blue, and green LEDs. Whereas InGaAlP (indium gallium aluminum phosphide) is used for green, yellow orange and red LEDs [13].

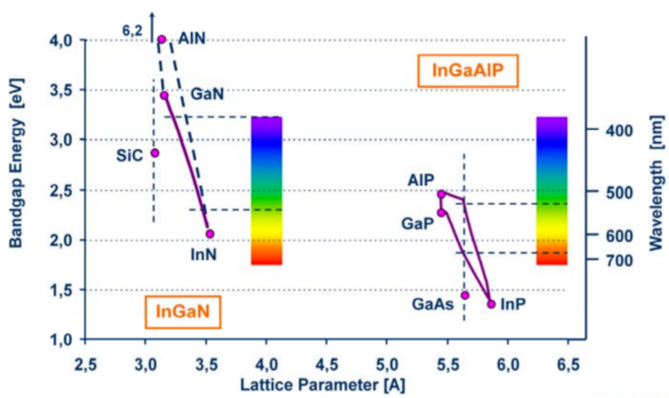

Figure 4: Band gap energies & wavelengths[14]

The wavelength of light is determined by its energy. The energy of a photon emitted by an LED is equivalent to the band gap of the semiconductor material used, which is an intrinsic feature of the semiconductor material itself. Manufacturing an LED with a designated wavelength is all about engineering the semiconductor materials and their band-gaps.

A single color, or monochromatic LED emits light in a narrow spectral band. The Spectral Power Distribution represents the radiant power emitted by a light source, as a function of its wavelength. InGaN (indium gallium nitride) and InGaAlP (indium gallium aluminum phosphide) are the two primary semiconductor materials and slight changes in the composition of these alloys changes the colour of the emitted light[13].

Aside from monochromatic LEDs, white LEDs are also used in a number of applications. One approach to generating white light utilizes the combination of RGB colours: red, green, and blue LEDs. Another approach is to use blue and yellow LED chips together in a certain ratio to produce

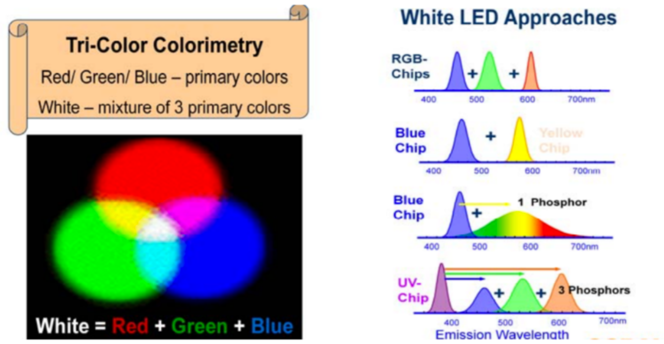

Figure 5: White LED production strategies[14]

white light. A third approach would be to use a blue chip and a yellow phosphor to generate white light. Finally, using a UV LED to excite red, green, and blue phosphors is also another approach. The most widely adopted approach to produce a white LED is to use a blue LED chip combined with a phosphor. This method is preferred due to its low cost and ease of application. The phosphor layer absorbs some of the blue light and emits light at longer wavelengths; the phosphor concentration defines how much of the blue light is converted.

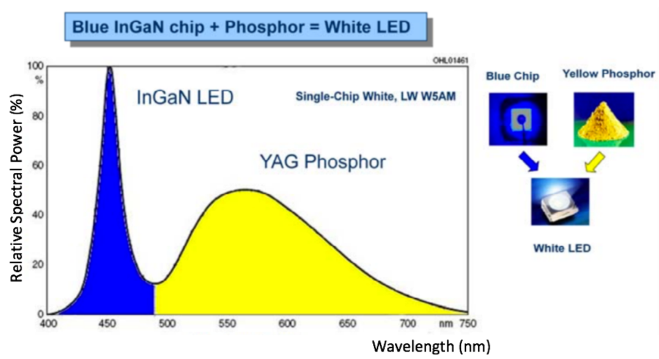

Figure 6: Spectral composition of blue LED with yellow phosphor coating[14].

Changing the phosphor content enables different colour temperatures of white light. The colour correlated temperature (CCT) for a light source gives a good indication of the lamp's general appearance, but does not give information on its' spectral power distribution. In other words, two lamps may appear to be the same white colour, but their spectral composition could be different such that a plant for example would respond very differently to them both.

As previously discussed, thermal properties and variations on an LED have significant consequences for its lumen output, electrical characteristics and also lifetime. Thus, for LEDs to function optimally, heat generated by them must be managed, being easily transferable away from the LED area, particularly the PN junctions of the LEDs must have their temperature regulated. This is done through careful consideration of the LED's assembly and operation[15].

Thermal resistance is a material's ability to resist heat flow through it, high thermal resistance means a slow transfer of heat. Thermal resistance has units of Kelvin per Watts. Thermal capacity is the second important parameter and is the ability of the material to store thermal energy. The temperature drop on a material can be calculated with respect to these two variables.

Thermal calculations are performed with the thermal model of the circuit element and used for various electronic components which dissipate heat[14]. For heat transfer, the thermal model is used to calculate the temperature value at the junction point of LED or the expected thermal resistance value for the heat-sink. The temperature difference between two points from ambient to LED junction is found by calculating the total thermal resistance between two points. LEDs dissipate some of their power as heat and some as light.

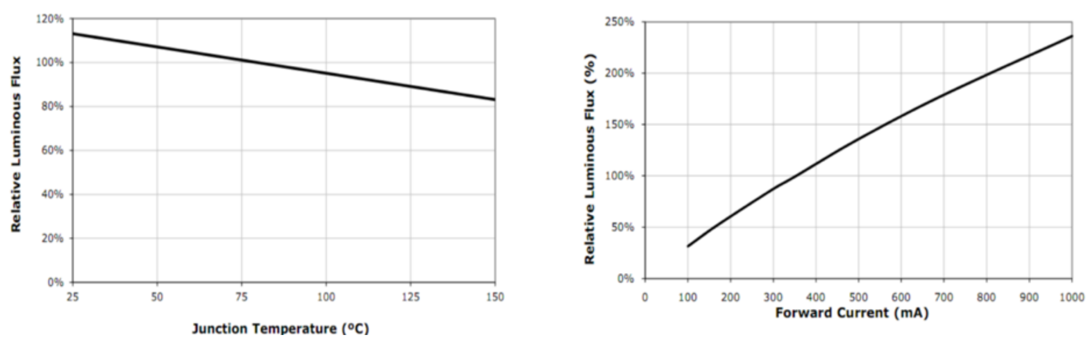

Figure 7: Junction temperature effect on luminous flux and luminous flux vs forward current[14]

An LED's lumen output is highly dependent on the current of the LEDs. As shown in the above figure, the change of 500 mA creates around 100% lumen output difference[15].

The basic drive circuit for LEDs includes linear DC drivers which involve a voltage regulator such as LM317 or an op-amp and active switch. These devices are used as current-sink or current-source circuits in order to comply with constant current output for LEDs. These drivers are preferred on the basis of ease of application and no EMI radiation. However, these devices have some limitations; LED voltage has to be smaller than the supply voltage and voltage differences between supply and

LEDs has to be low. This voltage will drop on the active device, and this device dissipates this as excess power. Linear drivers are inefficient solutions because of their operation principle. Another concern is that power dissipation radiates with heat and this can be transferred with a bulk heat-sink. If the supply voltage and led-voltage have a significant difference, the circuit cannot be applied because of heat and device size conditions. Linear power supplies have been declining in popularity for years, being replaced by Switch Mode Power Supplies (SMPS), which is superior in size and efficiency.

A DC-DC converter, also known as a switching regulator is a power converter that converts a DC energy source from one voltage level to another. Average output voltage is controlled by varying the conduction time of the switch. The DC-DC converters can be designed with regulated output voltage. For the LED drivers especially, the converters have regulated output currents. DC-DC converters are a necessity for LEDs to have regulated output and high power efficiency. Typically, first generation converters are used because of ease of application and low cost. The fundamental converters are Buck (Step-Down), Boost (Step-Up) and Buck-Boost (Step-Up and Step-Down). Transformer type and developed converters have a wide range of the output voltage and power like; Flyback, Forward, Push-Pull, Half-Bridge, Bridge and Zeta Converter. These converters have transformers and isolate the input and output circuit. Transformers add an extra property of changeable voltage gain with the ratio of transformer windings and isolation. Additionally there are more developed converters like; P/O (positive output) Luo-converter, N/O (negative output) Luo-converter, Double output Luo converter, Cuk converter, Single-ended primary inductance converter (SEPIC). These converters have more components, having less output voltage ripple than the previous converters.

LEDs have been used in horticulture studies for around 20 years, with so much still unknown despite there being a great amount of data. It is since the plant responses to wavelengths are specific, even though there some consensus about affects of some wavelengths.

Red light (600-700nm) has the highest quantum efficiency for photosynthesis, while also having many photomorphogenic effects on plant development mediated by the photoreversible pigment phytochrome, such as: enhancing leaf expansion, biomass accumulation, stem elongation and seed germination.

For blue light (400-500nm), there are also contributing effects on phototropism, stomatal aperture, leaf thickness, and chlorophyll content. Growth conditions seem very sensitive to blue light intensity when indoors more than outdoors and this is where blue lights can effect as a growth inhibitor. Also, the contribution of blue light to any wavelength mixture is a question which hasn't been answered yet, the optimum mixture of blue has been investigated in many studies and various outcomes taken, as well as it is plant specific the variations of intensity in blue light are also observed to create significant variation of responses.

Green light (500-600 nm) often is disregarded as an unimportant waveband in photosynthesis because absorption spectra of extracted leaf chlorophyll pigments indicate very weak absorption in the green region of the PAR[16]. Because chlorophyll has major absorption peaks only in the red and blue regions, researchers initially selected first red, later blue LEDs for first generation LED arrays to support plant growth. However, intact leaves do absorb considerable green light, and in a relative quantum efficiency curve for photosynthesis vs. PAR wavelengths, some wavelengths of broad band green actually are more efficient than certain wavelengths of the blue band, when leaf canopies close, red and blue light are absorbed strongly by upper or outer leaf layers, whereas green light penetrates to interior leaf layers, where it subsequently is absorbed and drives photosynthesis of the inner canopy. Thus interestingly, light sources containing a certain amount of green light can be more effective in stimulating crop growth than a red and blue mix alone. Additionally, green light is that the human eye perceives red, green and blue (RGB) combination light as white light, so if all three wavebands are present simultaneously in a plant growth lamp, to visually evaluate the stress status of crops, the incidence of physiological disorders, and true leaf color is possible, meanwhile only red and blue combination is delusive for human eye observation of plants during experiment.[16].

On the other hand, white LEDs (blue LED plus phosphor coating) have a wide spectrum and are the choice of many growers because of this quality, but it mainly lacks the red spectrum. Also, energy losses associated with the secondary broad-band photon emissions of the excited phosphor make white LEDs significantly less electrically efficient than emissions from pure monochromatic blue LEDs, additionally, the proportions of red, green, and blue wavebands in white LED obtained with phosphor coating varies widely among cool white, neutral white, and warm white LED types,that non of them are a close match for the RGB distribution of midday solar light. therefore, to make white light from monochromatic RGB LEDs than to use white ones has more electrical efficiency and precision potential[16]. The recent availability of far red (700-800 nm). Solar light contains both UVA (320-400 nm) and UVB (280-320 nm) wavelengths that plants are adapted to, so indoor agriculture scenarios providing electrical sources of solid state lighting, especially of the narrow-spectrum type, can confront with situations that plants quality or appearance is effected by lack of ultraviolet rays in the environment. There is a reluctance to introduce UVB into indoor commercial growth environments for safety reasons, but it may be possible to use UVA if certain worker precautions are taken[17].

Table 1: Effect of light wavelength on plant growth.

Optical wavelength(nm)	The influence on the growth of plants
280–315	Minimal impact on morphological and physiological process
315–400	Chlorophyll absorbs less, photoperiod effect, tissue and stem elongation
400–520	Chlorophyll and carotenoid absorption proportion is the largest, the biggest influence on photosynthesis
520–610	The pigment absorption rate is not high
610–720	Chlorophyll absorption rate is low, have significant effects on photosynthesis and light cycle effect
720–1000	Absorption rate is low, stimulate cell extended, affecting flowering and seed germination
>1000	Converted into heat

2.2 Plant Physiology

Light is a form of electromagnetic energy, conveniently thought of as a wave. Visible light represents only a small part of the electromagnetic spectrum between 400 and 740 nanometers. Photons energy carriage capacity is inversely proportional to their wavelengths, so shorter wavelength light has higher energy. The strength of the photoelectric effect depends on the wavelength of light; short wavelengths are much more effective than long ones in producing the photoelectric effect. The highest energy photons, at the short-wavelength end of the electromagnetic spectrum are gamma rays, with wavelengths of less than 1 nanometer; the lowest energy photons, with wavelengths of up to thousands of meters, are radio waves. Within the visible portion of the spectrum, violet light has the shortest wavelength and the most energetic photons, and red light has the longest wavelength and the least energetic photons.

Plants require light for photosynthesis, proper growth and physiological development. Plants are additionally sensitive to the spectral composition of their source of light, and the specific impact on plant responses of photosynthesis, photomorphogenesis and phototropism. Plant growth and development are impacted by light intensity, light quality, duration, and photoperiod [19].

When a photon interacts with a molecule, its energy is either lost as heat or absorbed by the electrons of the molecule, boosting those electrons into higher energy levels. Whether or not the

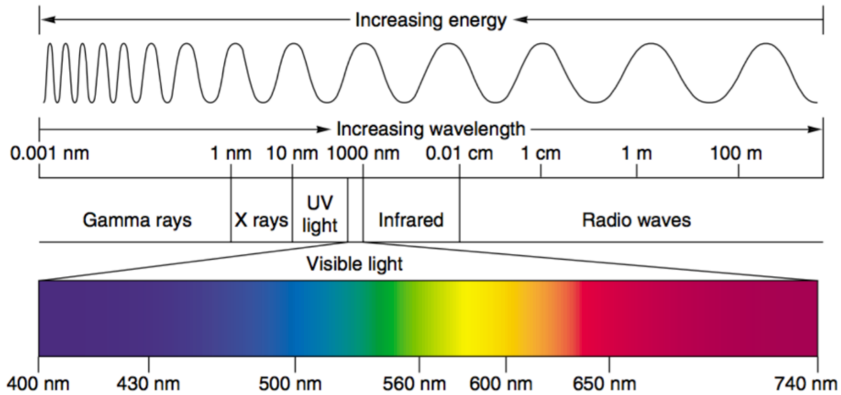

Figure 8: The electromagnetic spectrum[18].

photon's energy is absorbed depends on how much energy it carries (defined by its wavelength) and on the chemical nature of the molecule it hits. To boost an electron into a different energy level requires just the right amount of energy. A specific atom can absorb only certain photons that correspond to the atom's available electron energy levels. As a result, each molecule has a characteristic absorption spectrum, the range and efficiency of photons it is capable of absorbing. Molecules that are good absorbers of light in the visible range are called pigments. Organisms have evolved a variety of different pigments, but there are only two general types used in green plant photosynthesis: carotenoids and chlorophylls. Chlorophylls absorb photons within narrow energy ranges[19]. Two kinds of chlorophyll in plants, chlorophylls (a) and (b), preferentially absorb violet-blue and red light. Neither of these pigments absorbs photons with wavelengths between about 500 and 600 nanometers, and light of these wavelengths is, therefore, reflected by plants that we perceive as green. Chlorophyll (a) is the main photosynthetic pigment and is the only pigment that can act directly to convert light energy to chemical energy and chlorophyll (b), acting as an accessory or secondary light absorbing pigment, complements and adds to the light absorption of chlorophyll (a). Chlorophyll (b) has an absorption spectrum shifted toward the green wavelengths. Therefore, chlorophyll (b) can absorb photons chlorophyll (a) cannot. Chlorophyll (b) therefore greatly increases the proportion of the photons in sunlight that plants can harvest. An important group of accessory pigments, the carotenoids, take an action in photosynthesis at the wavelengths that are not efficiently absorbed by either chlorophyll[19].

The peaks in figure 9 represent wavelengths of sunlight that the two common forms of photosynthetic pigment, chlorophyll (a) and chlorophyll (b), strongly absorb. These pigments absorb predominately violet-blue and red light in two narrow bands of the spectrum and reflect the green light in the mid-

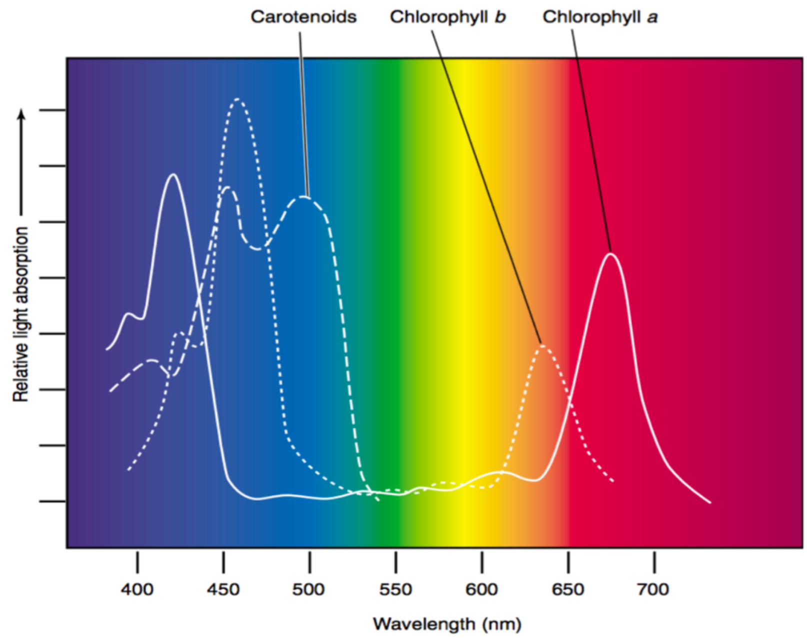

Figure 9: The absorption spectrum of chlorophyll[19].

dle of the spectrum. Carotenoids absorb mostly blue and green light and reflect orange and yellow light. In photosynthesis, photons of light are absorbed by pigments; the wavelength of light absorbed depends upon the specific pigment.

LEDs as a source of plant lighting were used more than 20 years ago when lettuce (the plant which is the focus of the preliminary tests discussed later in the report) was grown under red LEDs and blue fluorescent lamps. Several reports have confirmed successful growth of plants under LED illumination. Different spectral combinations have been used to study the effect of light on plant growth and development and it has been confirmed that plants show a high degree of physiological and morphological plasticity to changes in spectral quality. Red (610-720 nm) light is required for the development of the photosynthetic apparatus and photosynthesis, whereas blue (400-500 nm) light is also important for the synthesis of chlorophyll, chloroplast development, stomatal opening and photomorphogenesis. Several horticultural experiments with potato, radish and lettuce have shown the requirement of blue (400-500 nm) light for higher biomass and leaf area.[20] However, different wavelengths of red (660, 670, 680 and 690 nm) and blue (430, 440, 460 and 475 nm) light might have uneven effects on plants depending on plant species. Far red LED light (700- 725 nm) which is beyond the PAR has been shown to support the plant growth and photosynthesis.

Biomass yield of lettuce increased when the wavelength of red LED emitted light increased from 660 to 690 nm. Comparative study on the effect of red LED (640 nm) light with far-red LED (730 nm) on the physiology of red leaf lettuce showed that application of far-red (730 nm) with red (640 nm) caused an increase in total biomass and leaf length while anthocyanin and antioxidant potential was suppressed[21].LED (640 nm) light as a sole source and results showed increase in anthocyanin contents in red leaf cabbage. Addition of far-red (735 nm) to the red (660 nm) LED light on sweet pepper resulted in taller plants with higher stem biomass than red LEDs alone[22].

Positive effects of blue (400-500 nm) LED light in combination with red LED light on green vegetable growth and nutritional value have been shown in several experiments. LEDs (440 and 476 nm) used in combination with red LEDs caused higher chlorophyll ratio in Chinese cabbage plants. These cabbages can complete their life cycle under red LEDs alone, but larger plants (higher shoot dry matter) and greater amounts of seed are produced in the presence of red LEDs supplemented with a quantity of blue light. Similar experiments have shown increased nutritional value and enhanced antioxidant status in green vegetables: increased carotenoid, vitamin C, anthocyanin and polyphenol[23]. Several reports have shown that plant response (growth, flowering time and secondary metabolite) to light quality is species specific. Green light also contributes to the plant growth several experiments. Green LEDs with high photosynthetic photon flux are most effective to enhance the growth of lettuce. Green (505 and 530 nm) LED light in combination with HPS lamps contributed to the better growth of cucumber. The effect of green (525 nm) LED light on germination of Arabidopsis seedlings and results showed that seedlings grown under green, red and blue LED light are longer than those grown under red (630 nm) and blue (470 nm) alone. Supplementation of green light enhanced lettuce growth under red and blue LED illumination. Green light alone is not enough to support the growth of plants because it is least absorbed by the plant but when used in combination with red, blue, and far-red, green light will certainly show some important physiological effects.

Photomorphogenic effects are mainly influenced by Phytochromes. Phytochromes pr (red) and pfr (far red) mainly influence the germination, plant growth, leaf building and flowering. The phytomorphogenic effects are controlled by applying a spectrum with a certain mix of 660nm and 730nm in order to stimulate the pr and pfr phytochromes. One influence of far red light on a plant is the active shade escape reaction. If the plant is illuminated mainly with 660nm it feels like its illuminated in the direct sun and growth normally. If the plant is illuminated mainly with 730nm it feels like growing in the shadow of another plant that shades the sun light. Therefore, the plant is reacting with an increased length growth to escape the shadow. This leads to taller plants but not necessarily impacting the cumulated bio mass.Pr and Pfr convert back and forth. Pr is converted into Pfr under red light illumination and Pfr into Pr with far-red light. The active form which triggers flowering is Pfr[24]. Pr is produced naturally in the plant. The ratio of Pr to Pfr is in equilibrium when the plant receives light (day) because Pr is converted into Pfr by red light and Pfr is converted back to Pr by far-red light. Back conversion of Pfr is however also possible in a dark reaction, so it is the night (dark) period which mainly affects the ratio of Pr to Pfr and controls the flowering time in plants. Ornamental plants are of high economic importance, therefore manipulating this mechanism with LEDs would contribute positively to this sector.

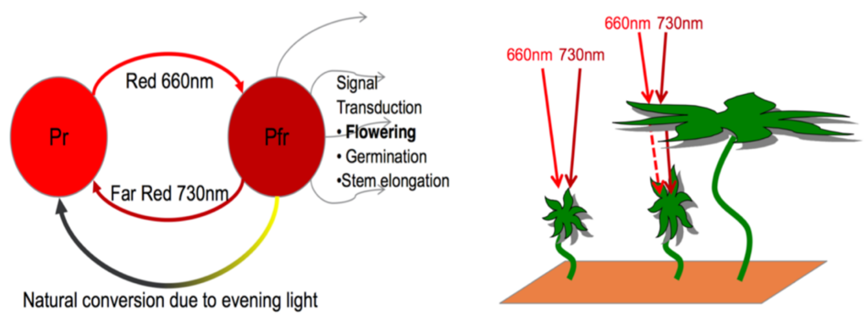

Figure 10: Pr-Pfr cycle and shade avoidance[24]

LEDs are optimal tools for studies on spectral plant responses as well as having great market potential for the same reason; tailored plant recipes with less consumption of electricity than traditional sources. From 1990 there has been significant research on spectral responses of plants to LED light, especially NASA's Kennedy Space Center and Purdue University, who have made great contributions to LED lighting technology [25,26]. Rapid development of LED technology from the 2000s has led LED spectral possibilities to expand more and more to particular wavelengths, through these developments, topics on light responses to light spectral quality by plant biology and physiology began to be more deeply investigated.

Initial researchers on LEDs mainly investigated them as sole source or as greenhouse supplemental lighting. Circa in 1990s researched photosynthetically active radiation and biological/physiological effects of blue and red light wavelengths and red and blue light combinations for lettuce [26], strawberry [27] pepper [28], wheat [29] and rice [30]. In one of the studies on wheat it is stated that the plant can complete the whole life cycle under only red LEDs [31], however in the case of bigger plants and more seeds produced under red light when it has some blue LED addition. Another study indicated thats rice plants have higher photosynthetic rate when under combination of red and blue lights than for solely red LEDs[32]. A report [33] summarised the studies made previously with blue LEDs and reported that yield of lettuce, spinach, and radish crops grown under only red LEDs are less than the ones had additional blue LEDs, with same total photosynthetic photon flux (PPF) emitted from light sources. a study on peppers, that includes different colour combinations of LEDs' effect on leaf thickness and chlorophyll content of leaves, indicated that the blue LEDs combined with red LEDs are inducing more chloroplast in leaf cells than red and far red combinations [34], again lamps were having same PPF values. Many horticultural studies showed with the trials of sole red, sole blue and white and red and the blue combinations tried on various crops and best results in yield and quality taken n the experiments done with combination of red and blue LEDs, like; lettuce [35] spinach [36], strawberry [37]. Earlier experiments gave emphasis to ratios of blue and red LEDs, especially what is the optimum percentage of blue LEDs addition to red ones gives the best results in yield and quality of crop, as well as the red/ far red ratios' effects on plant, as conclusion, like white light, red and blue lights also necessary for yield and crop quality, the effectiveness increases when they used together. Other light spectrum also studied; green LEDs' addition to red and blue mix by 24% is contributed the lettuce growth, green light being better at penetrating to the plant canopy and has potential to increase plant photosynthesis and plant growth [38]. Likewise, other light wavelengths like yellow, orange, purple, cyan etc can have potential for horticultural crops to some extent under certain circumstances [39,40]. Another research indicated that plants under red&blue and red&blue&green LEDs were considerably stronger and shorter, whereas plants treated with green, yellow and red light were weaker and higher compared with the white light.

Additionally there are many studies which investigate the potential of using supplemental selected UV irradiation [41,42]. UV radiation can be regarded as a stress factor which is capable of significantly affecting plant growth characteristics. Generally, plant height, leaf area, leaf length have been showed to decrease, whereas leaf thickness was increased in response to UVB radiation [43].

3 Research Aims and Methodology

The overall aim of this research is to understand how plants respond to light. This is researched by both experimental and software/modelling based methods. Experiments can be designed with various mixtures of light and setup arrangements to be tested on different plants of interest, both in horticulture and agriculture.

In terms of experiment, data obtained can give information about which conditions, in terms of light intensity and frequency, temperature, exposure time etc give the most desirable plant growth results, regarding not only size and speed of growth simply, but other aspects such as aesthetic appeal (for ornamentals) or taste quality (for crops).

From a modelling perspective, software along with mathematical models can be used to simulate lighting arrangements and help elucidate the setups which best favour plant growth. For example, this can involve testing reflector systems to maximise light utilisation on the plant.

With understanding of how plants respond to light, obtained from modelling and experiment, sophisticated lighting systems can be designed to optimise plant growth and also maximise energy and space efficiency for growing.

	Percentage of Chips						Chip numbers			
TREATMENTS	UV	Blue	Green (or white)	Red	Total	Total chip number	UV	B	Green (or white)	Red
1	0	33.333	33.333	33.333	99.999	24	0	8	8	8
2	0	50	50	0	100	24	0	12	12	0
3	0	50	0	50	100	24	0	12	0	12
4	0	100	0	0	100	24	0	24	0	0
5	0	0	50	50	100	24	0	0	12	12
6	0	0	100	0	100	24	0	0	24	0
7	0	0	0	100	100	24	0	0	0	24
8	0	0	0	0	0	24	0	0	0	0
9	25	25	25	25	100	24	6	6	6	6
10	33.333	33.333	33.333	0	99.999	24	8	8	8	0
11	33.333	33.333	0	33.333	99.999	24	8	8	0	8
12	50	50	0	0	100	24	12	12	0	0
13	33.333	0	33.333	33.333	99.999	24	8	0	8	8
14	50	0	50	0	100	24	12	0	12	0
15	50	0	0	50	100	24	12	0	0	12
16	100	0	0	0	100	24	24	0	0	0

Figure 11: Systematic test plan for LED boards.

In order to work towards these broad aims, a preliminary simplified experiment was designed to verify setup and methodology, whilst also becoming familiar with relevant techniques, processes and measurements necessary for larger future tests.

3.1 Preliminary Tests

In order to implement the planned systematic tests, a preliminary set of tests are prepared. This includes some of the treatments from the systematic test plan outlined in figure 11. These are red (660nm), blue (440nm), green (525nm), green & red, blue & red and warm white (2600-3200K). The initial idea was to purchase high brightness SMD LEDs for higher W/m^2 values and fewer components, as well as the fact that the LEDs from reputable companies have the ray-files for the TracePro software which can be very useful for precise modelling of the light source. However, to use LEDs with bigger package is more manageable if a problem occurs, since it is easier to repair the circuit if necessary, thus it was decided as more convenient approach for preliminary tests. A linear constant current circuit and LED board designed with Altium Designer program, printed and hand soldered all components included LEDs.

3.1.1 LED Product Selection

LEDs in the selected wavelengths of Bridgelux company were chosen for preliminary tests, especially since they have appropriate size for hand soldering and they are easily fixable if a problem occurs while running the experiments. The main systematic tests that are implemented include boards with 24 chips, since it allows one to make varied ratios of selected wavelengths. For circuit design, 1W chips selected. LEDs have uniform distribution of light with a 120° viewing angle and each LED having a forward current of 350mA except red LEDs which have 400mA. Maximum junction temperature is 115°C. Heat tests for junction temperature are conducted and circuits supplied with minimum necessary voltage values. Figure 13 below demonstrates the introduction of the selected LEDs to Trace Pro software for modelling the light distribution, to simulate light on and around the tray of lettuces to see the level of light which is wasted, to then calculate the best setup. On the other hand, since the trays were having small area the change of irradiation between center and the corners of tray observed was very low in some cases and in some cases varied considerably, see figures 18-23.

Figure 12: Bridgelux LEDs chosen for preliminary tests (left) and Osram's more compact LED design (right).

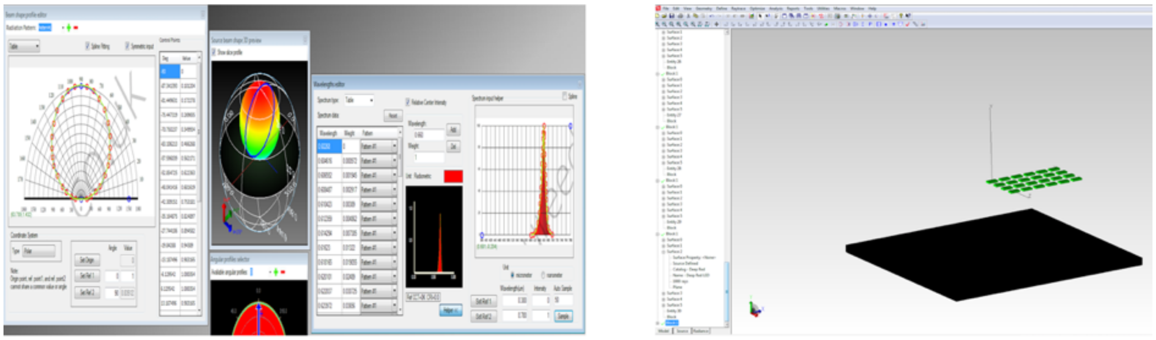

Figure 13: Introduction of angle radiation pattern and relative spectral distribution of selected LED to Trace Pro software

3.1.2 Board Designing, Building and Heat Testing

Different board geometries and combinations were designed using Altium Designer, these can be seen in figure 12. Due to the test plant trays being rectangular, rectangle shaped boards were used for circuit printing. The circuit board was planned to be both simple and robust. LED chips and constant current circuit was designed on the same board different sides for ease of connection. Each board consist of series connection of 6 LEDs per branch and 4 branches per board, with a constant current circuit with LM317t chosen as is a robust solution for such low current values rather than sensor control.

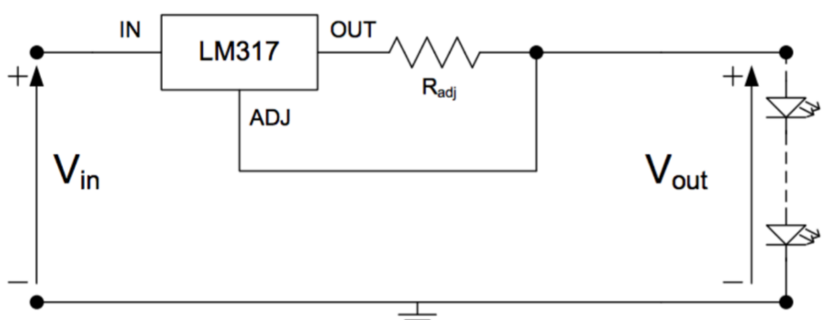

Figure 14: Constant current circuit that implemented 4 channel per board.

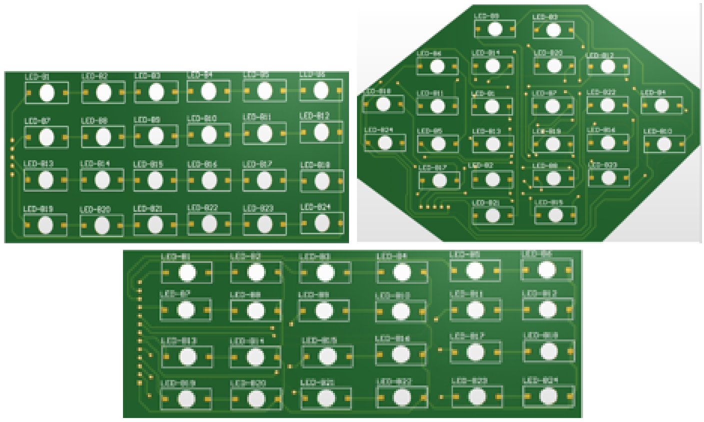

Figure 15: LED board circuit designs.The top left side shows the design used for the preliminary tests. The top right shows alternative geometry, more suitable for a single plant or axisymmetric trays for example. The bottom side shows a design with more channels,increasing capability to customise colour combinations (up to 12).

Once all boards were assembled and soldered, the circuits were tested without plants in a closed tent environment and the temperature measured to make sure overheating isn't a problem, for components and for the plants. LEDs are having 115°C max junction temperature threshold and is 125°C for LM317t. Maximum growing temperature for the selected plant was defined as 25 °C and multiple heat tests were made to reassure the safety of grow tents while the experiment is running. As a result of these tests, use of a cooling fan was found necessary, even if the supply voltages for circuits were just at necessary values. For cooling, 3600rpm 12V 0.41A brushless DC fan was found to be sufficient for cooling of 1 tent. The tents already had 2 holes for ventilation, so a fan was placed over the bottom hole and the setup was arranged such that airflow wasn't blocked, see figure 17. This was achieved by building a middle tent barrier which had gaps at the side to allow air through, but was sufficiently large so as to not allow interference between tent compartments, the barrier was also covered with reflective material to maximise internal light reflection on to the plants.

3.1.3 Experimental Setup

After LED boards with aforementioned wavelengths were designed, built and implemented with a suitable cooling solution found, the experimental setup to allow 6 LED boards to run simultaneously

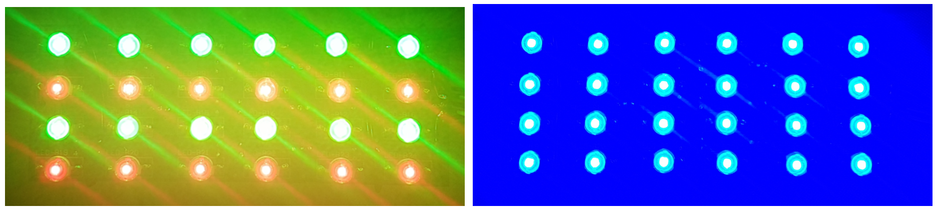

Figure 16: Two of the working LED boards: red & green (left), and blue (right).

was set up. Each tent divided to two compartments by reflective surfaces, the inside of the tents are also reflective and outside is opaque, thus for each compartment, interference is minimised while internal reflection is maximised. For the power, one power supply with rating 30V/10A is used to feed all branches with 350mA - all LED channels apart from the red LED channels which require 400mA or forward current and feed from another power supply separately.

Temperature probes were put into tents during the experiment to be regularly checked, observed maximum temperature was 24°C and average was 22°C. The power supplies connected to the mains via a timer which remained on for 16 hours and off for 8 hours. For optimal plant lighting, lights were on 16 hours per day to emulate summer daylight hours, from 6am until 10pm along the 21 day experiment.

Lettuce was chosen as the first crop to test growth on, due to it being one of the easier and more reliable plants to grow. In each tray 12 lettuce seeds were sowed, to ensure the lights' effect on multiple plants also to eliminate the fact each batch of seeds has variation of quality and some of them statistically wont germinate. Eight trays of little gem lettuce seeds (Lactuca sativa) were sowed and left in the heated greenhouse until germination time. After germination, which took approximately seven days in the heated greenhouse, 7 of the trays were collected to be experimented under prepared light test rigs and one left in dark, but with same warmth and water as the trays under lights. This was to observe how long the plants will sustain without any light and one of them left in heated greenhouse as reference to the LED experiment to compare the results.

Once the equipment was in place, rectangular trays were placed below the LED board parallel to its orientation. Spectrometer and luxmeter were then used to determine light intensity in terms of absolute irradiance unit and photometric unit of light intensity created according to human eye perception which is lux. Table 1 shows the results for lux for each tray. Spectrometer measurements made from middle of the tray on top of canopy levels, and 4 corner of the tray to observe the intensity variation with the center of tray, if there is. Below graphs created from spectrometer data from middle of the tray and 4 corners of the tray.

Table 2: Lux values for LED boards at the separation distance of the trays, describing apparent light intensity.

Board Colour	Lux Value
Red	2520
Green	2670
Blue	7930
Red & Blue	4480
Red & Green	2820
White	4860

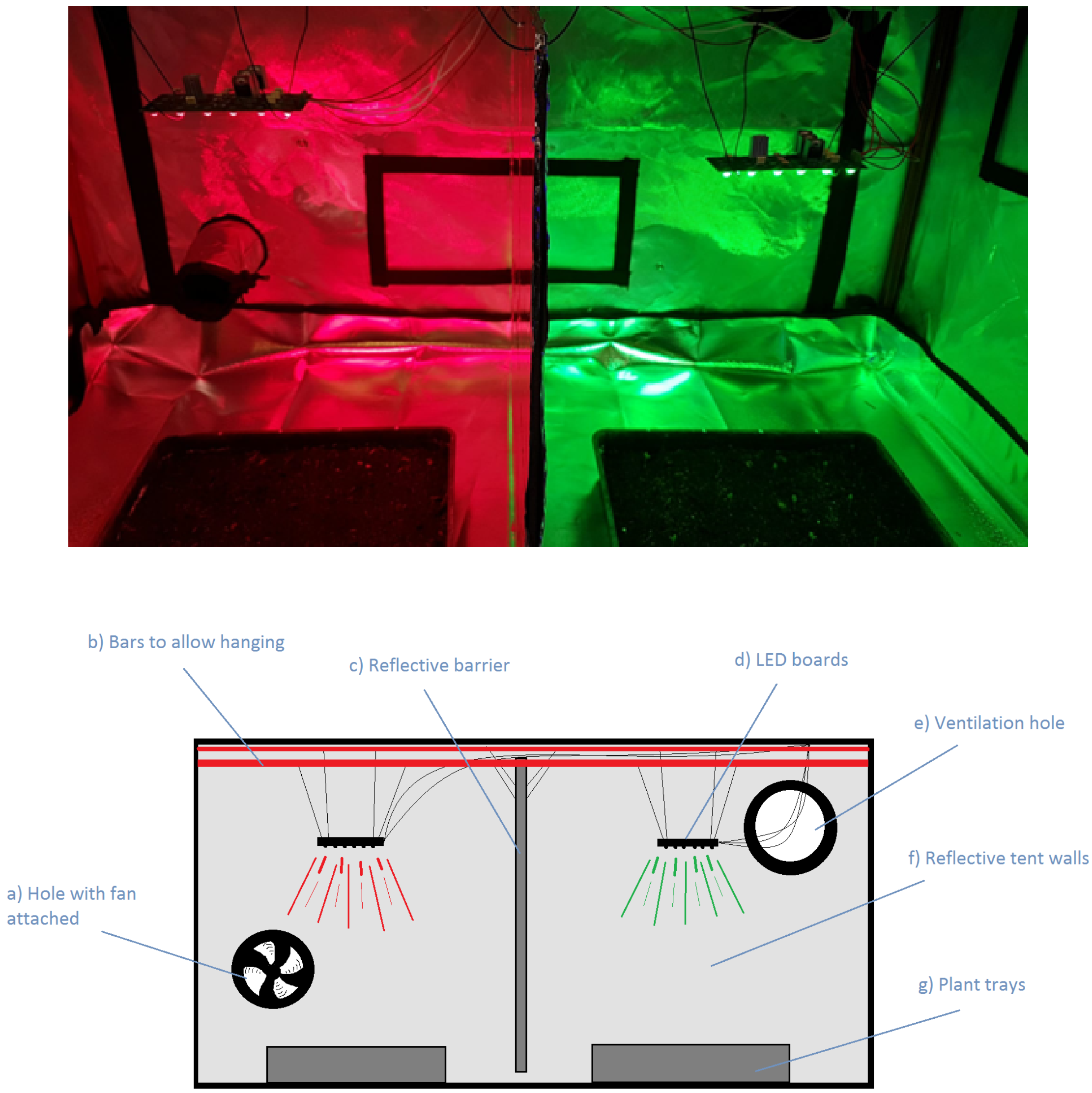

Figure 17: Setup of the preliminary tests. The top figure shows a photograph of the tent functioning. The bottom figure shows a schematic drawing of the setup, labelling the important parts. Note, the dimensions of the tent are 70cm x 70cm x 140cm, where the 140cm length is divided into two compartments, thus the compartments are cubic.

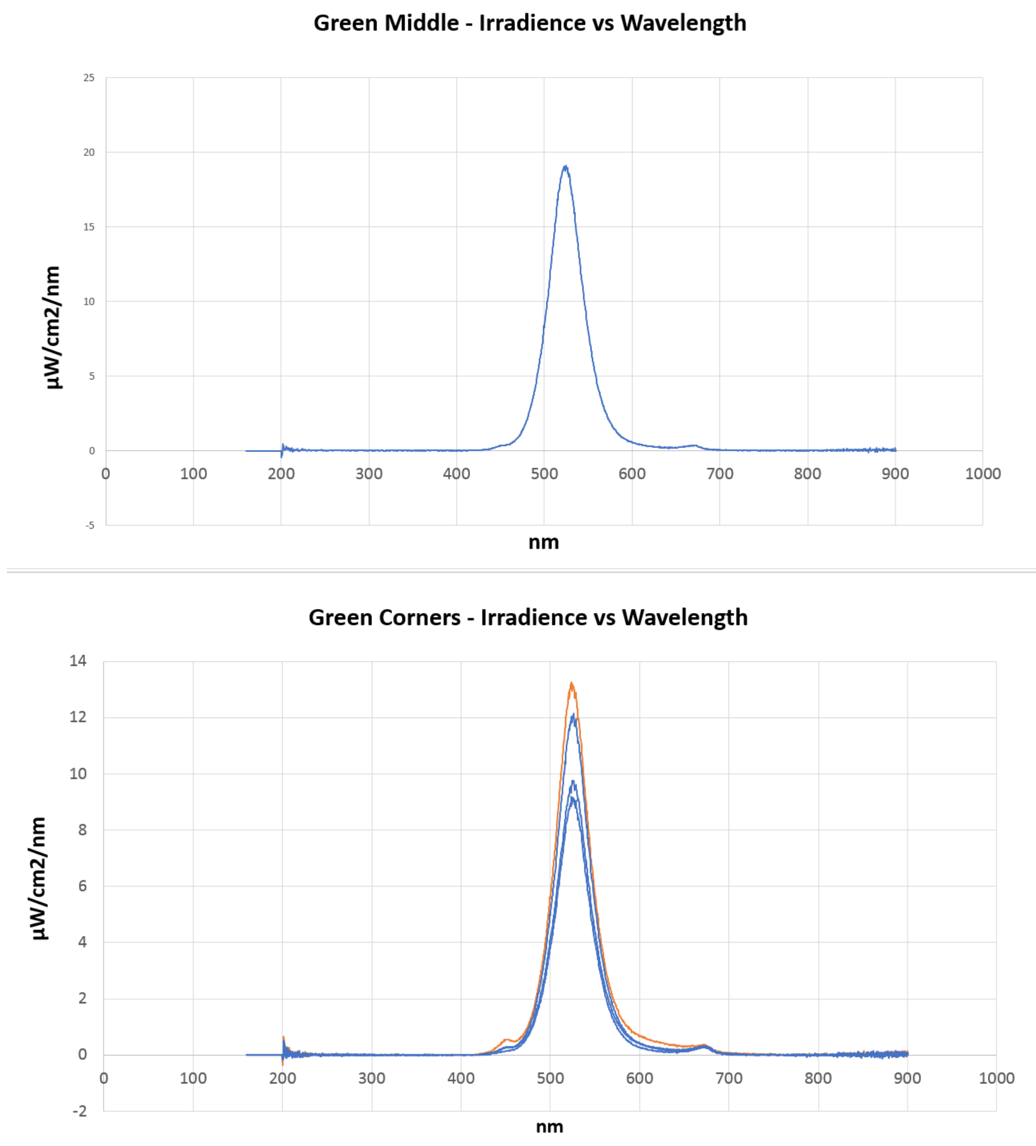

Figure 18: Green board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

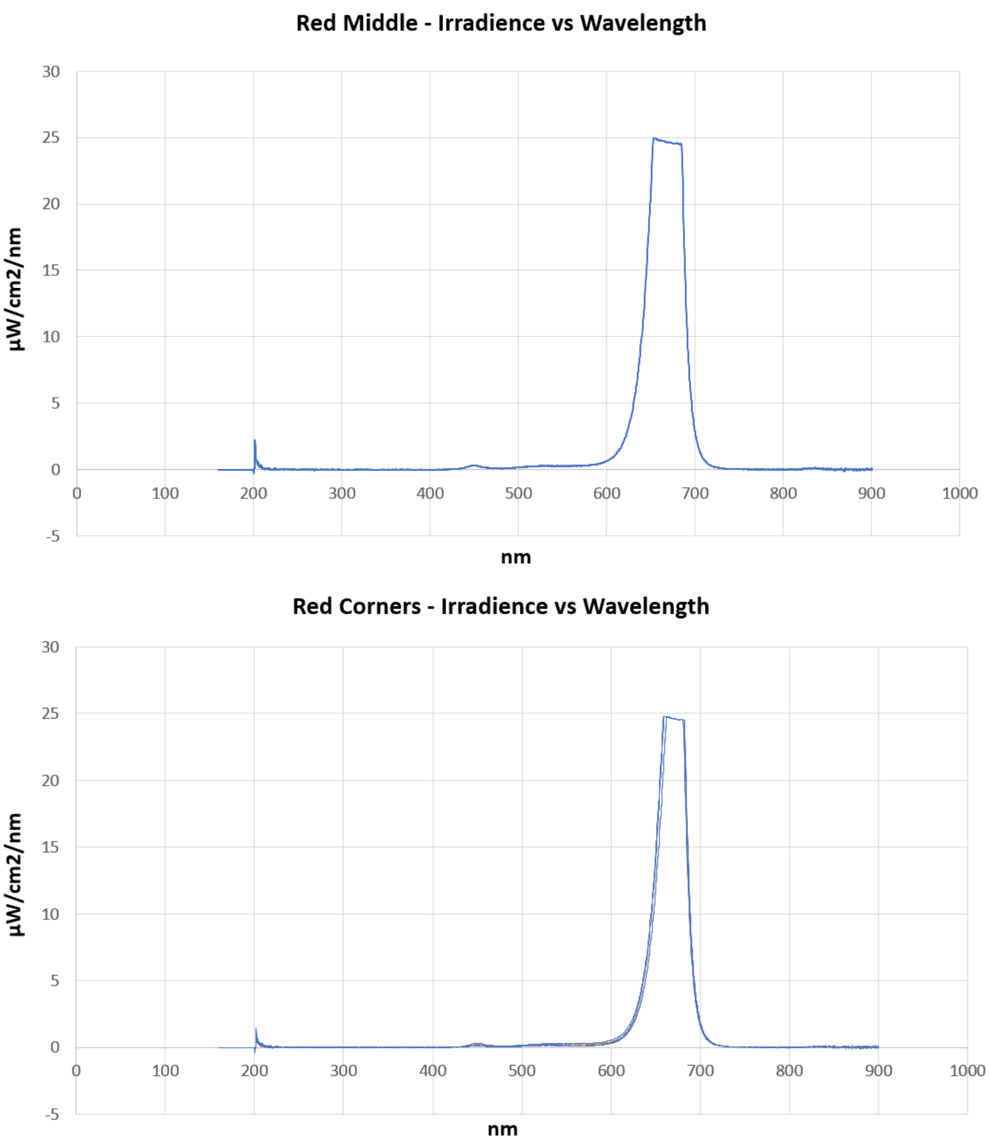

Figure 19: Red board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

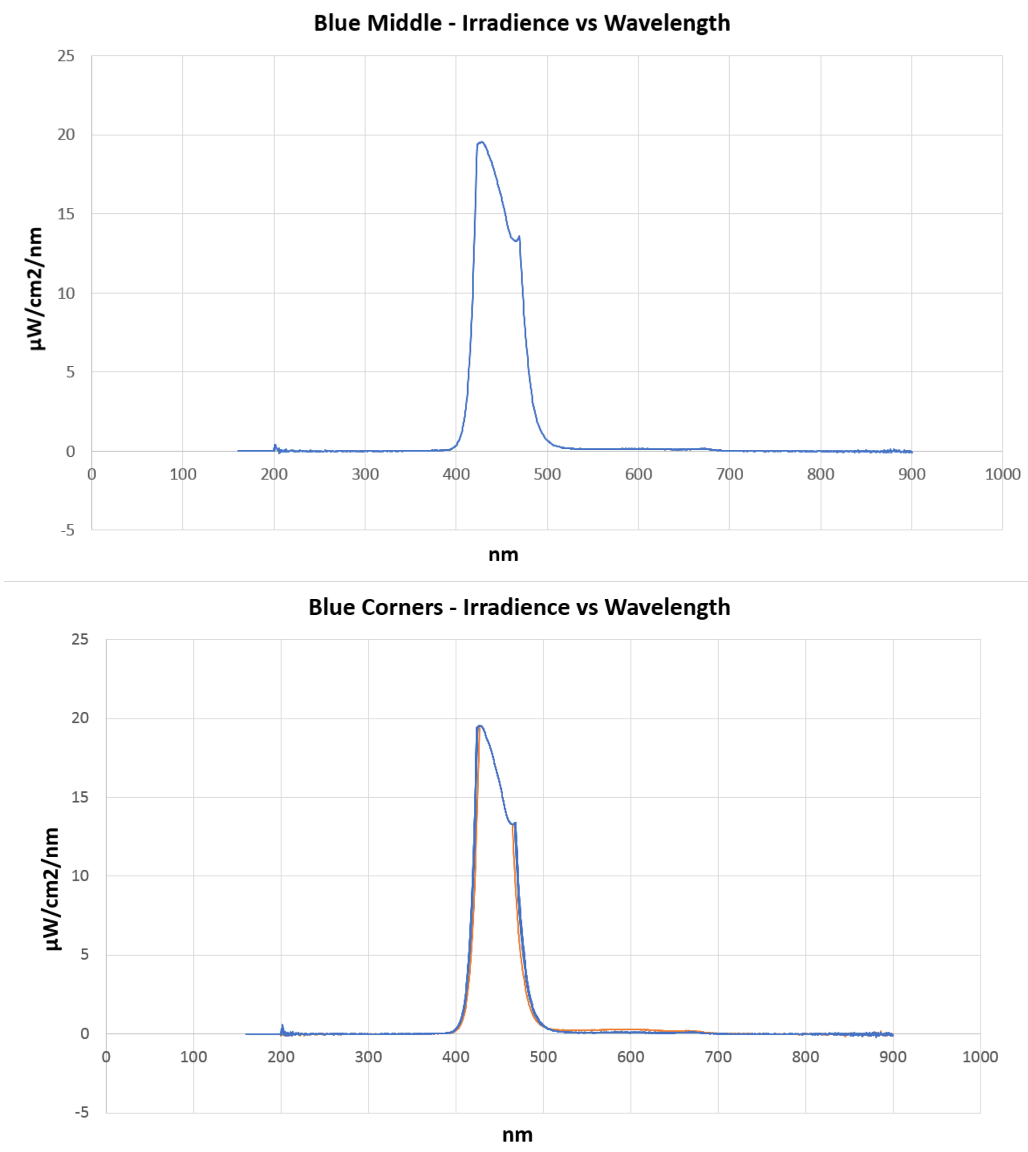

Figure 20: Blue board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

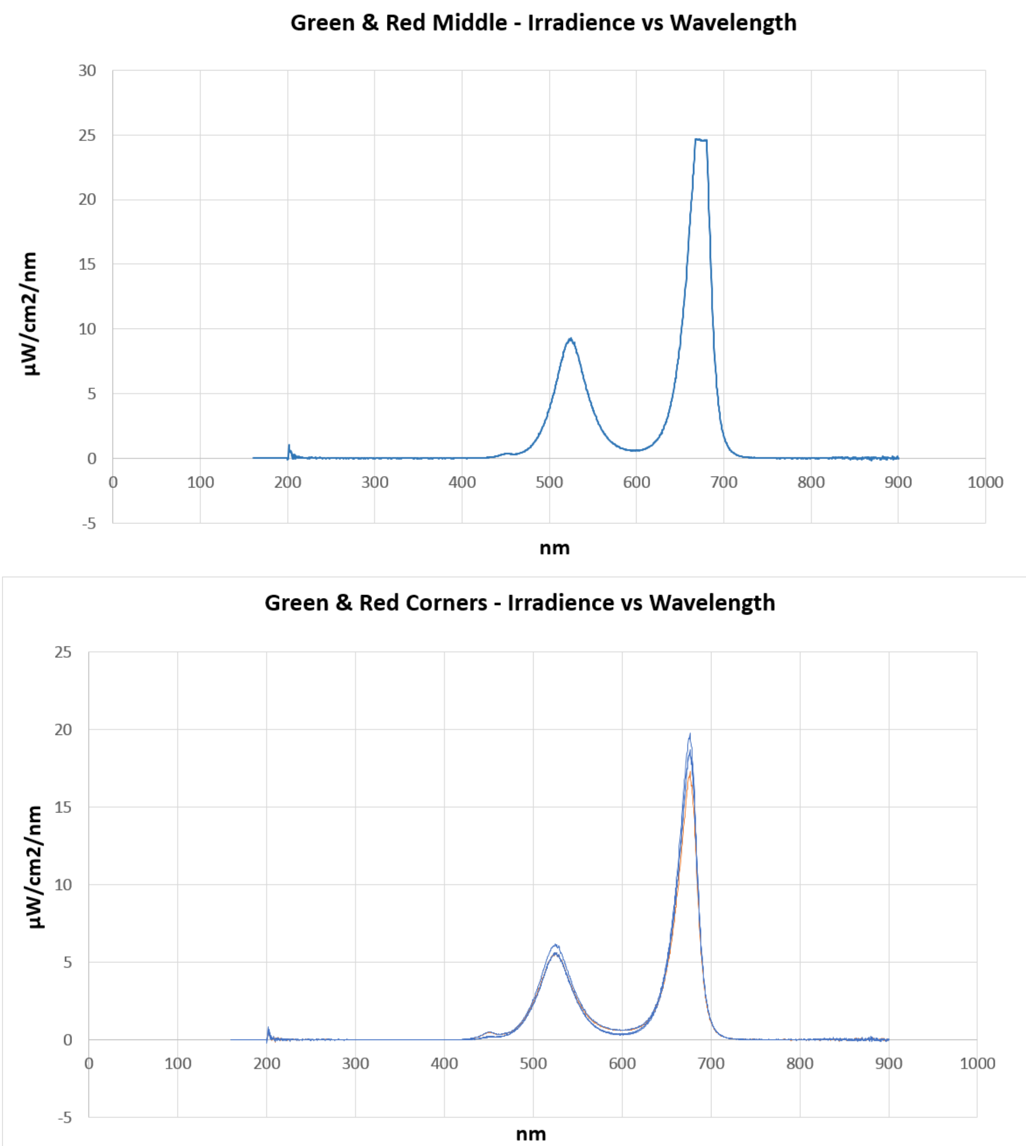

Figure 21: Green & red board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

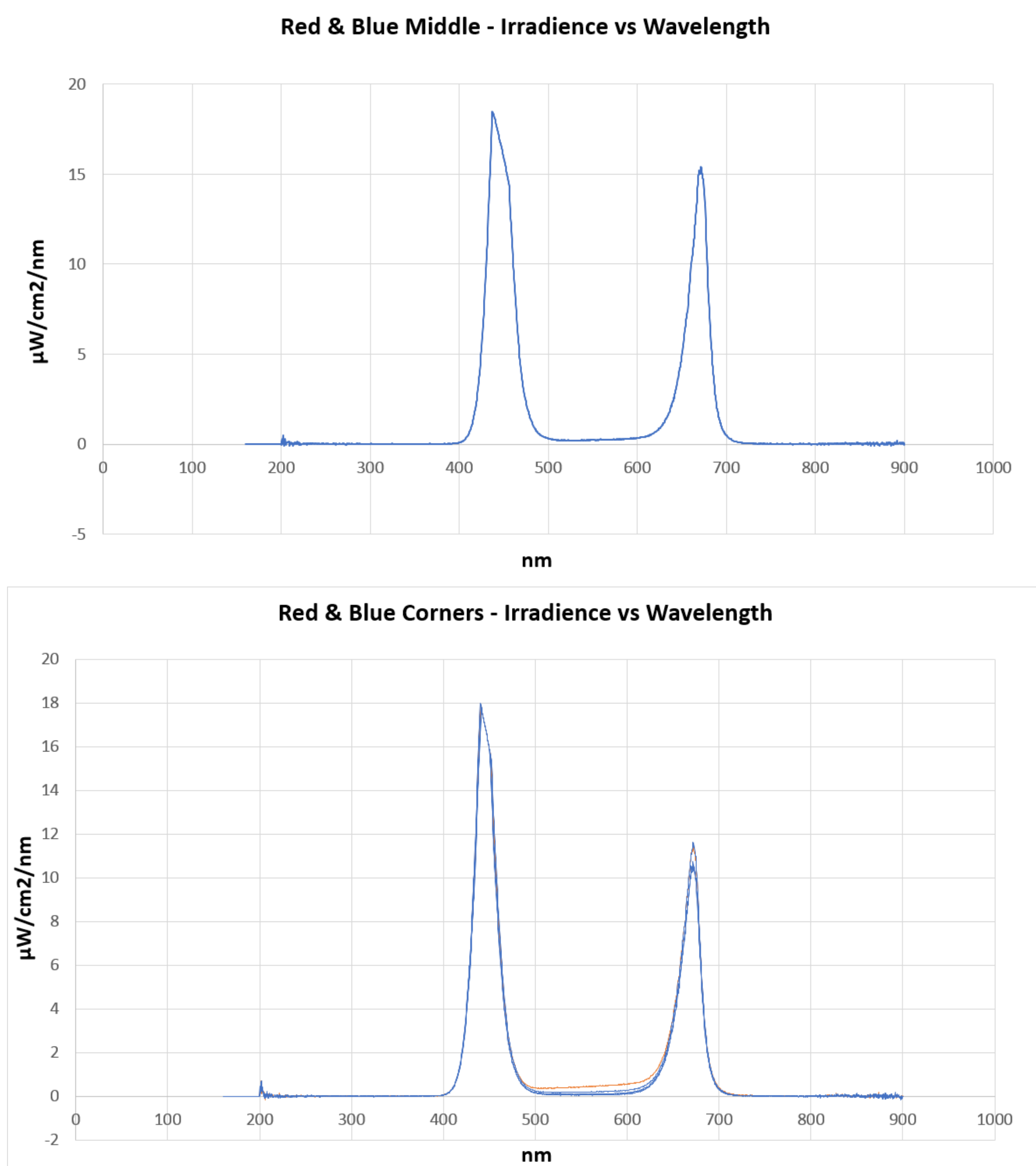

Figure 22: Red & blue board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

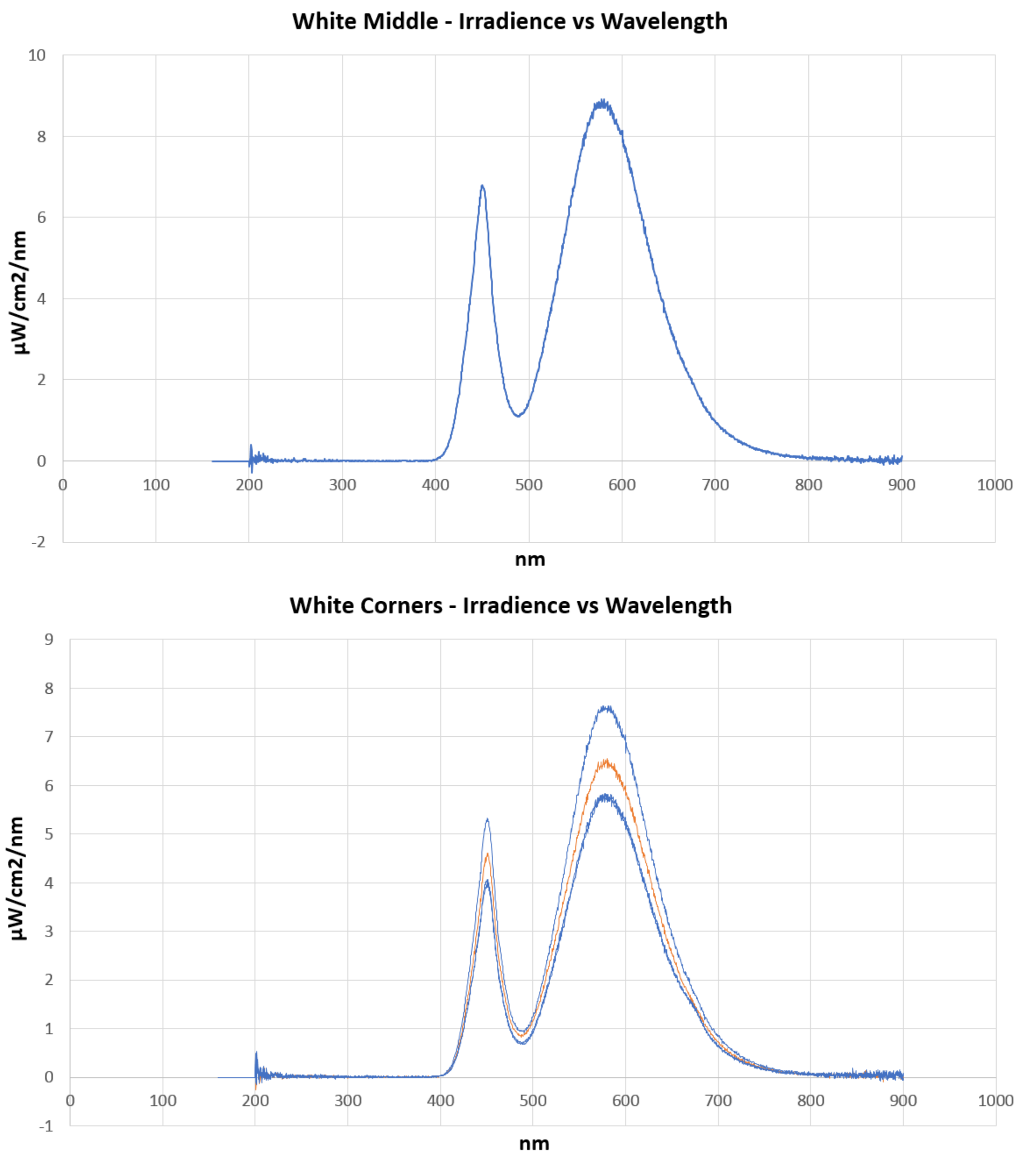

Figure 23: Green & red board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

Table 2 shows the lux values for the different LED boards, measured at the position of the centre of the trays. All values give over 2500 lux which suggests that none of the trays were too far from the lights to be disadvantaged by dimness.

From the irradience plots, mixed behaviour is observed; for some boards there are clear differences between peaks, such as for the green, red & blue, green & red, and white lights, where irradience peaks are clearly lower at the corners than in the centre, as one would expect. In most cases there are also differences in the peaks between corners, which one may also expect from an imperfect experimental setup, where some corners are closer to the light source than others.

The confusing element of these results lies within the cases which don't show a notable difference between the corners and the centres, i.e. in the cases of red and blue. The cause of this isn't yet apparent, but may be due to problems regarding the equipment or software by which it works.

These measurements and results are recent, thus there is not yet a confident explanation of why this behaviour is observed. Further experiments and/or thoughtful investigation may however reveal the answer.

However, despite there being confusing behaviour of results, the general trend shows that there is a non-negligible difference in irradiance between the centre and corners of plant trays, thus future tests and modelling endeavors should aim to acknowledge and accommodate for this difference.

3.1.4 Methodology and Measurement

The light treatments consist of LED boards of 24W with various wavelengths, running from 6 am to 10 pm to emulate summer daylight on little gem lettuces. The tent's inside temperature was controlled, between 20°C- 24°C while outside the tent is set at 20°C. Watering the lettuces was a process which was learned by observation, the volume and periodicity of watering was perfected after around 3 days of trial and error. This was mainly due to the tent conditions being much dryer than greenhouse, as soil is dried by the fans and the intense light for 16 hours per day dries the soil faster than winter sunlight. After 3 days, 150 ml per day was given and the watering process done after 10pm when lights had closed, this watering process was then continually conducted until the end of the experiment.

At the end of the 21 day grow, following properties of each tray were measured; fresh weight,dry weight, leaf area, leaf number,leaf height and width, apex length. These measurements were indicated in the literature as suggested assessments for plant growth and quality/harvestability of crops, as well as some other tests done with special measurement devices, such as chlorophyll content measurement and color measurement (for accurate results).

4 Preliminary Tests - Results and Discussion

4.1 Lettuce Growth

At the end of 21st day, the experiment time finished. From the lettuces that were initially planted, the tray under no light died within 1 week, while all of the trays under light show growth in different characteristics, as can be seen in below figure 24. The lettuce tray left in the heated glasshouse (approx 15°C) as a reference showed very slow development by the end of 21 days, this shows the effect of the winter short daylight hours as well as temperature sensitivity of little gem lettuces.

In figure 25, the weights of all the crops are displayed, these represent the weights of the plant

Table 3: Weight of crops before and after drying, to show water retention.

Board Colour	Weight	Dry Weight	**Fractional Loss**
Red	7.19	0.4	**0.94**
Green	0.72	0.14	**0.81**
Blue	8.00	0.6	**0.93**
Red & Blue	12.70	0.8	**0.94**
Red & Green	3.85	0.26	**0.93**
White	3.68	0.28	**0.92**
Greenhouse	0.57	0.18	**0.68**

cut from the root immediately after being cut. It is interesting to note the variety of weights both within one tray and across the experiment.

From table 3, results are shown measuring the weight of the crops both immediately after cutting from trays and then after 12 hours of drying at 80 degrees. Most of the trays under LED lighting boards show a fractional weight loss of 0.92 - 0.94, apart from green which had a fractional loss of only 0.81. This could be possibly due to the fact that, as discussed earlier, red and blue frequencies of light are more related to the photosynthesis process. Green is the only LED board without any element of red or blue, as can be seen from figure 18. Also, for the very low fractional loss of the greenhouse tray, the conditions were very much colder and light intake levels much lower, thus the level of photosynthesis possible is also greatly inhibited.

As figure 24 below shows the lettuces' physiology varied greatly between trays after 21 days. Starting from top left, the lettuces fed with red and blue (50%-50%) light mix gave the most healthy and compact result with big dark green leaves that have close length and width values, plants has small apex length but strong and show no bending unlike all other lettuces. This tray gave the biggest yield.

The next picture shows 2nd best results, from 100% blue light. The plants seem compact and having large and dark green leaves, apex length is small but not as strong as for the red+blue and has small bending. Leaves have close length and width so has a compact look.

On the other hand the lettuces grown under red light (100%) have the opposite growth pattern, with excess elongation at branches and very stretched leaves with poor length/width ratio of the leaves make the plant grow horizontally without the ability to hold their own weight and tangle with each other. However, as yield this tray was the 3rd biggest among them, both in weight and leaf area.

For the green and red light trays (5o%-50%) LED mix gave the weak points of 100% red and 100% as having branch elongation while having smaller leaves. Plants under green (100%) light treatment gave the weakest results by having smallest leaf area and long apex length with weak body. White LEDs gave a moderate result more similar to green-red mix but with slightly bigger leaves with better leaf L/W ratio. The plants which grew in the greenhouse appear to be in a much earlier phase of growth, end of 1st week LED experiment lettuces were looked like this. This probably due to short day length and 7-10 °C temperature variation even though the glasshouse is heated.

Overall, it is clear from both the photos and measurements of weight, water retention and leaf/shoot size that the boards which produced the best lettuces were the blue, and blue & red lights, the latter being the best of all. Both the green and the greenhouse reference tray produced the weakest growth. As visual characteristics red & blue and blue gave best result in colour, compact growth and total weight. Sole green light is observed to produce the weakest crops among all other LED boards in the trial. Red light gave excessive elongation while having a reasonably good amount of leaf area and dry weight.

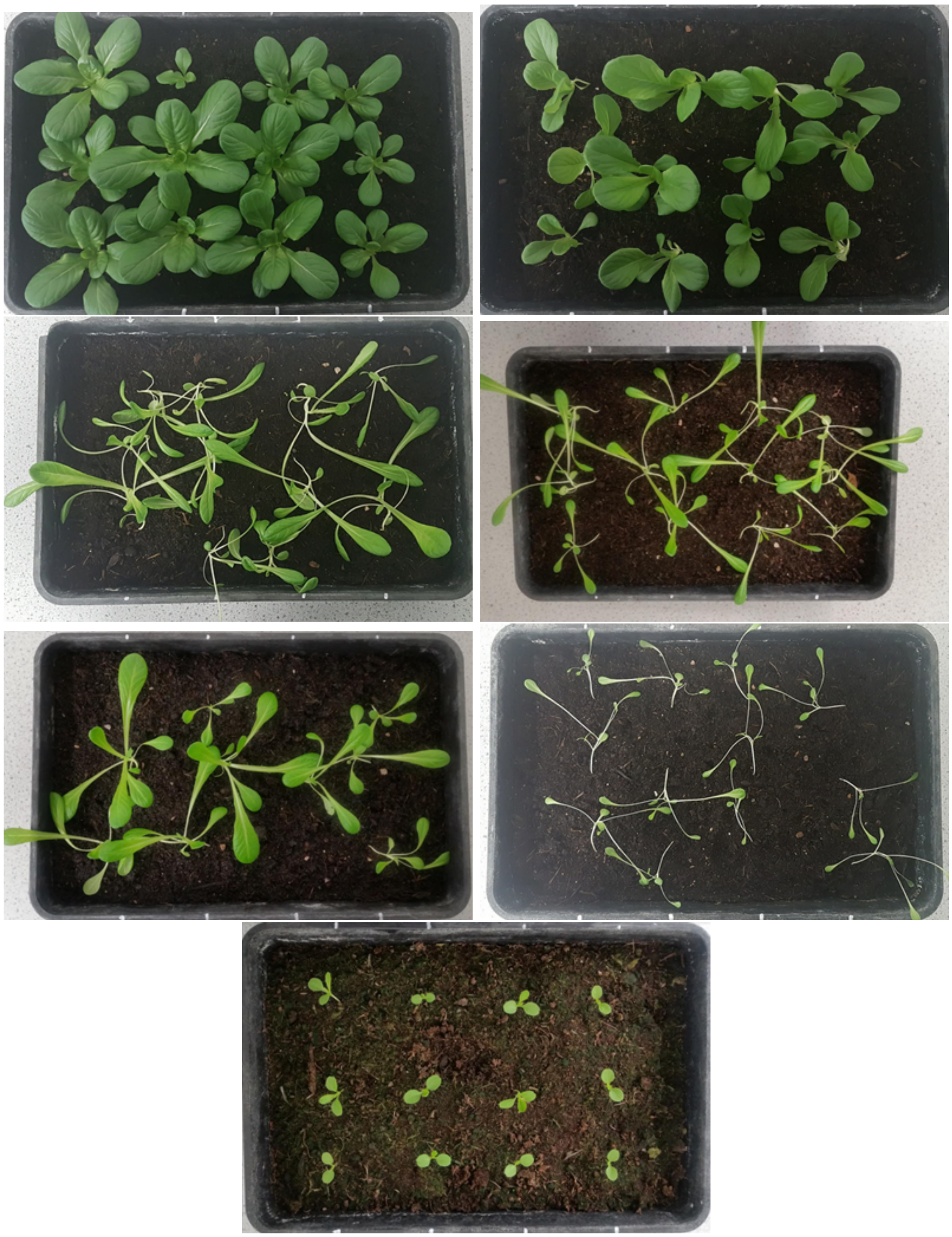

Figure 24: Lettuce trays after 21 days of growing. In order: red & blue, blue, red, red & green, white, green and the reference greenhouse at the bottom.

Lettuce Crops After 21 Days *Weight of Crop (g)*						
Blue & Red	**Blue**	**Red**	**White**	**Red & Green**	**Green**	**Greenhouse**
2.07	1.22	1.13	0.85	0.46	0.1	0.11
1.55	1.09	1.03	0.76	0.45	0.09	0.08
1.5	0.94	0.95	0.61	0.45	0.08	0.06
1.35	0.75	0.8	0.44	0.41	0.08	0.06
1.32	0.71	0.61	0.29	0.39	0.07	0.06
1.2	0.66	0.58	0.29	0.37	0.07	0.04
0.98	0.63	0.56	0.18	0.35	0.06	0.04
0.93	0.55	0.48	0.16	0.26	0.04	0.03
0.67	0.47	0.46	0.1	0.25	0.04	0.03
0.58	0.39	0.33	N/A	0.18	0.04	0.03
0.41	0.37	0.26	N/A	0.18	0.03	0.02
0.14	0.22	N/A	N/A	0.1	0.02	0.01
12.7	**8**	**7.19**	**3.68**	**3.85**	**0.72**	**0.57**

Figure 25: Lettuce crop weights after 21 days of growing, with green and red describing a relatively high and low weight compared to the mean of the crops respectively. The final value of each column is equal to the total of all of the separate crops.

Treatments	White	Red	Blue	Green	Red+Green	Red+Blue	Greenhouse
Average leaf number	7.125	7.4	7	5.5	6.55	8.3	2.83
Maximum shoot (apex) length	1.7cm	1.2cm	1.5cm	2.5cm	1.5cm	1cm	1.5cm
Minimum shoot (apex) length	1cm	1cm	0.9cm	1cm	1cm	0.4cm	0.9cm
Average shoot (apex) length	1.34	1.16cm	1.18cm	1.8cm	1.32cm	0.55cm	11.3cm
Maximum leaf area	6.75 cm^2	7.5 cm^2	12.25 cm^2	0.75cm^2	2.5 cm^2	10.625 cm^2	1.125 cm^2
Minimum leaf area	1.5 cm^2	4.125 cm^2	6.75 cm^2	0.125 cm^2	1.875 cm^2	3.375 cm^2	0.875 cm^2
Average leaf area	4.375 cm^2	5.725 cm^2	8.875 cm^2	0.583 cm^2	2.275 cm^2	8.1875 cm^2	1.05 cm^2
Maximum leaf height and width	H=5.7cm W=2.2cm	H=5.8cm cm W=2.2cm	H=5.7 cm W=3.7cm	H=1.8 cm W=0.7cm	H=3.8cm W=1.9cm	H=5 cm W=4.5cm	H=1.6 cm W=1.6cm
Minimum leaf height and width	H=3cm W=1cm	H=4.5cm W=1.6cm	H=3.3 cm W=1.9cm	H=0.5cm W=0.3cm	H=3cm W=1cm	H=3cm W=2cm	H=1.4cm W=1.1cm
Average leaf height and width	H=4.24 cm W=1.58cm	H=5.26 cm W=1.82 cm	H=4.85 cm W=3cm	H=1.3 cm W=0.6cm	H=3.5 cm W=1.36cm	H=4.2cm W=3.01cm	H=1.52 cm W=1.22cm

Figure 26: Lettuce parameter measurements, including shoot lengths, leaf areas, and leaf geometries taken from multiple leaves from each tray.

4.2 Possible Improvements

The fact that these preliminary tests were both short term and had a 'from scratch' element to the design and implementation, there are areas which could be improved on for more extensive future tests.

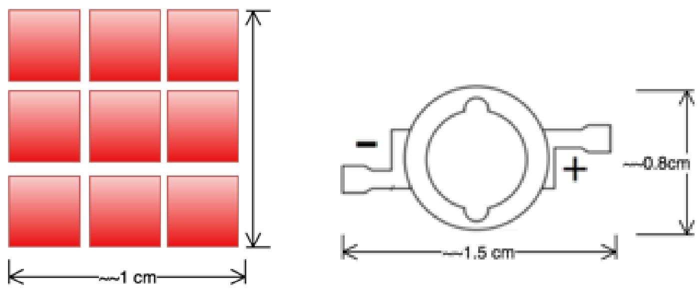

Figure 27: Nine osram LED units could fit into $1cm^2$ of space shown on the left, this is comparable to one Bridgelux light as seen on the right.

With regards to the board and LEDs chosen, a potential improvement could be to instead choose the Osram LEDs instead of the Bridgelux. During the preliminary tests, some of the solder joints became loose and affected the performance of the board, requiring to be resoldered. This issue could be eradicated by using the Osram lights and having the lights professionally fixed to the circuit. Also, as shown in figure 15, the Osram lights are considerably more spatially compact, meaning a higher efficacy.An arduino based temperature trip will be designed to make the tests safer and easier to menage. SMPS Power supply design will be started to implement different duty cycles on the lighting rig.

In terms of results taken and analysis, due to the 21 day experiment finishing only three days before this report, the analysis is limited. Possible improvements would involve statistical analysis of weight and leaf/shoot size measurements, such as calculations of standard deviation and variance within plants grown in each board. This could give an indication of how reliable the plants could be with regards to harvesting appeal.

Also, in terms of parameters measured and equipment used, the use of a colorimeter could be useful to determine precisely the colours of the plants. Measurements of chlorophyll should also be considered to gain full information about the health of the plants.

5 Future Work

5.1 Preliminary Tests Extended

A full set of systematic tests indicated in previous sections will be implemented, extending on elements of the preliminary tests which have recently finished. This experiment will consist of 15 different wavelengths and combinations of different ratios will be tested simultaneously and in the same conditions for validity of results. The measurements will be taken throughout the growing process so the development can be demonstrated and understood to a greater level. More colour combinations will be added to the planned systematic tests including potentially red, blue and green, because in the literature review, it was discussed that green can enhance growth of lettuce with red and blue lights. Lighting source position and reflectors modelling using Trace Pro software will be conducted to decrease the light waste, increasing efficiency. The systematic tests will be implemented initially on lettuce then various other selected plants.

In the literature, there is sparse data about plant growth as mentioned in previous sections. Such systematic tests on the same plant will give various valuable data to understand its whole plant responses to light spectral quality, giving opportunities to create light formulae or recipes.

5.2 Pulsing Lights

Pulsing light treatments of various frequencies have recently been taking attention in lots of research. There are a vast number of possibilities to try and see the effects of pulsed treatments - can electricity consumption be decreases while the plant remains similar in its responses to light? Additionally there has been interest of literature on pulsed treatments of UV and FR lights, the wavelengths having adverse effects in continuous exposure but short time pulsed treatments may be effective in some mechanisms for some useful purposes, such as pulsed UV for reducing levels of bacteria and yeast on the plant surface.

5.3 Development and Implementation of Sensors

For greenhouse implementations of LED boards for supplemental lighting, HPS is still is the most dominant lighting choice, with LEDs being gradually adopted. Applications with LEDs have none or very poor control over light intensity during the time in which they are switched on. However, in the day time, there are many sufficiently sunny times that render the lights' maximum intensity unnecessary. Thus, implementation of a dynamic control of supplementary lighting system would be useful. This would work via photosynthetically active radiation sensors, to keep the light intensity that the plant receives constant throughout the day and also reducing the waste lighting from LED boards are working at maximum intensity despite high sunlight levels also reaching the plants.

A dimming system via sensor can regulate the light intensity plants are receiving and keep it at a constant value by dimming the LED board when the weather is sunny and increasing intensity when it is cloudy or dark along the day, this could decrease electrical energy consumption significantly, further adding to the efficiency benefits of LED plant applications.

5.4 Tracepro and Optimising Light Received

For optimal plant growth, the light received by the plant should be even along its surface, with least light possible wasted. Reflectors and diffusing lens materials can provide these. Design and optimisation of lighting fixtures for horticulture is crucial, especially for vertical farming where rows of production stack onto each other in a compact greenhouse environment. On vertical farms, sun rays become very limited in the lower rows and thus need sufficient supplemental lighting. Trace Pro is a powerful tool that can include daylight historical data for optimised light conditions with designed luminaire that ensures that minimal light is wasted and also is evenly distributed on the plant surface.

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