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Investigating optimum wavelength(s) for growth of Lactuca sativa, L. using tunable LED sources and developing thin-film filters for glass greenhouses

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Investigating optimum wavelength(s) for growth of *Lactuca sativa,* L. using tunable LED sources and developing thin-film filters for glass greenhouses

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2 LIST OF ABBREVIATIONS

^{o}C	Degrees Celsius
ESRI	Electron Science Research Institute
L.	Latin
Lactuca sativa, L.	Lettuce, Latin
LED	Light emitting diode
L. sativa plants	Lettuce plants
LSC	Luminescent solar concentrator
PV	Photovoltaic
RBW	Red Blue White
UN FAO	United Nations Food and Agriculture Organisation
W/cm^2	Watts per square centimetre
FWHM	Full Width Half Maximum measurement

3 LIST OF PUBLICATIONS

1. Thomas, J.A.; Vasiliev, M.; Nur-E-Alam, M.; Alameh, K. Increasing the Yield of *Lactuca sativa*, L. in Glass Greenhouses through Illumination Spectral Filtering and Development of an Optical Thin Film Filter. *Sustainability* **2020**, *12*, 3740.
2. Mohammad Nur E Alam; Mikhail Vasiliev; Jacqualine Thomas. A step forward towards advanced and self-sustainable greenhouse agriculture. https://encyclopedia.pub/872.

4 ABSTRACT

With the increase in world population, the continued advances in modern greenhouse agriculture and plant growth practices are expected to help overcome the global problem of future food shortages. This research investigates a way to assist in stemming the problem of food shortage by using optimised light irradiation (within the constraints of the experiment) on a sample plant species of lettuce (*Lactuca sativa*, L.). Whilst lettuce is often grown in hydroponic systems, the current research is conducted in stand-alone pots with hand watering, due to the requirements of health and safety and available resources.

The experiments were designed such that firstly a sample of 30 lettuce plants in three different grow tents, having a separate light treatment in each tent (white visible light in Tent 1; red and blue visible light in Tent 2; and red, blue and far-red visible light in Tent 3), totalling 90 lettuce plants, grown for 39 days. The plants were then culled and the wet weight and dry weight of the above-ground parts of the plants were measured, and the biomass of each individual plant determined. The results were then utilised to inform which of the three light treatments provided the 'optimum' biomass results for the lettuce plants, that being the red, blue and far-red visible light treatment. From identifying the optimum biomass producing light treatment, a model of a thin-film filter, which transmits the visible light in the red, blue and far-red visible regions and filters all other radiation was designed, using the Opti-Layer Pro program. The experimental results show that substantial biomass productivity improvements in the lettuce (up to approximately 14.7%) can be attained by using spectrally optimized illumination, instead of white light illumination.

The resultant 9-layer thin-film filter was then fabricated in ESRI's Clean Room using the E-Beam Evaporation system, with a balanced and symmetrical combination of ZnS, Al_2O_3 and Ag. It was then demonstrated that the fabricated thin-film filter could reproduce, when exposed to sunlight, very similar transmission output to the optimum LED spectrum that maximised the biomass in the grow tents. This paves the way for offering viable solutions to greenhouse operators wanting to utilise glass, instead of short-lifetime plastic coverings, to coat their glass with thin-film coatings that pass the optimal wavelengths that maximise the crop yield.

In the work to be conducted in the future, other plant species such as basil, tomatoes and capsicums can be investigated to determine their optimum biomass and other parameters, such as the wet and dry root masses, the nutritional quality of the plants produced, their chlorophyll

content, which define the plant quality. This also opens the possibility for thin-film filters to be applied to sections of the greenhouse so that more than one plant species can be optimally grown, simultaneously.

5 CONTENTS

1 Chapter One – Introduction; Literature Review; Aims; Outline; Setup and Experimental Equipment

1.1 Introduction

Food and its potential scarcity has been a topic of discussion for many years around the world [1]. At present, the main concern for growers is ensuring that produce grows at a quick and optimum rate whilst maintaining nutritional quality.

This research aimed to investigate the potential correlation between optimum growth of *Lactuca sativa*, L. (*L. sativa* - lettuce) plants and the optimum wavelength range of visible light. Once the optimum wavelength range was determined, thin film layers deposited onto a glass substrate were developed to filter incoming light and transmit only the required wavelength range determined to provide optimum growth conditions for lettuce plants.

Experimentally, the outcome was achieved by growing *L. sativa* plants under LED lights, and determining a result for translation into a greenhouse environment.

L. sativa is a staple food in many cultures cuisines [2]. *L. sativa* is often grown in hydroponic conditions inside glass greenhouses. Finding the optimum wavelength range of electromagnetic radiation that *L. sativa* require and utilising that wavelength to develop a thin film filter for use on a greenhouse roof, to obtain optimum lettuce growth would be a beneficial finding for the agricultural industry, and a step towards providing quicker food growth. This would assist in mitigating the impending food crisis predicted to occur in 2050 [3].

1.2 Literature Review

1.2.1 Introduction

Thin film techniques such as Radio Frequency Magnetron Sputtering (RFMS) have been used over the years to form thin film layers on glass or other material substrates for many different purposes, for example, semiconductor devices, electro-optic coatings [4]. However, it appears that combining inorganic thin film technology with agriculture has not yet been attempted.

Specifically, determining the wavelength range of visible light that provides optimum growth of a plant and translating this into an inorganic thin film filter on a glass substrate to be used in a greenhouse to filter and control the wavelengths of light transmitted to plants within a greenhouse has not been proposed or attempted it appears, in the literature. This provides a gap in the current literature that this research aimed to address.

The advantage of utilising thin film technology for glass in a greenhouse lies in the longevity of inorganic materials such as those used to create thin film layers on a glass substrate, as opposed to the current methods, for example, of coloured dye which use organic materials [5]. Organic materials are more unstable than inorganic materials and generally break down before inorganic materials. Additionally, whilst thin film filters are generally expensive to initially manufacture than dye filters, the proposed longevity of the thin film filters will outweigh the length of time that the filter is operational.

Additionally, in the future, if found to be viable, filters could potentially be manufactured for filtering different ranges of wavelengths, as determined to be required for various plants grown in greenhouses. This would allow sections of greenhouses to be designated for particular filters. Therefore, building a greenhouse would involve using panels of the different filters and each filter type being designated a particular section, so that the plant that requires the particular wavelength ranges provided by the given filter is grown in that section of the greenhouse.

In order to address all aspects of this multi-disciplinary research, the literature review has been divided into four sections – Botanical; LED lighting and Agricultural; Greenhouse Materials (Past and Present); and Engineering of Thin-Films.

1.2.2 Botanical

Whilst lettuce plants are mostly grown hydroponically in industry at present, due to the limitations of the growing environment for the lettuce plants in this experiment, it was decided to hand water each plant. The lettuce for this experiment was grown from seedling rather than from seed, due to time constraints and the probability of success of obtaining a mature plant eventually, being greater when growing from seedling, rather than growing from seed.

The stages of growth of a lettuce plant are shown in Figure 1.

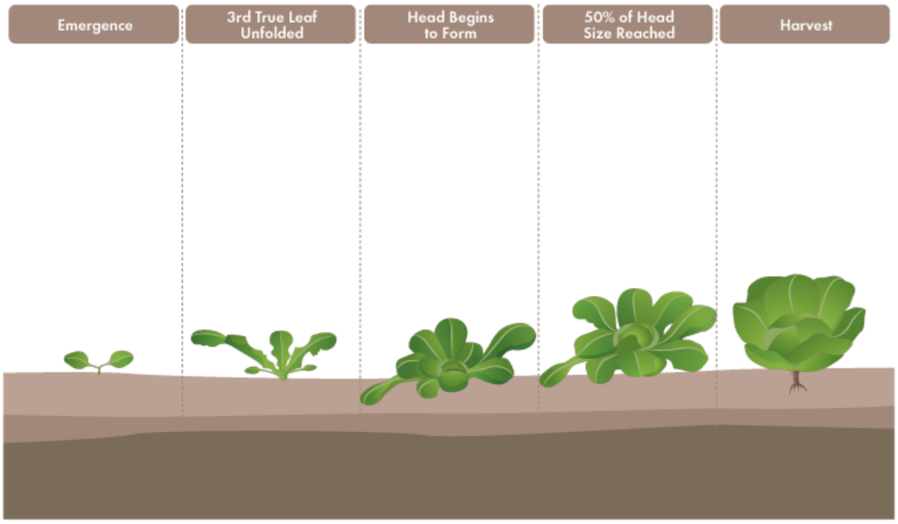


Figure 1. Stages in the lifecycle of lettuce (*Lactuca, sativa,* L.) [6].

In order to prevent the *L. sativa* from 'bolting' (growing quicker, longer (in length) and flowering before desirable) [7], it will be necessary to maintain the temperature at a high temperature as lower temperatures appear to inhibit growth and encourage 'bolting' [7].

Kang et al. [8], indicate that for a hydroponic system, the temperature should be kept at approximately 21^{o}C +/- 1^{o}C, with a relative humidity of 70+/- 10%. The optimum photoperiods informed by this paper are 18 hours of LED light on, and 6 hours of LED light off (night); or 6 hours of LED on, and 2 hours of LED off, for three cycles [8]. Under 18 hours of light and 6 hours of dark, with a high light intensity of 290 µmol.m^{-2}.s^{-1}, the combination provided the highest fresh (wet) and dry masses [8], which is desirable when seeking to obtain optimum biomass results. It has previously been reported that high-energy lighting conditions provide increases in dry mass and relative plant growth rates in lettuce grown in growth chambers [9]. A long photoperiod such as 18 hours on and 6 hours off has also previously been reported by Koontz and Prince [10] to provide substantial increases in fresh mass for various lettuce plant varieties [10]. As the aim of the lettuce growing part of this research was to determine the wavelength range of visible light that provides optimum biomass results, it was determined that using the long photoperiod of Koontz and Prince [10] would provide the optimum lighting environment in order to determine the optimum biomass for the lettuce plants.

It is also noted that although Kang et al. [8] conducted their experiment under hydroponic growth conditions, the results were still able to be used to inform towards the intensity of light to be used, and the number of light and dark hours to be provided to the lettuce plants in the experiments conducted in this research.

1.2.3 LED lighting and Agricultural

Chang and Chang [11] have succinctly summarised the optimum wavelengths of light studies completed prior to their paper of 2014. Chang and Chang [11] have indicated that Kim et al. [12] in 2004 showed that supplemental red and blue LED irradiated with green light from fluorescent lamps resulted in *L. sativa* plants having larger leaf areas and higher dry fresh masses than L. sativa plants grown under single irradiation with green, red and blue or white light [12].

As indicated by Chang and Chang, a good combination of light wavebands can improve the efficiency of photosynthesis, and the amount of photosynthetically active radiation (PAR) applied to plants does also affect the quality of the crop being grown [11]. As referred to in [11], and researched by Yanagi et al. [13], the dry and fresh masses of lettuce were higher when the PAR was higher, in this case $170\mu molm^{-2}s^{-1}$ instead of at the lower value of $85\mu molm^{-2}s^{-1}$.

Chang and Chang [11] have also advised against using a conventional stable light condition, recommending continuous adjustment of the light quantum rates, wavelength combinations and photoperiods in order to control plant production and morphology [11].

The wavelength of light supplied was also found to be colour dependent [11]. In their experiments, Chang and Chang found that a wavelength of 495nm, which corresponds to cyan light, improved lettuce growth more than a wavelength of 525nm (essentially green light) [11]. Particularly, Chang and Chang found that the shoot fresh mass (wet mass) of lettuce plants treated with supplemental cyan LED light resulted in an 87% increase in shoot fresh mass, compared to plants that did not receive supplemental cyan light [11].

Chang and Chang also observed that plants treated with light that included ultraviolet (UV) radiation showed better growth than those plants without UV supplied in the light irradiation [11]. In particular, UV-A irradiation (approximately within the range 320nm – 400nm) provided during the seedling and vegetative stages was found to have substantial impact on

biomass in the lettuce plants [11]. The combination of LED light suggested by Chang and Chang [11] from their study is to use red, blue, and UV-A radiation during the vegetative stage of *L. sativa* plants, as this will reduce the nitrate content [11, 14]. Reducing the nitrate content is desirable, as nitrate has been shown to have a toxic effect on humans [14].

The red, cyan, blue combination was then recommended for both seedling and vegetative stages of *L. sativa* plants , and cyan light was found to be more suitable for *L. sativa* plant growth than green light [11]. Chang and Chang have also indicated that adopting red, cyan, blue light at the seedling stage and red, blue, UV-A at the vegetative stage can provide the highest chlorophyll-a and lowest nutrient [presumed typographical error and should refer to 'nitrate'] contents, which will enable growers to cultivate good *L. sativa* plants [11].

Kang et al. [8] indicate that the dry shoot mass at the optimum light intensity of 290 $\mu molm^{-2}s^{-1}$ PPFD with a photoperiod of 18 hours light and 6 hours dark was 3.48g. Whilst a photoperiod of 6 hours light, 2 hours dark for 3 cycles and a light intensity kept the same as previous (290 $\mu molm^{-2}s^{-1}$) gave a higher dry root mass of 4.41g [8]. Additionally, the dry root mass of the plants increased from 3.48g to 4.02g when the light intensity was decreased to 200 $\mu molm^{-2}s^{-1}$ with a photoperiod of 18 hours light and 6 hours dark [8]. Interestingly, the dry root mass of the lettuce decreased from 4.41g to 3.00g when the photoperiod was kept the same at 6 hours light and 2 hours dark for three cycles, with a reduction in the light intensity to 200 $\mu molm^{-2}s^{-1}$. The *L. sativa* variety being grown in this experiment was Hongyeom Jeockchukmyeon, however, it is unclear whether this is the Korean name for a variety of lettuce, as no translation is available at present. Despite not knowing the English equivalent of these words, these results will provide an indication as to masses likely to be obtained when determining the biomass of each plant, through measuring the dry mass of the plants.

Chang and Chang have indicated that the variety of *L. sativa* grown in their experiments was the crispa variety, which is a loose leaf variety [11]. As indicated previously, the conditions for producing a good biomass for *L. sativa* plants were under red, blue and UV-A light. These conditions gave a shoot dry mass of 2.72g +/- 0.21g. Therefore, the dry mass of a lettuce plant will vary depending on which variety of lettuce is grown, however, these masses will provide an indication as to what is a good shoot dry mass of *L. sativa* plants. These masses

provided approximations to the masses that should be obtained from the experiments conducted.

Choosing the variety of *L. sativa* was important in regard to whether the variety has a low or high resistance to bolting [15]. For example, in Silva et al. [15] four varieties of *L. sativa* were classified as to whether they had a low or high resistance to bolting. Of the four varieties, two varieties, Vitoria (a loose leaf lettuce) and Elisa (a butter head lettuce), had a high resistance to bolting (that is, they were late-bolting) [15].

Therefore, choosing an *L. sativa* variety to be a butter head was important to minimise bolting as much as possible.

1.2.4 Greenhouse Materials (Past and Present)

Emmott et al. [16] outline three photovoltaic greenhouses, as shown in Figure 2 [16]. Diagram 'a' clearly shows the partial shading of a greenhouse roof using opaque photovoltaic (PV) cells or modules. In diagram 'b', the use of Fresnel lens that have been embedded into the greenhouse roof are used to focus and direct light onto PV modules. In diagram 'c', semi-transparent PV modules are used. These modules allow some light through and use the blocked light for electricity generation.

This research relates to using inorganic materials to create a filter and potentially using the light that has been filtered, to generate electricity (in future work). In contrast, the semi-transparent PV modules of Emmott et al. [16] involve PV modules attempting to filter but as the modules are semi-transparent, shading will still be occurring. These semi-transparent PV modules are limited in that the absorption spectra of these PV modules cannot be tuned [16]. That is, the wavelengths absorbed by the PV module are not tunable.

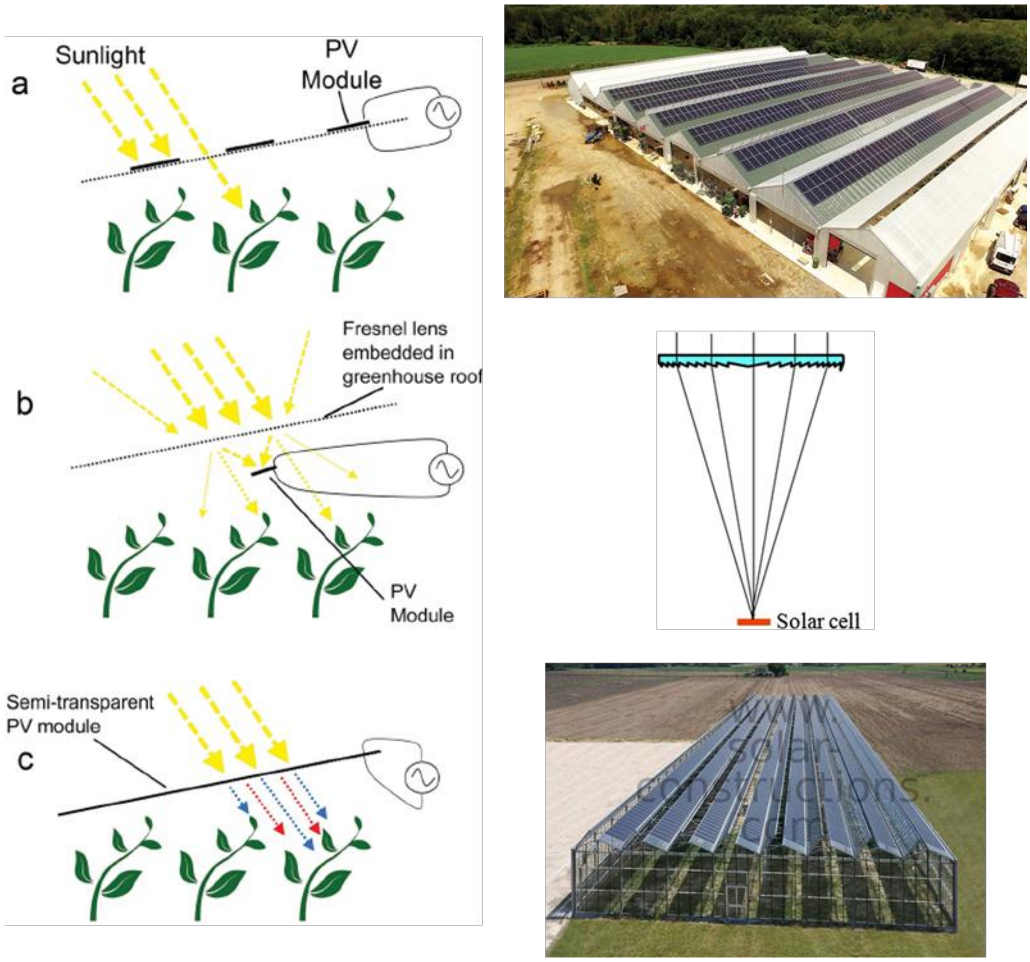


Figure 2. Three types of Photovoltaic (PV) greenhouses, sourced from Emmott et al. [16] showing equivalent examples of the types of materials in the field, in particular the shading is observed in the third image on the bottom right [17-19].

Emmott et al. [16] have proposed that a solution to overcoming the shortfalls with these three types of PV greenhouses is to instead use organic PV material which gives a finite bandwidth absorption through manipulating the molecular structure and absorb via tuning the light not required for crop growth [16].

A dye based technology was investigated by the University of California, Santa Cruz [5] in 2017. The technology uses wavelength-selective photovoltaic systems [5] to select the wavelength of light to be transmitted through the magenta dyed panels to the plants, as shown in Figure 3. The absorbed wavelengths are laterally transmitted to solar cells at the edges of the panels [5].

Figure 3. Loik et al. magenta dyed panels on a greenhouse [5].

The problem with this system lies in the instability over time of organic materials as opposed to inorganic materials. The results from Loik et al's [5] research concluded that the use of unstable organic, instead of stable inorganic, materials must be avoided.

The problem with organic materials is their finite lifetime, being shorter than that of inorganic materials [16], along with the problem of shading. Accordingly, this research was to arrive at an inorganic optical filter that can filter incoming visible light and then to compare that to theoretical modelling results. Subsequently, further research is proposed to investigate the filter created, to prove that the optimum wavelength of light found using the Heliospectra LED lights provides growth results for *L. sativa* in the same magnitude as the results obtained in the grow tents of this research, and potentially may be combined with ClearVue^{PV} patented technology to generate electricity and create self-sustainable greenhouses.

In regard to the power generation capabilities of a greenhouse, Corrado et al. have investigated the power output by luminescent solar concentrator greenhouses [20]. The PV cells were attached to the roof panels of the greenhouses, and the placement and types of PV cells were varied in order to obtain comparisons between the power performance of the PV

cells. After monitoring for 1 year, the results indicated a 37% increase in power production compared to the control reference. Therefore, this can also be used to inform how to combine the filter with the existing ClearVue^{PV} technology in order to obtain good power production from the connected PV cells, in future work.

1.2.5 Engineering of Thin-Films

Lin et al. have provided a starting point from which the thin-film filter was able to be developed, providing filtering in the red, green and blue regions of the electromagnetic spectrum [18]. They proposed a filter that is a non-absorption inorganic thin film colour filter. Previously, as outlined in [21], colour filters were manufactured by using layers of organic-based photoresist coatings [22, 23], followed by ink-jet printing [24] and laser pattern transfer [25] to produce the red, green and blue colours in the colour filter for thin film transistor – liquid crystal displays (TFT-LCD) [21].

The particular three colour filters proposed by Lin et al. [21] each have layers of Ag/SiO_2/Ag, where the red filter has layer thicknesses of 30nm/170nm/30nm, respectively, whilst the green filter has layer thicknesses of 30nm/131nm/30nm, respectively, and the blue filter has layer thicknesses of 30nm/100nm/30nm, respectively [21].

The simulation results reported by Lin et al. indicated that these values provide better saturation of the colours as well as better transmittance [21]. It was decided that using this as a basis, similar materials to Ag and SiO_2 could be found and layers incorporating only the red and blue filters proposed by Lin et al. could be trialled in a simulation on OptiLayer Pro to determine if a filter, incorporating all layers combined together of just the red and blue filters, can provide transmittance values of the range around 70% as indicated by the single filters.

1.2.6 Summary

To summarise, Table 1 below outlines the key points, which have been reported in the literature to influence the experimental conditions and expectations.

Reference to Literature	Literature Informs that…
Silva et al. [15]	Variety of lettuce grown should have high resistance to bolting
Chang & Chang [11]	Seedling stage: irradiate with red, cyan, blue visible light Vegetative stage: irradiate with red, blue, UV-A light
Kang et al. [8]	Photoperiod of 18 hrs ON, 6 hrs OFF for LED to get optimal growth
Kang et al. [8]	Light intensity to be at around 290 µmol/m^{2}s for optimal biomass
Lin et al. [21]	Ag, SiO_2 & similar materials in varying thickness to be used to start thin film optical filter development

Table 1. Summary of the primary literature review articles

Based on the above-discussed literature review, there appeared to be a gap in the literature in regard to developing a thin film to transmit only the wavelength range required by *Lactuca sativa*, L. plants for optimum growth.

1.3 Project Aims

The purpose of this research was to determine which electromagnetic spectrum wavelength range will enable *Lactuca sativa*, L. (a long-day plant) [7] to achieve the quickest time to optimum maturity, and determine which wavelength range provides the best biomass of the plants. The determined wavelength range was then utilised to develop thin film layers on a glass substrate to filter the unnecessary wavelengths of the electromagnetic spectrum that *L. sativa* plants do not require, and in future work potentially harvesting the unnecessary wavelengths to generate electricity via solar cells by utilising technology already developed and patented by ClearVue^{PV}. The filter would then transmit only the wavelengths deemed necessary for the optimum growth of *L. sativa* plants.

The importance of this research lies in determining the optimum growth conditions to obtain the best biomass of *L. sativa* plants, from which the thin-film filter can be developed. *L. sativa* is a staple food around the world [7] and easily grown hydroponically inside greenhouses. Developing a thin-film filter that harnesses the incoming sunlight and transmits only the wavelength range required for optimum growth of *L. sativa* provides a long-term solution for growers attempting to optimise growth of their plants.

If in addition, the wavelength ranges not transmitted could be used to generate electricity, then this could be used to simultaneously cool the greenhouse in the summer months, and to power filtered or wavelength programmable LED lights in the winter months when the days are shorter (e.g., in Australia), which would be a beneficial outcome.

1.4 Research Outline

The outputs of this work were:

- determine the optimum wavelength range for *L. sativa* by growing *L. sativa* plants under LED lights in grow tents;
- develop a thin-film filter on a glass substrate;
- compare the theoretical and experimental transmissivity results for the thin-film filter;
- publish findings; and
- outline future work.

The first output related to determining the optimum wavelength range for *L. sativa* was to perform controlled experiments under different light treatments so as to determine which light treatment provided the optimum biomass results between the 3 tents. This first experiment was conducted using 3 grow tents, which were black on the outside with a reflective coating on the inside in order to maximise the amount of light shining within each grow tent. The grow tents were set up to each have a Heliospectra light source hanging from the ceiling of the tents and 30 plants in individual pots placed symmetrically in the base of each tent. The Heliospectra light source was calibrated and tuned to be emitting at particular wavelengths (a particular set of wavelengths for each tent) as determined from literature and those that were available on the Heliospectra light source. The pots were randomly rearranged within each tent on a weekly basis. The experiment was conducted over 39 days, after which the *L. sativa* plants were harvested at the base, dried and weighed to determine the biomass of each plant.

Having determined the optimum wavelength ranges across the three tents, the second output, was to model from literature and the optimum range, a thin-film filter using the computer package OptiLayer Pro with the determined parameters. Once a suitable thin-film filter was achieved, it was fabricated in the laboratory. This took approximately 6-7 months of experimental work in the laboratory, with each iteration getting closer and closer to the

expected results. The thin-film filter was initially fabricated on a glass substrate using the Radio Frequency Magnetron Sputtering (RFMS) machine. This method of deposition proved to vary greatly from the expected results, due to errors with the machine, and the machine requiring cleaning. The next method of deposition used was the electron-beam evaporation method (the dielectric materials of Al_2O_3 and ZnS were evaporated using the e-beam, whilst the Ag was evaporated thermally within the same chamber), which eventually provided a good result that matched closely to the expected modelled output.

The third output, inherent in the second output, was to compare the results of the modelled to the experimental results. This was conducted by using a UV/Vis Spectrophotometer to measure the transmissivity of the thin film filter, and to then compare the theoretical transmissivity to the measured results.

The fourth output was to publish the findings, as outlined in Chapter 2, and this was achieved by successfully publishing the research results in MDPI Sustainability.

The fifth output was to recommend future work, and this is outlined in Chapter 2. Essentially, future work will involve manufacturing through a supplier, the thin-film filter in large enough quantities so as to build a small green house, and to compare the results from filtered sunlight, to the results from the LED lights, and to determine if these are comparable, and if the thin-film filter will be suitable for *L. sativa* growers to utilise in their greenhouses.

1.5 Experimental Setup

The setup of the grow tents and associated equipment for the growth of *L. sativa* plants are described in Chapter 2. The grow tents were constructed in the available space within the Electron Science Research Institute (ESRI), postgraduate research area. This was suitable, as there was not a need for a water supply as each plant was watered by hand, and watering was conducted whilst the lights were off, reducing risk factors around water and electricity. As shown in Figure 4(a), the inside of the tent was silver and reflective. The Heliospectra LED source was suspended by rope ties from the ceiling, with wooden supports supporting the metal frame of the ceiling to avoid collapse as shown in Figure 4(b).

(a) 

(b) 

Figure 4. Heliospectra LED light array showing (a) LED array from underneath; (b) securing of the Heliospectra LED system to the top of the tent.

When the LED lights were operating over an 18-hour day (between 4pm and 10am) the tent was closed at the front and sides in order to avoid minimal light loss, whilst the vents remained open to allow air to still flow in.

1.5.1 Heliospectra LED Lights

The Heliospectra LED light source array shown in Figure 4(a) (view taken from underneath the Heliospectra LED light source), comprised LED sources able to provide light at the wavelengths 450nm (blue), 660nm (red), 735nm (far red) and white (colour temperature of 5700K).

The Heliospectra LED tunable light sources were chosen as the wavelength of light output by the LEDs could be tuned to specific wavelengths by plugging in, via an internet cable, into the system and dialling into the Internet Protocol (IP) address of the light source being tuned. The web interface (shown in Figure 5) was then used to set the desired wavelength of light from those available via a laptop keyboard or other device, e.g. an iPad.

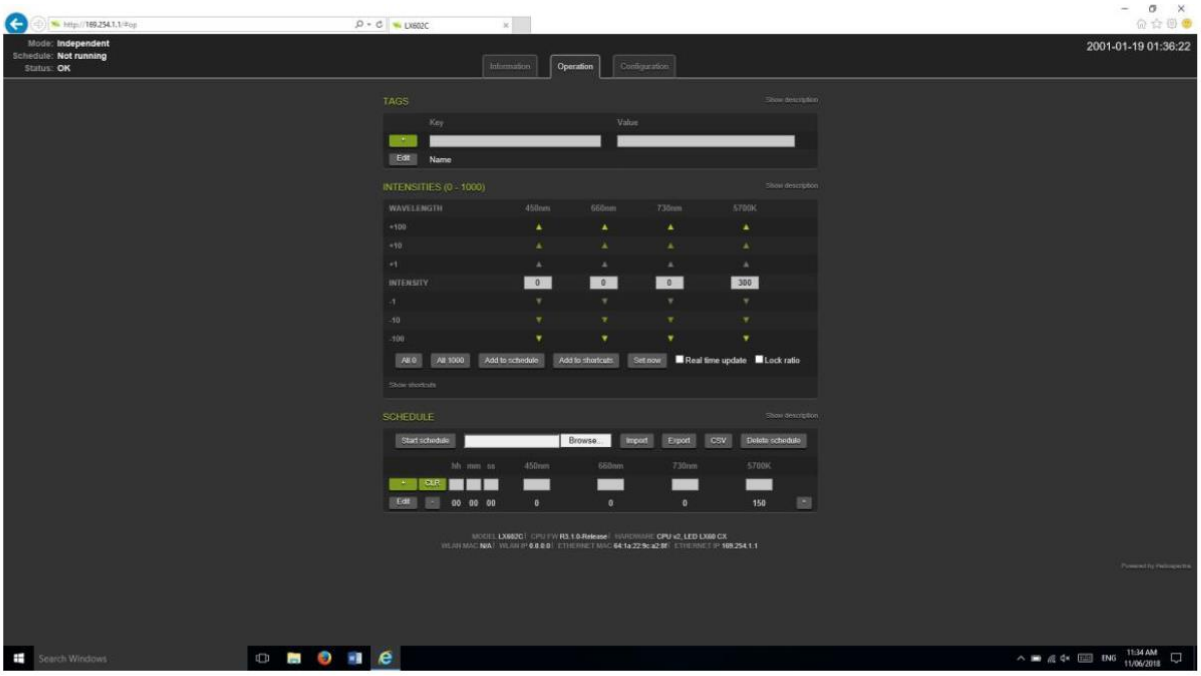


Figure 5. Heliospectra web interface for tuning the wavelength of light output by the LEDs. Shown is the setting of 0% Blue (450nm), 0% Red (660nm), 0% Far Red (730nm), 300% White).

It was possible to use the web interface in real time, that is, as the intensities were varied for the selected wavelengths, these changes were immediately observed in the output LED light of the Heliospectra system. In addition, more than one wavelength could be set to be output at a specific time. For example, the values entered into the web interface controlled the power output by the Heliospectra LED light source for the particular LED colour that the value entered is to change, which in turn controlled the intensity of the light being output by the LED. The ‘intensity’ was a variable between 0 and 1000, which corresponds to 0% to 100% of the maximum output power of the LED light source.

1.5.1.1 Grow Tent Power Values from the Heliospectra LED Light Source

The Heliospectra LED light source could be tailored to the desired wavelengths of Tent 1 being a control wavelength with solely white light at 100% power. Tent 2, as recommended from literature, was selected to be a red and blue mixed wavelength tent. Blue was at 100% power, whilst red was at a reduced power of 45.8% (of the 100% power available from the source in the red range of LEDs). Tent 3, also recommended from literature, was selected to be the same as Tent 2, with the addition of far-red at 100% power available from the far-red LED lights on the Heliospectra array, that is, blue at 100% power, red at 45.8% power and far-red at 100% power. The calculations for the choice of these power values are detailed in

Chapter 2, along with the calibration of the Heliospectra LED light source, which is explained further below.

1.5.1.2 *Calibration of the Heliospectra LED Light Source*

The calibration was performed using a handheld laser power meter (LaserCheck [26]), which has a power measurement range from 10µW-10mW and is able to calibrate for wavelengths between 400nm-1064nm, therefore it was suitable for calibrating all the wavelengths output from the Heliospectra LEDs.

Figure 6. LaserCheck hand held laser power meter.

Through using the diameter of the LaserCheck's aperture and the wattage that the LaserCheck measures (mW), it is possible to calculate the Energy (Power) density (W/m^2) of the system at a particular height from the ground. The calculation for red, 666nm is shown below for 10% intensity measured at a height of 1.55 m with power measured by the LaserCheck as 10.7 mW.

$$\lambda = 666\text{nm};\ \text{diameter} = 8\text{mm} = 0.008\ \text{m}$$

$$\text{Area(circular aperture)} = \pi r^2 = \pi\left(\frac{0.008}{2}\right)^2 = 5.0265\text{x}10^{-5}\ \text{m}^2$$

$$\therefore\ \text{Energy density (W/m}^2\text{)} = \frac{10.7\ \text{x}\ 10^{-3}\ \text{W}}{5.0265\ \text{x}\ 10^{-5}\text{m}^2} = 212.87\ \text{Wm}^{-2}$$

Using the Energy (Power) density (Wm^{-2}) value, the Photosynthetic Photon Flux Density (mol.m^{-2}.s^{-1}) can be determined, where 1Js^{-1} = 1W [27].

$$\text{Photon Flux(mol.m}^{-2}\text{s}^{-1}) = \frac{\text{E(J)}}{\left(\frac{\text{c.h}}{\lambda}\right).\text{N}} = \frac{212.87}{\left(\frac{(2.998\text{x}10^{8})(6.63\text{x}10^{-34})}{666\ \text{x}\ 10^{-9}}\right).(6.023\text{x}10^{23})}$$

$$= 1.18\text{x}10^{-3}\text{mol/m}^2.\text{s}$$

Plotting the photon flux against the % of power output (referred to by Heliospectra as a % of 'intensity') for increasing distances from the Heliospectra LED source (in 20cm increments) for the 666nm (red) wavelength, provides the plot of Figure 7.

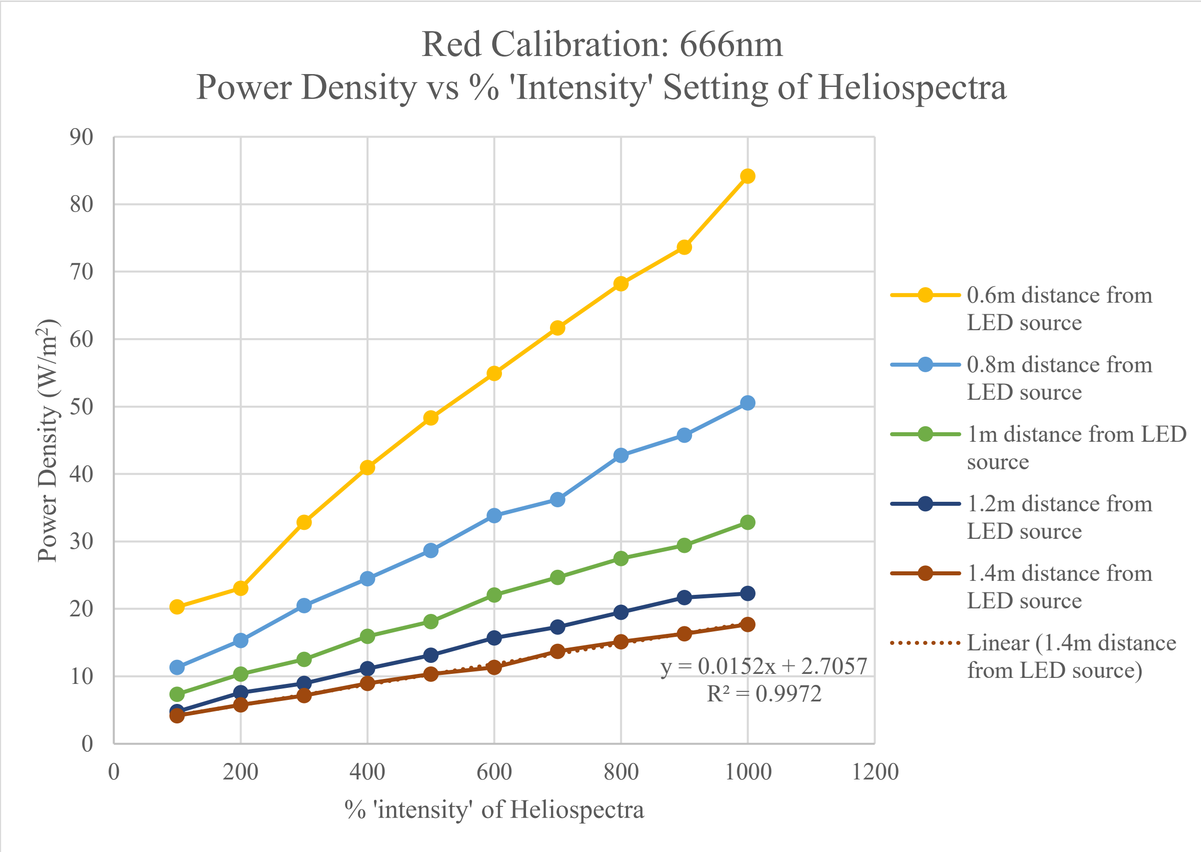


Figure 7. Graphical plot illustrating the measured power density at different distances from the LED source for various % 'intensity' values.

The leaves of the plant were approximately at 1.4m in distance from the LEDs of the Heliospectra light source. Therefore, using the 1.4m line, this approximate linear equation was obtained for red: $y = 0.0152x + 2.7057$. Then, using the approximate value from the Tropiglas estimation program for the Full Width Half Maximum (FWHM), the amount of energy from sunlight at 666nm that can be expected, was estimated at 33.4 W/m^2. Using an estimated average of 4.5 hours of sunlight each day across a sun year, then the following set of conversions were used to determine the amount of estimated % 'intensity' (i.e. power) that the Heliospectra LED in the red range should be operated at, to emulate natural sunlight.

$\therefore$ as $1Js^{-1} = 1W$, then: $33.4\ W/m^2 \times 4.5hrs \times 3600s = 541.08\ kJ/m^2$ (4.5hr day)

This was then compared to the 1000 % 'intensity' value from the Red LED graph, which is: 17.9057W/m^2 = 17.9057J/m^2s where in one day (18 hours), the amount of red light emitted onto the lettuce plants from the LED light source was: 17.9057 x 18hrs x 3600s = 1160.29 kJ/m^2(18hr day). In comparison, the energy emitted from the LED light source was 1160.29kJ/m^2(18hr day)/541.08kJ/m^2(4.5hr day) = 2.14 times greater than that emitted from the sun. Therefore, reducing the LED light source by approximately half its power, approximately matched the power output by the sun (hence 458% 'intensity' setting).

The blue and far red settings were determined in the same manner. This provided that both the blue and far red will need to be kept at 1000 'intensity' setting (full power) in order to provide only some of the desired far red and blue light that the sun provides.

1.5.2 Plant Configuration within the Grow Tents

Each of the three tents were setup as shown in Figure 8. A random number generator available over the internet [28] was utilised to randomise the position of the plants within each tent (but not between tents) at the end of each week during the experiment, in order to reduce the effects of shading within each tent. The numbers were written onto the floor of each reflective tent in permanent marker, then each pot was individually marked and initially placed into the setup as shown in Figure 8.

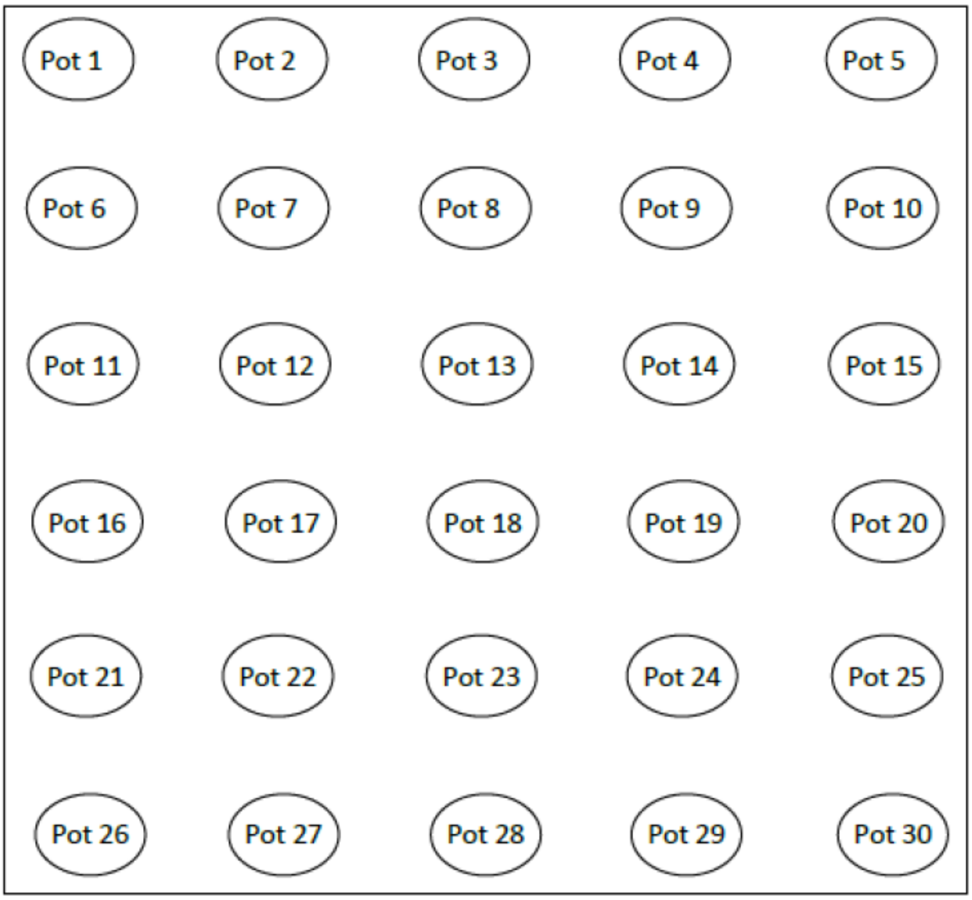


Figure 8. Setup matrix of pots with lettuce (*Lactuca sativa*, L.) placed in the base of each grow tent.

The randomisation was performed by removing the pots from one tent at a time, and placing these onto a trolley, then placing them back into the tent, in accordance with the random number generator, where each number correlates to another number as shown in Table 2.

Tent 1	Goes to
1	13
2	3
3	26
4	18
5	4
6	17
7	24
8	2
9	21
10	1
11	23
12	11
13	29
14	9

Tent 1	Goes to
15	8
16	19
17	25
18	27
19	6
20	30
21	14
22	16
23	10
24	22
25	12
26	7
27	20
28	5
29	15
30	28

Table 2. Randomisation of plants performed on 18 October 2018.

The movement of the plants was performed as quickly as possible during the ‘off’ time of the LED lights, at approximately 10am, at the end of each week.

1.6 EXPERIMENTAL EQUIPMENT

The equipment used for measuring during the various stages of the experiment and to fabricate the thin film filter are outlined below.

1.6.1 Growth Stage Measuring Equipment

1.6.1.1 Spectral Measurements

The spectrum of the different light treatments across the three tents were measured using optical fibre cables connected to an Ocean Optics (now Ocean Insight) USB2000 visible spectrometer shown in Figure 9.

Figure 9. Ocean Optics USB2000 visible spectrometer used to measure the light spectrum in each grow tent.

1.6.1.2 Biomass Measurements and Drying Equipment

The biomass was measured by using an initial sample of five seedlings, which were cut at the base where the plant touches the soil, and dried in a laboratory drying oven [29] inside paper bags at 60ºC for a period of 48 hours, as shown in Figures 10(a) and 10(b). The dried samples were then weighed individually using a laboratory grade set of scales as shown in Figure 11, and the weights averaged to obtain the zero-biomass starting point.

The experiments were then conducted, and after 39 days the 90 lettuce plants were individually cut at the base, weighed to obtain their final wet weights for comparison to the dry weights, then dried in individual paper bags per lettuce within the same S.E.M. drying oven at 60ºC for 10 days. The dried lettuce plants were then reweighed, and the zero-biomass starting point subtracted from each individual weight to obtain the dry-weight biomass of each individual lettuce plant.

(a) (b)

Figure 10. S.E.M. drying oven used to dry the culled lettuce. (a) showing the outside of the oven, and (b) showing the inside of the oven.

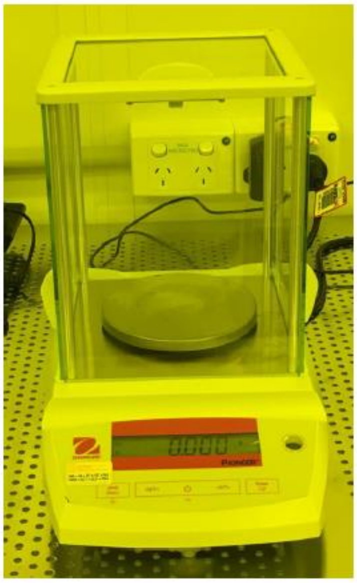


Figure 11. Laboratory grade scales accurate to 3 decimal places.

1.6.1.3 E-Beam Evaporation Machine for Thin-Film Filter Design

In order to fabricate the thin-film filter, successive layers of three different materials (Al_2O_3, ZnS and Ag) were deposited onto a glass substrate using an Electron-beam (E-beam) evaporation machine, shown in Figure 12.

Figure 12. E-Beam evaporation machine utilised for fabricating the thin-film filter.

The E-beam evaporation machine shown used a type of Physical Vapour Deposition (PVD) that involved placing the dielectric materials (Al_2O_3 and ZnS) to be deposited into separate crucibles within the chamber, in small granular form. The crucible, which contained the first layer material (in this instance, Al_2O_3) was then opened and a beam of electrons from a charged tungsten filament was bombarded onto the crucible in the chamber. This resulted in the deposition material evaporating and being converted into a gaseous state. As the material in its gaseous form struck the glass substrate (held within the chamber on a holding platform), the material precipitated and created a thin-film coating of the material on the glass substrate [30], also shown diagrammatically in Figure 13. Thermal evaporation was used to deposit the Ag in the same chamber, with the crucibles containing the dielectric materials rotated to the shut/off position to avoid cross-contamination between materials.

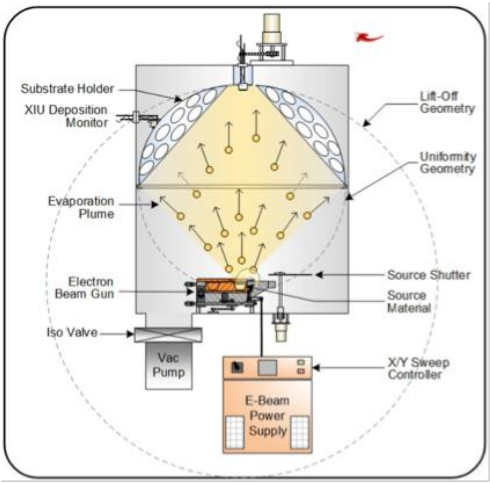


Figure 13. Semicore [31] Diagrammatic Operation of the E-Beam Evaporation Machine.

Several different materials and thicknesses were trialled before a final combination of materials were found which closely matched the modelled data. The final filter design had 9 layers, as shown in Figure 14, which were symmetrically centred around a 50 nm fifth layer, (central layer), of Al_2O_3.

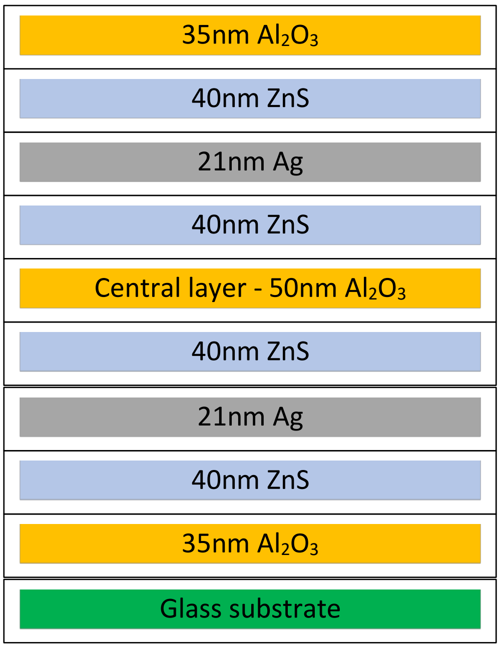


Figure 14. Layer composition of the final 9 layer thin-film filter design.

The tooling factors and experimental conditions for the 9-layer thin-film filter design are detailed further in Chapter 2.

2 Chapter Two – MDPI Sustainability Publication - Increasing the Energy Savings and Yield of *Lactuca Sativa*, L., in Glass Greenhouses Through Illumination Spectral Filtering

2.1 Abstract

With the increase in world population, the continued advances in modern greenhouse agriculture and plant growth practices are expected to help overcome the global problem of future food shortages. The next generation greenhouse design practices will need to address a range of issues, ranging from energy and land use efficiency to providing plant-optimized growth techniques. In this paper, we focus on investigating the optimum irradiation spectra matched to the lettuce species (*Lactuca sativa*, L.), commonly grown in greenhouse environments, in order to develop low-emissivity glass panes that maximize the biomass productivity of glass greenhouses. This low-emissivity glass passes the solar spectral components needed for crop growth, while rejecting other unwanted radiations. This could potentially lead to significant energy savings and other beneficial effects related to greenhouse climate control, in a range of climates. The experimental results show that substantial biomass productivity improvements in lettuce (up to approximately 14.7%) can be attained by using spectrally optimized illumination, instead of white light illumination. This optimized wavelength is then demonstrated as being used to develop an advanced metal-dielectric thin-film filter that produces the optimized illumination spectrum when exposed to sunlight.

2.2 Introduction

In 2050 the world could potentially be facing a food crisis. According to the United Nations Food and Agriculture Organisation (UN FAO), the world population is projected to be 39% above that of 2006, by 2050. However, several of the most food-insecure countries are projected to have much larger population increases, e.g. Niger (the country with the highest total fertility rate in the world), is projected to grow from 14 million in 2006 to 58 million in 2050, a 4.3-fold increase. Almost all of these countries have been in nearly perennial food insecurity for several decades [1]. A possible way forward has been proposed recently in The Lancet [32], which is to consider amending the diet of the population, to improve nutrition,

but also ensure environmental sustainability. According to the EAT-Lancet Commission, food systems can provide a healthy reference diet for an estimated global population of about 10 billion people by 2050 and remain within a safe operating space.

However, even small increases in consumption of red meat or dairy foods would make this goal difficult or impossible to achieve [33]. Within the proposed reference diet of the EAT-Lancet Commission, there is a strong focus on vegetables. All vegetables make up ~200-600 g/day of the macronutrient intake of a person on the proposed reference diet [33]. Of this range, approximately 100g/day is comprised of dark green vegetables [33]. These "dark green vegetables" are a rather broad category of plant species, loosely defined by their leaf coloration type. Spinach, and several lettuce sub-species also fit into this category.

Advanced growth technologies, such as innovative greenhouse production methods, are widely expected [8, 11, 12, 34, 35] to provide the practical solutions to these issues. Despite the growing body of knowledge and numerous literature reports detailing the beneficial effects of using some particular types of spectrally-optimized artificial irradiation profiles on plant growth, it becomes apparent, at present, that new multi-disciplinary approaches need to be developed for future greenhousing, combining the advantages of natural, filtered natural, artificial, and filtered-artificial irradiation regimes with energy efficiency improvements.

With this in mind, it will be beneficial to the world population along with the agriculture industry, if green vegetables, such as lettuce (*Lactuca sativa*, L.), could be efficiently mass-produced with minimal energy use, whilst maintaining the nutritional quality, simultaneously with achieving increases in the biomass growth productivity. To achieve this, harvesting solar energy using highly transparent solar photovoltaic (PV) windows has been considered. Solar PV is one of the most promising approaches to improving energy-efficiency in greenhouses, and can be combined synergistically with spectral shaping of the incoming solar radiation using thin-film filters, which can also reduce the solar heat gain (in hot climates), and help keep the heat trapped inside (in colder climates), whilst having the optical transmission peaks tuned to the photosynthetically- or yield-sensitive absorption bands of plant tissues.

Lactuca sativa L. was chosen as the sample plant, as it is a quantitative long-day plant at high temperatures and a day-neutral plant at low temperatures [7]. This allowed production yields to be maximized, by controlling both the irradiation timing and the ambient temperature so that when the length of day exceeds the length of the night that the plant detects, the plant

will not bolt, but will instead grow optimally. Additionally, the choice of plant type was also limited to available optical intensity levels at plant leaf surfaces, due to using LED sources of low power consumption and the necessity of providing an LED irradiation area as uniform as possible. High temperatures are considered to be approximately room temperature, 18–20 ◦C minimum [12]. Accordingly, the grow tents were kept at a temperature of approximately 21.4^{o}C. *Lactuca sativa* L. will "bolt", that is, flower too soon, when the temperature is not kept high and steady [7]. Bolting effects were not observed in our growth experiments. Increasing the length of day from that provided by the sun, would be necessary (throughout most or all locations based in moderate latitudes) for lettuce plants to grow optimally [7, 8, 12]. For greenhouse locations within or near the Arctic Circle, a summer growth season will include naturally-occurring long daylight conditions; however, the natural irradiation intensity will be much weaker, even near midday, compared to more temperate or hot climates. Utilizing artificial lighting, for example, LED lighting, is then either highly desirable, or necessary, and energy-efficiency considerations are of essential importance for large scale agricultural production [16, 20, 36], whether the greenhouse facilities are located in moderate or cold climates.

Greenhouse materials cover a broad range, from simple glass or plastics, to building integrated or building-applied advanced photovoltaic (BIPV or BAPV, respectively) greenhouse components. This has resulted in the emergence of a new field, Agrivoltaics [16]. The idea of a photovoltaic greenhouse is that photovoltaic modules are placed in various positions and configurations onto a greenhouse roof or walls, and the incident sunlight is used to not only grow the plants, but also generate electricity when the incident sunlight strikes the PV modules [16]. The problem with all or most photovoltaic greenhouses reported up to date, lies in the problem of PV modules taking up areas on the building envelope of the greenhouse, thus strongly shading the plants. These shading effects can also potentially lead to the undesirable bolting of plants [15]. Even the recently demonstrated organic advanced luminescent solar concentrator (LSC) technologies using luminescent solar cell technologies with conventional silicon-based PV, which are beginning to be adapted to greenhouses, are not free of this shading problem [5]. We attempt to remove this shading problem through combining high transparency spectrally selective thin-film technologies with all-inorganic glass and modern results in advanced agricultural practices, for example, spectrally optimized LED lighting.

During this study, we concentrated on growing lettuce plants in soil, within controlled grow tents, not dissimilar to growth chambers. The research aim was to determine which wavelength range(s) of visible electromagnetic radiation from LED light sources outputting narrow wavelength ranges, are required to obtain optimum biomass productivity in lettuce plants. This result would then be translated into research aimed at developing thin-film optical filters for application to glass for future proposed use on the roof or walls of a greenhouse. The thin-film optical filter will pass through only the solar spectral components required for optimum biomass growth of the sample plant (lettuce). Alternatively, the same thin-film components can be used to filter a range of broad-bandwidth artificial light sources used at nighttime, to further boost the overall greenhouse productivity, simultaneously with reducing the heat load inside the greenhouse. The results can then be translated into a customized thin-film filter which can then be used to filter the light spectra of any conventional broad-spectrum sources. Alternatively, these filters on glass substrates could be used as components of the Electron Science Research Institute's (ESRI) recently developed transparent solar energy harvesting windows [37, 38].

Biomass was chosen as the control factor, as it is an indicator of how well a plant has photosynthesized incoming sunlight to produce energy for growth and grown mass accordingly [7, 39]. The results obtained with spectrally optimized irradiation show an approximate 14% increase in dry biomass yield improvement when using the reduced spectrum Blue, Red and Far Red LED grow tent, compared to the white LED control grow tent. Additionally, an approximate 6% increase in biomass yield was demonstrated when using the reduced spectrum Blue and Red grow tent. This is a significant increase in biomass productivity, given that the available light for photosynthesis has been decreased in both grow tents in comparison to the white LED control tent. The present research presents a viable way forward towards the next generation of spectrally-selective greenhouses. We also point out that genetic measurements of the harvested lettuce plants were not taken in this experiment. Future experiments will consider the question as to whether the lettuce that was grown under the LEDs and also under the thin film filter with sunlight as the source, are suitably nutritionally edible.

In order to lengthen the photo period per day in a greenhouse, many PV greenhouses use the electricity generated to power artificial lighting systems [36]. This is not efficient overall, since a product of three conversion efficiency factors (the PV efficiency, the battery storage

efficiency, and the electrical-to-optical conversion efficiency applicable to the light sources) will require further consideration [20, 37]. Even if the most efficient electronic systems and LED components were used, the result is still not particularly efficient.

These considerations suggest that using passive optical components for filtering the natural sunlight spectrum is a more efficient approach to providing improved energy consumption, in comparison to using the most efficient of LED lighting systems. The energy balance improvements potentially offered by the use of these spectrally selective filters could be further enhanced if the films are integrated into transparent solar windows [37]. Regarding future research efforts, the investigation of the combined beneficial effects on both the plant growth and the greenhouse energy efficiency in outdoor installations will be of interest. This would have to be researched using a combination of natural lighting optimally filtered through solar window coatings, and spectrally tuned artificial lighting systems or filtered white artificial lighting systems.

2.3 Background, Prior Studies and Experimental Methodologies

Research already conducted in this area has reported increased biomass productivity when using combinations of various LED light sources in comparison to fluorescent lamp-based lighting as the control group [39]. Additionally, using different combinations of LED lights at various stages of lettuce plant growth has also been reported to increase dry biomass [11]. Currently, the published literature sources have not investigated using white LED lighting systems as a control group, and comparing the biomass increases under various different light conditions to this control. In this paper, we particularly correlate illumination spectra that comprise far-red wavebands to the biomass of the lettuce plants.

By adjusting the outputs of the LED lighting systems so as to approximate within the technical limits applicable to the maximum light source outputs at each wavelength, the absorption of naturally occurring sunlight as far as possible intercepted by the leaves during each 24-hour period within either the full spectrum of a combined-LED source, or the spectral radiation components of discrete LED sources, quantitative characterisation of irradiating light is enabled. Then, the biomass results could be considered comparable to experiments conducted in a greenhouse employing glass coated with thin-film filters designed to shape the spectra accordingly. The subsequent sections describe the details of our

approach, methodologies, experimental activities and results. The results were able to be used to design a customized metal dielectric thin-film optical filter suitable for improving plant productivity concurrently with being suitable for integration into energy generating solar windows.

The experiments were conducted using three Heliospectra LX602C LED light sources supplied by Heliospectra (Göteborg, Sweden). The core hypothesis was that improved lettuce plant productivity could be achieved by focusing on each of the three important regions of illumination, that is, blue, red, and far red (visible region of NIR). This was when compared to broad-band energy-efficient LED artificial lighting emulating a white spectrum, for lettuce. This hypothesis was based on the existing body of literature, in which the existence of photosynthetic productive spectral ranges, where the importance of far-red, has been reported [39, 40]. However, no direct growth productivity comparisons are available for *Lactuca sativa*, L., in which white LED sources were used as a reference in regard to biomass. While the far-red light is not absorbed sufficiently strongly in plants to be important for photosynthesis, other phenomena (e.g. photomorphogenetic phenomena in plants) depend on this range of wavelengths – thus, the biomass production can still benefit from far red supplementary lighting.

Due to a much wider market acceptance of white LED lighting sources compared to the narrow-linewidth red or blue LEDs used in specialized applications, it can easily be foreseen that the use of cost-efficient and economic white LED lighting of high optical power output per Watt of consumed energy will continue to grow in commercial greenhouse environments. The effect of different wavelengths on the relative efficiency of photosynthesis per incident photon for a single leaf in low-light conditions reported in [41] and illustrated in [42], also suggests the potential benefits of broad-band illumination versus using the narrow-linewidth discrete sources. The fact that almost all plant life has evolved under the naturally-occurring sunlight (a very broad-bandwidth light source) points to the potential usefulness of broad-bandwidth sources in greenhousing, even though white LEDs cannot match natural sunlight very closely for photosynthesis stimulation. A recent review article [43] provided some examples showing how the combinations of LED sources can approximately match the natural sunlight to ensure the growth and development of photosynthetic organisms, and how the changes in intensity and wavelength can manipulate plant metabolism. The multiple

benefits of using LED sources in greenhousing, compared to high intensity discharge lamps, such as metal halide and high-pressure sodium lamps, are also discussed in [43].

Additionally, ESRI's prior preliminary experiments growing capsicums in growth tents using Heliospectra light sources, having the combinations in individual grow tents of (blue and far-red), and (red and far-red) compared to white LED illumination, lead to the finding that far-red was a tangible and significant growth stimulator. This also led to observing up to a 46% increase in wet weight between the red, far-red light condition, compared to the white light condition (for capsicums). As it is known in the literature that blue LED light is also required for optimum plant growth resulting in optimum biomass [11, 39], the experiment was designed to compare one light treatment of blue and red LED light to another light treatment of blue, red and far-red LED light and both treatments compared to the control of white LED light.

The Heliospectra LED light sources are programmable to emit wavelengths of light at 448nm (visible blue spectrum), 666nm (visible red spectrum), 736nm (visible far-red spectrum) and the broader spectrum white LED light (5700K white visible light having peaks at approximately 446nm, 534nm and 625nm). The wavelengths can be tailored to emit in different combinations at varying power output (referred to as an 'intensity' setting on the Heliospectra system, however not actually an intensity measurement value). The spectral plots of the different light treatments in each grow tent are shown in Figure 14. The spectral plots were measured using a fiber visible spectrometer (Ocean Optics, USB 2000, calibrated according to the manufacturer instructions) configured for diffused reflectance spectrum measurements, with two measurements taken. Point 1 directly under the LED in the centre of each grow tent at plant height approximately 130mm above the pot, point 2 at the right of the tent in the center of the LED light also at plant height approximately 130mm above the pot. The averages of the two measurements are plotted in Figure 15 (a) – (c).

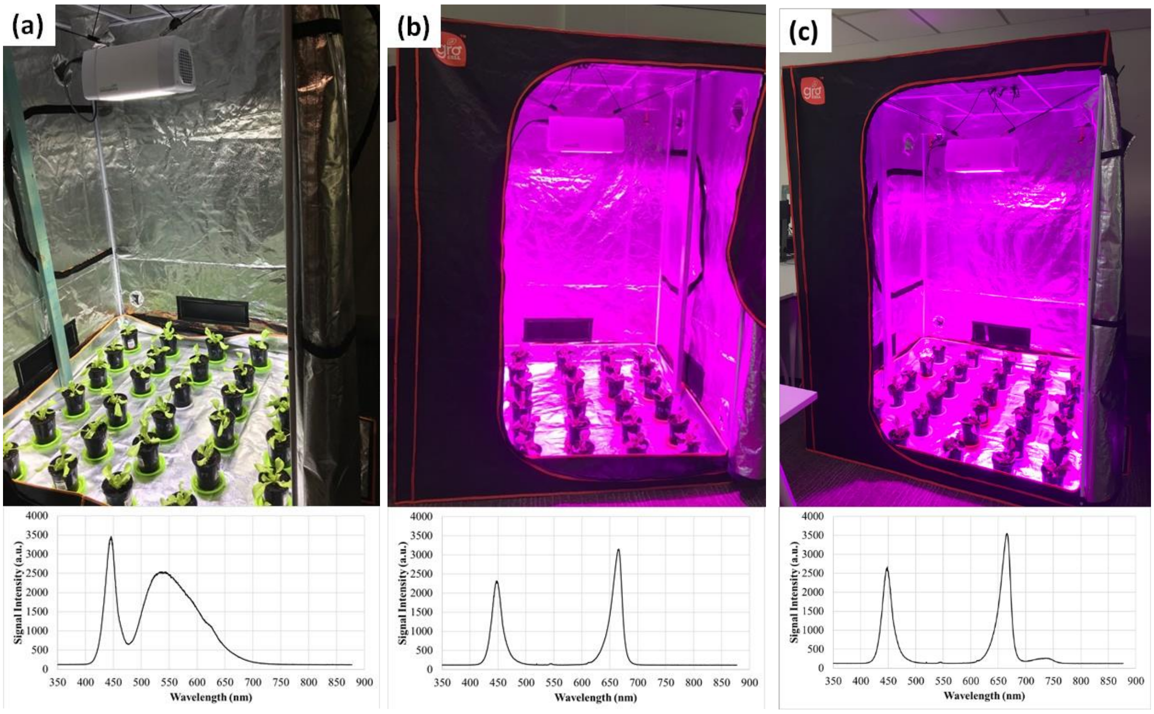


Figure 15. Illumination spectra used in each grow tent. (a) Grow Tent 1 has a white control spectrum of 1000 Heliospectra 'intensity' setting. (b) Grow Tent 2 has a blue and red control spectrum of blue 1000 Heliospectra 'intensity' setting, and red 458 Heliospectra 'intensity' setting. (c) Grow Tent 3 has a blue, red and far red control spectrum of blue 1000 Heliospectra 'intensity' setting, red 458 Heliospectra 'intensity' setting, and far red 1000 Heliospectra 'intensity' setting. The photos were taken at 9 days after planting from seedling.

The spectrum power ('intensity' reading) values were determined after calibrating the Heliospectra LED light source to the power output and distance from the LED light for the various wavelengths. A detailed description of the power calibration procedure is set out in Chapter 2.3.1**,** where the wavelength calibration procedure used to periodically re-check the performance of the Ocean Optics spectrometer is also described.

2.3.1 Calibration of the Heliospectra LED Source

The Heliospectra LED light source was calibrated using the hand-held laser power meter LaserCheck (Coherent, Oregon, USA). It was set to a specific wavelength to be measured, then the Heliospectra was turned on at intervals of 100 'intensity' readings, and the LaserCheck meter was used to measure the power density (Wm^{-2}) at 0.2 m height intervals from, directly under the LED source down to pot height. This was conducted to determine the power output required from the Heliospectra LED light source at plant height, in order to attempt to emulate the Heliospectra output to the output power from the sun, across an 18 hour day/6 hour night, time interval, as discussed in the literature to be an optimum daylight

time interval for lettuce [8, 10], within the constraints of the Heliospectra system. The calibration utilized the following data constraints, not to scale.

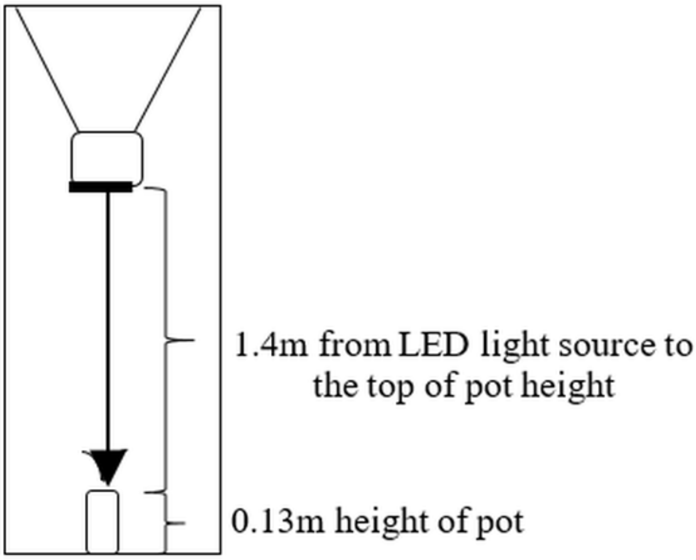
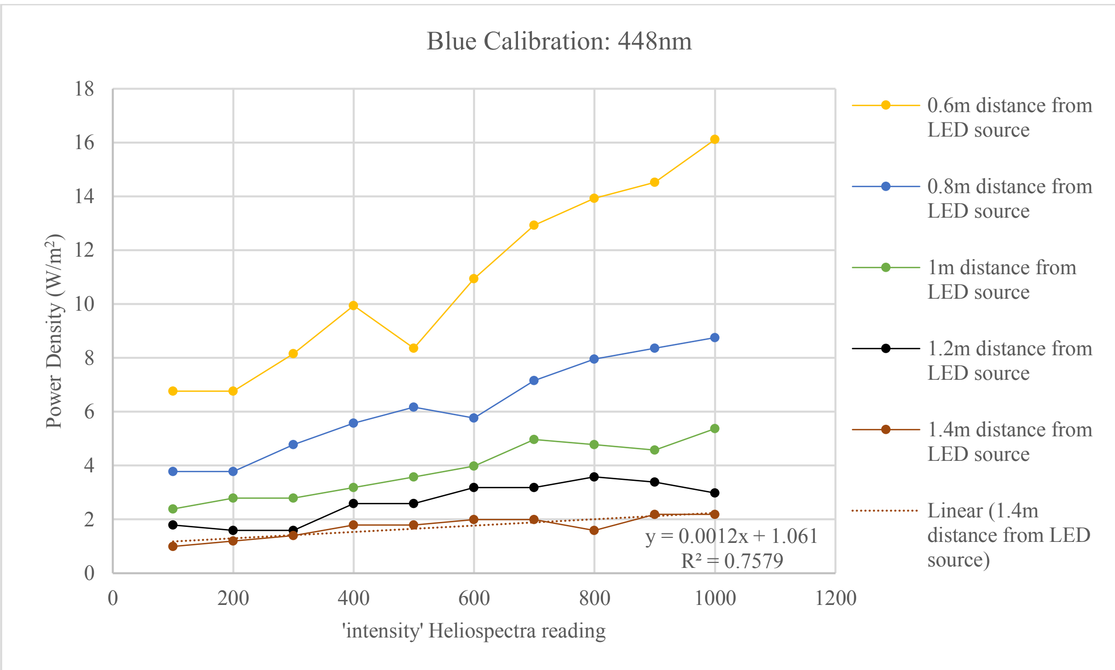
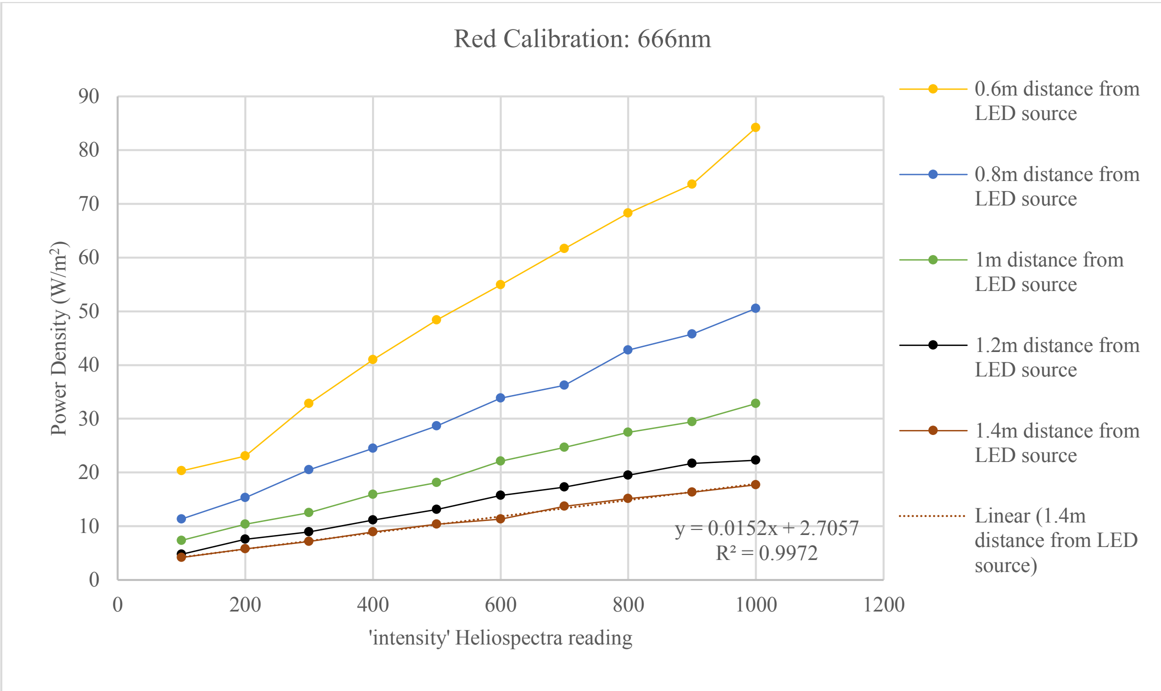


Figure 16. Schematic diagram of the Heliospectra LED source calibration setup.

The calibration graphs were obtained for the range 1.4–0.6 m from the LED data (where the plants grew between 1.2–1.4 m from the LED source in height, growing closer to the source, i.e., closer to 1.2 m as growing). A linear regression line was fitted to the 1.4 m from the LED source data, which is approximately at pot height (the pot top being approximately 13 cm from the ground).



(a)



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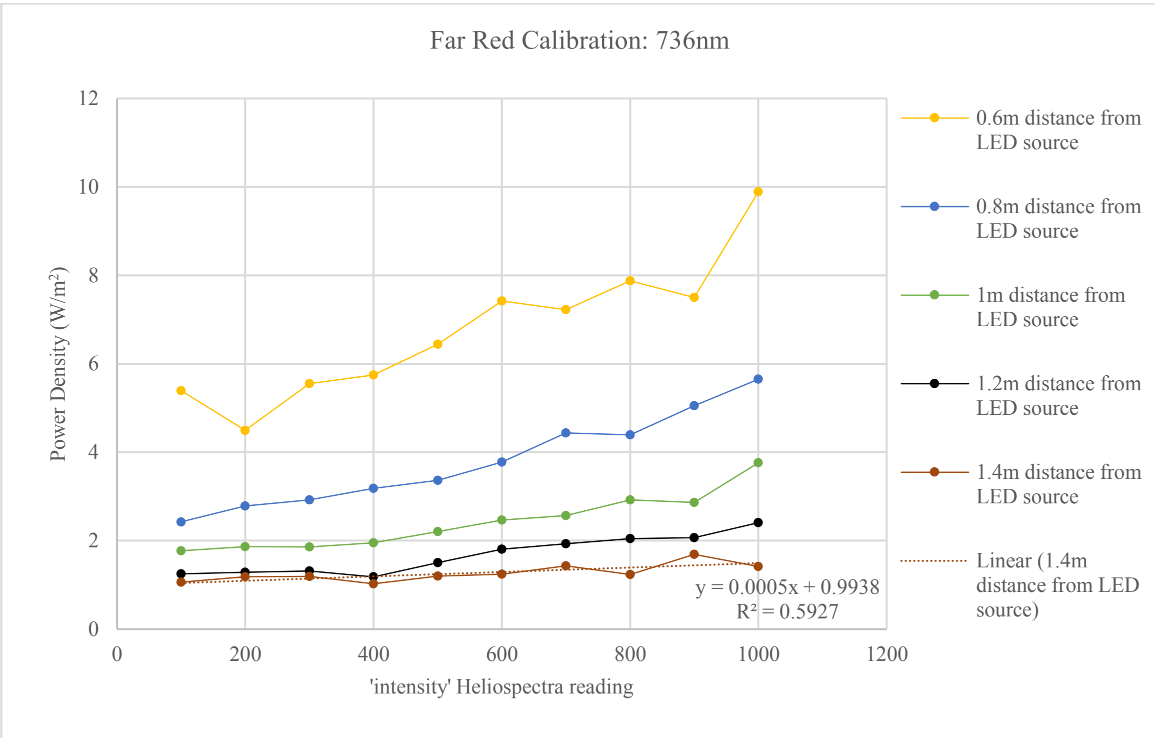


(c)

Figure 17 (a)-(c). The power density calibration plots of the Heliospectra LED source.

2.3.2 Photon Flux Density (PFD) Calibration to the Heliospectra 'Intensity' Reading

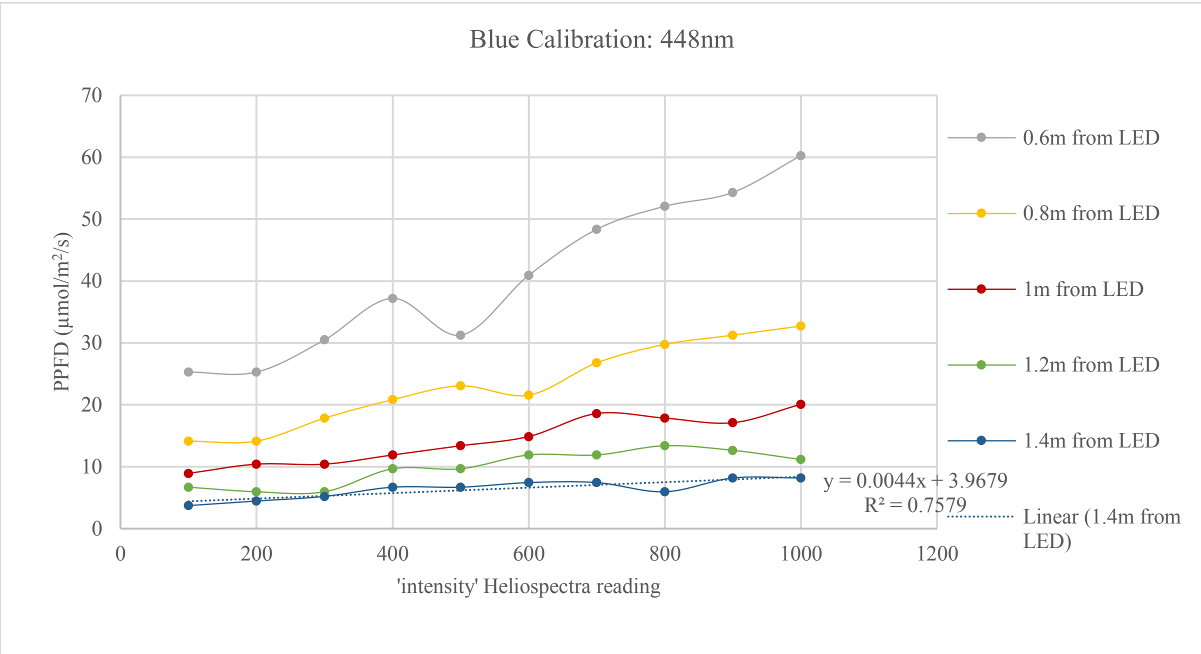
The photon flux density (PFD) is the number of photons in the wavelength regions under consideration ($\mu molm^{-2}s^{-1}$) [7]. The wavelength regions of interest are selected because of their relevance to either the photosynthetic response, and/or the plant production yield. Using the power density (W/m^2), and the formula to convert the power density to PFD, as shown below [44].

$1\ Js^{-1} = 1W$

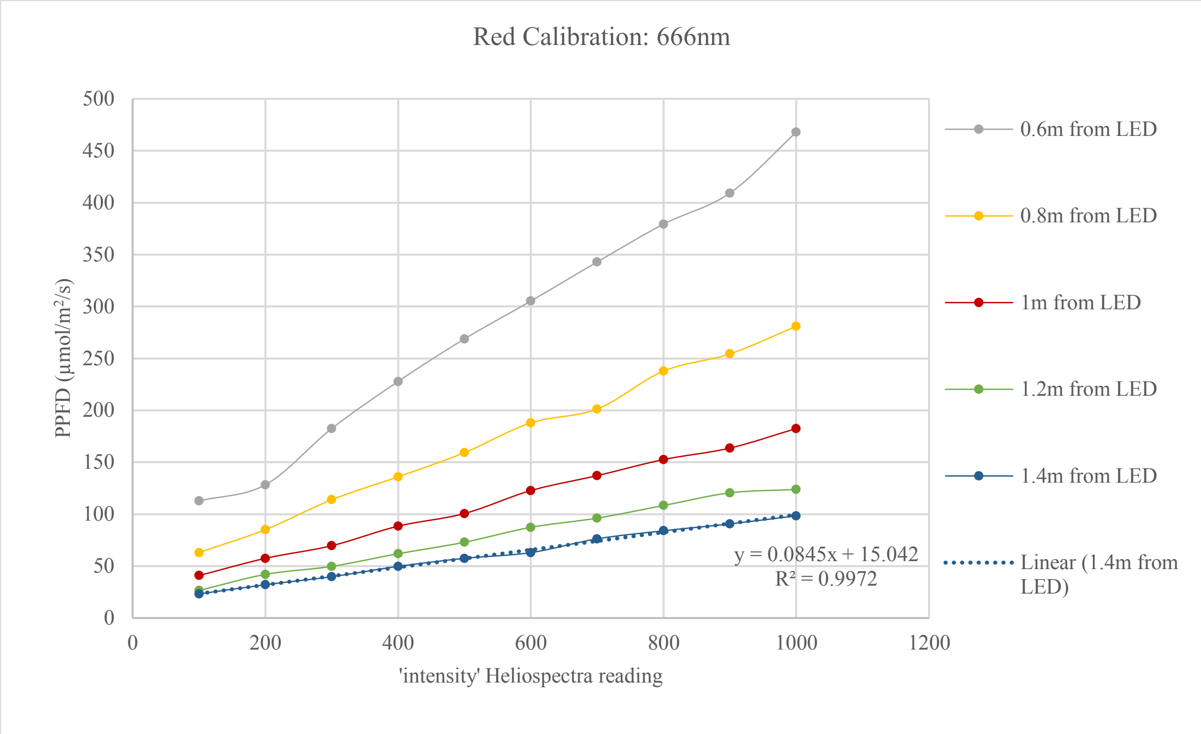
Photon Irradiance ($mol.m^{-2}s^{-1}$) or Photon Flux Density (PFD) = $\frac{E}{\left(\frac{c.h}{\lambda}\right).N}$

where:
E = Energy (J)
c = Speed of light = $3.0 \times 10^8 ms^{-1}$
h = Planck's constant = 6.63×10^{-34} Js
N = Avogadro's number = 6.023×10^{23} quanta mol^{-1}
λ = wavelength (m)

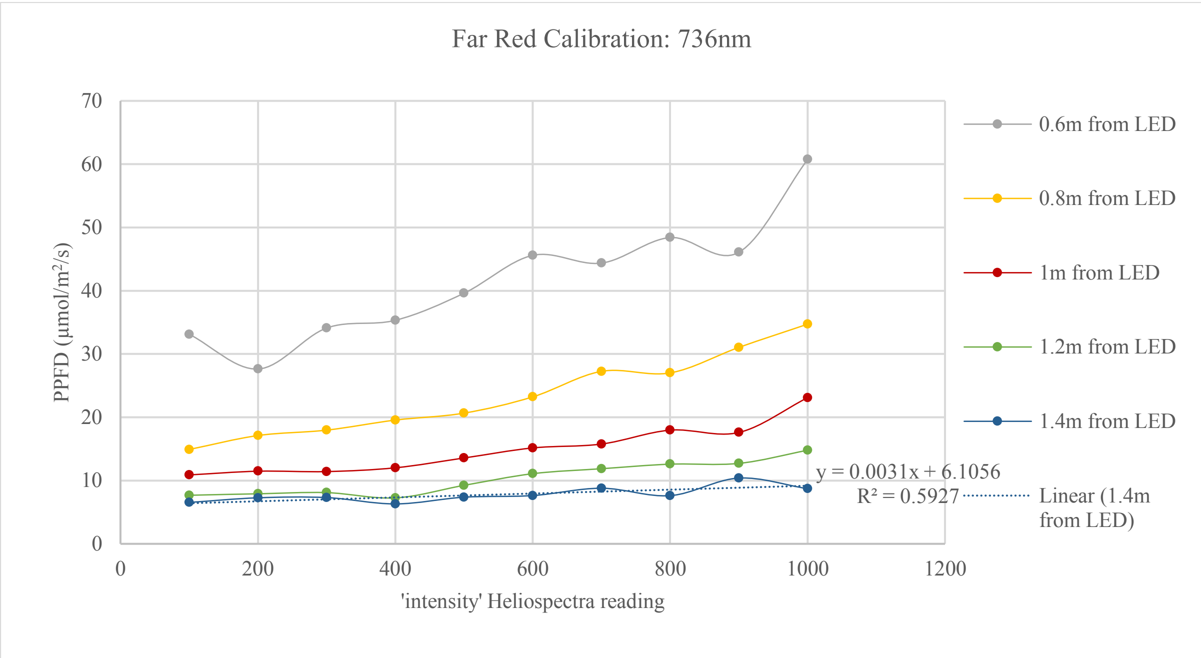
A linear regression was then applied to the 1.4 m results (measured from the LED down to the top of the pot).



(a)



(b)



(c)

Figure 18 (a)-(c). The photon flux density calibration plots of the Heliospectra LED source.

The PFD values determined were:

Tent 1—White at 1000 'intensity': ~101 $\mu molm^{-2}s^{-1}$ (3 s.f.)

Tent 2—Blue at 1000 'intensity', Red at 458 'intensity': ~61.9 $\mu molm^{-2}s^{-1}$ (3 s.f.)

Tent 3—Blue at 1000 'intensity', Red at 458 'intensity', Far Red at 1000 'intensity':

~70.6 μmol$m^{-2}s^{-1}$ (3 s.f.)

2.3.3 Wavelength Calibration of Ocean Optics Fiber Spectrometer

Periodically, tests of the wavelength calibration accuracy of the fiber spectrometer instrument were made, using a range of diode-pumped solid-state, semiconductor, and gas (red He–Ne) laser sources of known wavelength.

The technical essence of the procedure is checking that a light source of a particular central wavelength, Full Width Half Maximum (FWHM) bandwidth, and spectral emission line shape, is measured with the spectrometer as a spectral distribution fitting these specifications, to an acceptable degree of error (usually being about ± 1 nm for most optical source measurements not requiring mode distribution analysis, or the characterization of longitudinal coherence properties).

It is necessary to check the wavelength calibration stability and accuracy across the entire spectrum range of the measurements required. Therefore, three solid-state laser sources were commonly used, a 473 nm blue laser, 532 nm green diode-pumped solid state (DPSS) laser (featuring frequency doubling of a stable 1064 nm radiation line from an Nd:YAG crystal pumped by an 808 nm semiconductor laser), a 635 nm red DPSS laser, and a 670 nm semiconductor laser. These sources covered the entire spectral range of interest where the broadest (white LED) Heliospectra source had any significant optical output. The maximum spectral drifts noted so far in the spectrometer wavelength calibration never exceeded about ± 1 nm, gauged from the spectral positions of the measured emission peaks with respect to the known wavelengths.

2.4 Correlating Source Power Density to the Incident Energy Available to Plants Over Daytime Irradiation Periods

We used the spectral intensity distribution data measured for the optical compound-source output from the Heliospectra, to derive the full width half maximum (FWHM) partial-source LED bandwidth data at each of the central (peak) LED wavelengths, for each of the colours (448nm, 666nm and 736nm) generated by the Heliospectra system. These data and parameters are needed to correlate the total optical energy received by lettuce leaves (each 1cm2, per each artificial irradiation daytime duration), to the naturally occurring solar

irradiation conditions. This correlation cannot be made to exactly mimic the daily solar energy absorption, but this is not necessary, due to the intrinsic variability of natural sunlight, the impracticality of using large-area solar simulators in greenhouse experiments, and also due to the output power range limitations applicable to all available LED sources. The energy intercepted by leaves from the natural solar irradiation can be evaluated (for peak sunshine conditions) by numerically integrating the standard (AM1.5G) spectral power density distribution, over the spectral limits corresponding to the central wavelength of each LED source and its FWHM boundaries, and by multiplying the resulting flux density (per each source, in W/m2) by the typical peak-equivalent sunshine hours (PSH) value. The results of these calculations then approximate the total energy intercepted by leaves, per unit area, per unit irradiation time (or per average day, in the case of natural sunlight), thus, allowing adjustment of the LED source driver settings and choice of the most practical source-to-plant distance, together with the artificial daylight duration, to mimic within the limitations, the energy available to plants from natural sunlight daily. Considering the natural, weather and season-related variability of natural sunlight, being able to correlate the available energy within each discrete spectral band to within approx. the same order of magnitude (compared to the peak-time, clear-day sunshine conditions), will then approximately model the natural illumination. Natural sunlight also varies by about one order of magnitude in flux density, over the course of a typical sunny day. The visual appearance of the white can also confirm the suitability of white LED for mimicking natural sunlight LED illumination background at the floor level in tens (Figure 14a). This is also taking into consideration that the human eye, being an organ of vision, is a much more sensitive detector of the spectral intensity distribution of light, compared to at least the plant leaves, and the discrete-source artificial lighting background mimics sunlight in terms of its visual appearance.

The industrial use of white LED light sources in greenhousing is expanding continually at present, and the results reported in relation to plant growth experiments show that white LED irradiation did, in fact, lead to observing biomass growth improvements, compared to natural sunlight [21].

Thus, we believe that this type of broad-band light source can be used as a reference against which to compare the growth results obtained in other growth tents with more discrete-source, narrow-band combination-source spectra. The superior long-term stability of its spectral distribution and flux density (measured at leaf level during the 18-h daily irradiation

period) is also a very important factor in running quantitative biomass-growth experiments. Moreover, obtaining improved biomass productivity and/or growth rate results, using more narrow-band lighting, can indicate that using a combination of filtered natural and filtered artificial (broad-band, e.g., metal-halide) light sources could improve greenhouse productivity. This would be done through designing a thin-film filter that modifies the natural sunlight to the spectral specifications close to those of the LED source that were identified by the experiment as providing optimum biomass results for lettuce. Furthermore, this would need additional confirmation in experiments which will be conducted at the solar window greenhouse to be constructed at Murdoch University (Perth, WA, Australia), in 2020. The scope of this study is limited to growth tent experiments, which compare the uses of artificial broad-band (white-LED) and artificial narrow-band (a combination of other LEDs).

A custom-built spectral calculator (spectral integrator) program (designed by M. Vasiliev, ESRI, Edith Cowan University) was used to numerically integrate the standard NREL's data [45] for the sunlight power density distribution, using the spectral characterization data (integration limits) obtained for each artificial (LED) source. For the far-red LED source, the peak sunshine-equivalent natural-sunlight irradiation intensity was calculated to be 52.489 W/m^2 (rounded to 3 decimal places (3 d.p.)). The peak-equivalent daily sunshine conditions last for about 4.5 hours per day (4.5 PSH is a conservative estimate derived from averaging the peak-equivalent sunshine hours for Australia and the US [46, 47]). Using these data for the PSH and for the target power density to be achieved at plant leaf, the daily energy available to natural-sunlight driven processes incident at the far-red wavelength selected, equates to about 850.328 kJ/m^2/day. In comparison, full power (1000 'intensity' far-red setting) of the Heliospectra at approximately 1.4 m from the LED source, over an 18-hour day provides only 96.798 kJ/m^2/day. That is, the Heliospectra will need to be kept at full power over an 18-hour day and will still provide a fraction of the far-red energy, compared to what the sun provides, at this source-to-plant distance, on a clear sunny day. Thus, achieving any measurable biomass productivity improvements attributable (at least in part) to use this relatively low-power LED source can suggest that a proposed thin-film filter design for glass greenhouses should aim at maximising transmission of light in the far-red range.

The red and blue wavelengths were also considered in the same manner, yielding the blue power density to be achieved as approximately 28.519 W/m^2. This equates to about 462 kJ/m^2/day, considering 4.5 PSH and a clear sunny day. Comparing this to the full power (1000 'intensity' setting) of the Heliospectra at the initial plant height, being approximately at

1.4m from the LED source, over an 18-hour day this would provide approximately 146.5 kJ/m^2/day. That is, the full power setting of blue will need to be used. Therefore, it was determined to maintain the blue source also at full power, rather than drop the height of the LED source, as red LED energy output still needed to be considered. In a similar manner, the red power density to be achieved was approximately 33.4 W/m^2. This equates to approximately 541.14 kJ/m^2/day. Comparing this to the full power (1000 'intensity' setting) of the Heliospectra at the initial plant height, being approximately at 1.4m from the LED source, over an 18-hour day, this would provide approximately 1160 kJ/m^2/ day. That is, at the full power setting of red LED, the Heliospectra at a height from ground of 1.53m, will provide more light energy in the red visible range than the sun on an average clear sunny day. This issue was overcome by reducing the intensity of the red source from its full power to approximately half power as there was approximately a 2.1 factor increase in the 18-h daily energy from the Heliospectra for red LED, in comparison to the output of the sun over a 4.5 PSH day, in the same wavelength range defined by the source FWHM. Accordingly, the Heliospectra was operated at 458 'intensity clicks' reading in the red (666nm) power supply setting.

It was observed in prior preliminary experiments with capsicum plants, that if the LED light source is hung too close at approximately 0.6m from the ground, that this caused the plants on the outer peripheral edges of the tent to bolt, due to not receiving enough light, and the plants within the range of the light to become yellow, due to receiving too much light. Therefore, it was determined for even spread of the light within the tent, to hang the LED light as high as possible within the constraints of the tent. This allowed the reflective sides of the tent to be utilized to the fullest effect. In addition, the wooden posts supporting the tent were kept as close to the edges as possible, to provide only minimal shading to the plants, to prevent bolting as much as possible.

2.4.1 Power Consumption of LED Light Treatments

The power consumed by the light treatment in each grow tent was measured using an off-the-shelf energy cost meter (Electus Distribution Pty Ltd., Rydalmere, NSW, Australia). The meter was used to directly quantify the power consumed (W), as well as the voltages and currents required by the power supplies of the lighting appliances in each tent. The three

lighting configurations were comparable (almost identical) in terms of power consumption, as outlined in Table 3.

Table 3. The power being consumed (W) for the light treatments in each grow tent.

Grow Tent Light Treatment	Power Consumption (W)
White: Tent 1	245.2
Red, blue: Tent 2	209
Red, blue, far-red: Tent 3	256.8

Therefore, using the more complex lighting appliance configuration employing an optimized triple-wavelength combination source has maintained essentially the same energy-efficiency as a common white light LED source. These data also indicate that future commercial greenhouse installations may also benefit from replacing conventional lighting appliances with optimized multi-wavelength LED sources. This would be in conjunction with passive thin-film filters, so as to shape and optimize the illumination spectra as required, throughout the day.

2.5 Plant Materials and Experimental Setup Details

90 baby butter head lettuce (*Lactuca sativa* L.) seedlings were sown individually in high quality seed and cutting potting mix in pots of 13 cm height. An additional sample of five seedlings was culled, dried, weighed and averaged to obtain a zero-biomass starting point. The position of the plants within each tent was randomised every 7-8 days throughout the duration of the 39d experiment. 50mL of water was supplied by hand every day to each individual plant within each tent. Every 14 days, 50mL of diluted liquid nutrient (Scotts Osmocote Plus Organics non-MU concentrate liquid fertilizer and soil improver diluted to approximately 0.06g urea and approximately 0.04g of other non-hazardous ingredients) was supplied to each plant, without any additional water [48].

The plants were illuminated inside each closed grow tent under different light treatments for an 18h photoperiod. Grow Tent 1 received a light treatment of full power white light (1000 Heliospectra 'intensity' reading). Note: the 'intensity' of the Heliospectra LED light source is directly related to the power density, however the 'intensity' is not actually a measurement in the units of intensity. Therefore, for the purpose of this paper, the 'intensity' when referring

to the reading on the Heliospectra system, will be placed in inverted commas (‘’). Grow Tent 2 received a light treatment of full power blue 448nm LED light (1000 Heliospectra ‘intensity’ reading) and approximately half power red 666nm LED light (458 Heliospectra ‘intensity’ reading). Grow Tent 3 received a light treatment of full power blue 448nm LED light (1000 Heliospectra ‘intensity’ reading), approximately half power red 666nm LED light (458 Heliospectra ‘intensity’ reading), and full power far-red 736nm LED light (1000 Heliospectra ‘intensity’ reading).

The ‘intensity’ values chosen model sunlight as closely as possible within the constraints of the Heliospectra LED light source. The LEDs were operated during the afternoon and evening from approximately 16:00 – 10:00 and off for six hours between approximately 10:00 – 16:00. The grow tents were substantially closed, except for panels with netting to allow air flow in, on three of four sides towards the base of the tent for ventilation. The fourth side was the entrance to the tent, and the zip was left open towards the base to further increase air flow and ventilation. The tents were opened daily to water each plant, and when randomizing the position of the plants. Otherwise, the tents remained essentially closed.

The parameters measured included the wet weight (g/plant), dry weight (g/plant) and biomass (g) of each plant. The photosynthetically active radiation (PAR) was measured via correlation to the power density for each light treatment, and the photosynthetic photon flux density (µmolm-2s-1) was calculated. Figures of the growth results at different stages of the experiment are shown in Figure 19.

Photos of each plant were taken approximately at 2 week intervals during the experiment, specifically days 12/13, days 22/23 and day 34. Plant 8, from each grow tent is shown in Figure 19 as a random sample from the 90 plant set. As can be observed, the growth characteristics over the 39d growing period was visually similar, and this observation was confirmed by the average wet weights (g/plant) being very similar between the grow tents.

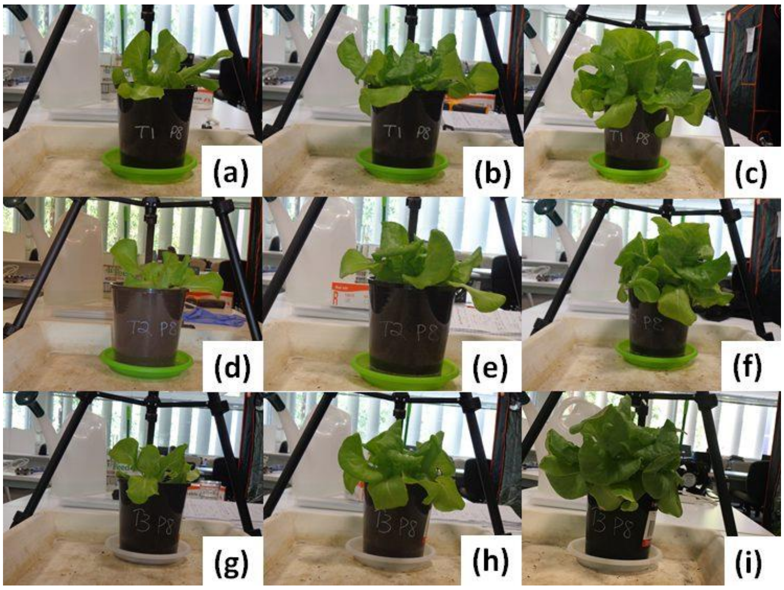


Figure 19. Growth of a randomly selected plant, the same plant number within each of the three different illuminated grow tents. (a)-(c) Grow Tent 1, Plant 8 growth from (a) day 12, (b) day 22 and (c) day 34. (d)-(f) Grow Tent 2, Plant 8 growth from (d) day 12, (e) day 23 and (f) day 34. (g)-(i) Grow Tent 3, Plant 8 growth from (g) day 13, (h) day 23 and (i) day 34.

Heliospectra LX602C LED light sources were used due to the availability of wavelength channels and the range of power output. Inside each grow tent, a Heliospectra LX602C LED light source was hung at 1.4m above the top of each pot, where the pots were placed on the ground. Wood bracing was used to brace the structure of the tent so as to support the weight of the light source. The photon flux density (PFD) values determined from the calibration method outlined in Chapter 2.3.2 are summarised in Table 4.

Table 4. The normalized ratio of blue to red LED light and red to far-red LED light using the calculated PFD. Please note that the calculated PFD figure has been evaluated with less accuracy for the white light source, compared to other LED, due to the nature of this compound-source spectrum.

Grow Tent	Photon Flux Density (PFD)	Blue to Red Ratio Normalized	Red to Far-Red Ratio Normalised
1 - White, 1000 ‘intensity’	~101µmolm^{-2}s^{-1} (3 s.f.)	N/A	N/A
2 – Blue, 1000 ‘intensity’; Red, 458 ‘intensity’	~ 61.9µmolm^{-2}s^{-1} (3 s.f.)	1:6.6	N/A
3 - Blue, 1000 ‘intensity’; Red, 458 ‘intensity’; Far Red, 1000 ‘intensity’	~70.6µmolm^{-2}s^{-1} (3 s.f.)	1:6.6	1:0.16

The first (White) control grow tent had a greater PFD than the third (blue, red, far-red) grow tent, yet the first (White) grow tent had the least biomass, and the third grow tent (blue, red, far-red) had the greatest biomass.

2.6 Principal Results and Discussion

Comparing data to that reported by other researchers, it was noted that Lee et al. [39] used various ratios of red to far-red LED light and blue LED light, however, the control for the experiment was a fluorescent lamp, not white LED. Therefore, the results could not be accurately compared to this paper [39], due to the difference in the controls and the blue to red, and red to far-red ratios being substantially different to that of the experiment conducted by ESRI. Lee et al. [39] used the ratios of blue to red 2:8, and red to far-red ratios of 0.7, 1.2, 4.1, 8.6. Han et al. [49] suggested that the ideal light for lettuce is a combination of red, yellow, and blue LED light. However, the comparison between the narrow white or broad white results, and the red, yellow, and blue results indicate that the biomass increase was about 1/3 more in total weight (g) for the red, yellow and blue results. Both results in the broad white and narrow white appear (from the results shown in the article [49]) to be approximately equal. After 22 days, the dry total weight of plants in the red, yellow, blue LED light-treatment experiment was approximately 5g. Extrapolating to compare to our experimental results at 22 days (from the 0-39 days growth timeframe) indicates that the red, blue, far red (R, B, FR) results at 22 days would have been approximately 3.2g. Whilst this figure is less than that reported by Han et al. [49], it can also be noted that the red, yellow, blue results of Han et al. were receiving more normalized PFD, in comparison to the other light treatments. The PFD values of our experiment were greatest in the white light tent (which had the least biomass results), and the second-largest in the blue, red, and far-red tent (which actually had the greatest biomass results). It is important to note that biomass growth results have been reported to not necessarily vary linearly with photon flux density [50]. The results for the average fresh leaf weight, dry leaf weight, and biomass of the plants are shown in Table 5.

Table 5. The average fresh weight (FW), average dry weight (DW) and average biomass over the 90-plant sample.

Day	LED Treatment	Leaf		
		Average FW (g/plant)	Average DW (g/plant)	Mean Biomass (g/plant); Standard Deviation (g)
0 - Zero biomass	N/A	1.68	0.07	0.07
39	White	83.45	4.91	4.84; 0.4156
	Blue + red	84.55	5.22	5.15; 0.4853
	Blue + red + far-red visible	84.23	5.62	5.55; 0.3553

The raw data on the dry biomass obtained from each of the samples in each of the grow tents are shown in Figure 20, together with the graphical analysis of the relevant data distributions. The results indicate that the light condition of blue + red + far-red visible LED light provided the highest average dry weight and the highest average biomass, and the second-highest average fresh weight. The highest wet weight was produced under the blue and red visible LED light treatment. The white LED light treatment, which was used as the control, produced the lowest average fresh weight, the lowest average dry weight and the lowest average biomass. The T-tests were run (using standard Microsoft Excel functions providing a 2-sample array-based t-test evaluation for 2-tailed sample population distributions with unequal variance) using the dry weight data arrays for each pair of datasets. The numerical value outputs of these t-tests return the probability associated with a Student's t-test, which determines whether the two samples are likely to have come from the same two underlying populations that have the same mean. The t-test results obtained revealed evidence of a strong, statistically significant difference between the population means, in each of the tests. Numerically, the t-test results obtained from each pair of grow tents were: TTEST(T1,T2) = 0.0104, TTEST(T1,T3) = 2.037×10^{-9}, and TTEST(T2,T3) = 0.00057.

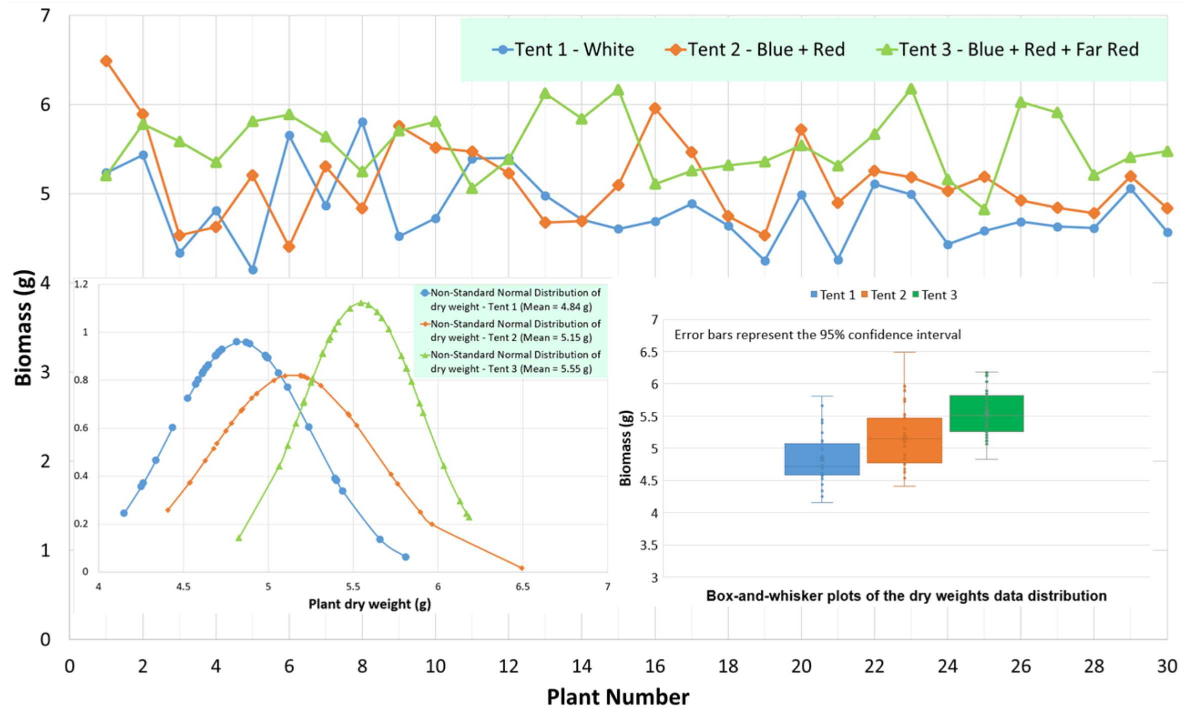


Figure 20. Graphical analysis of each of the grow tents, and the biomasses obtained by each plant within each tent (total of 90 plants).

The biomass results indicate that on comparison with the white (W) light treatment, the biomass in the blue + red + far-red light treatment was approximately 14.7% (3 s.f.) higher than the biomass in the W light treatment. Additionally, the biomass in the blue + red light treatment in comparison to the W light treatment, was approximately 6.41% (3 s.f.) higher than the W light treatment. The addition of far-red illumination source (adding approximately 8.7 $\mu molm^{-2}s^{-1}$ to the total PFD, which contributed an extra 14.05% to the total PFD) has led to a biomass increase of about 7.767%, compared to using the blue and red light only. The light in the W light treatment was broader and received more PPF than the discrete light treatments in the blue + red, and the blue + red + far-red light treatments. Therefore, it could be hypothesized that the W control tent would have the greatest biomass. At the very least, the control group has not excluded any particular wavelength range, avoiding any accidental productivity reductions, due to excluding any known wavelengths of importance. The results, however, contradict this hypothesis. Even though it could have been anticipated that providing a greater amount of photon energy widely distributed across the spectrum would lead to generating greater biomass, it is also known that the light intensity response curve of photosynthesis is not flat.

The experimental results indicate that within the experiment, the wavelength range offering substantial biomass improvements for *Lactuca sativa* L., in comparison with the White LED control grow tent, are LED sources in the following spectral ranges: 448nm (blue, FWHM 430nm – 470nm), and the range 666nm – 736nm (red, FWHM 650nm – 678nm, and far-red visible, FWHM 714nm – 758nm respectively). As such, the narrow band central wavelength of 448nm and the larger wavelength band of 666nm – 736nm were used to design the thin-film filter. All other wavelengths, that is, green (approximately 500-600nm) visible, ultraviolet (UV approximately 10nm – approximately 400nm) and infrared (IR approximately 780nm-1000μm [51]) were filtered.

2.7 Thin-Film Filter for Future Solar Window Greenhouses

As transmission characteristics of materials vary as a function of wavelength and type of material, it is necessary to choose materials that can provide the desired transmission characteristics when combined together into layers [52, 53]. A theoretical example having 18 layers and three materials (MgF_2, ZnS, Ag) is shown below, followed by a more practical fabrication example having nine layers with three materials (Al_2O_3, ZnS, Ag).

The thin-film optical filter will ideally attenuate the waveband from 300nm to 400nm, provide maximum transmission (allow the visible light to pass through) at 401-500nm (blue), then suppress the waveband from 501nm to 600nm (green and yellow), and provide maximum transmission from 601nm to 750nm (red and far-red). This will provide the blue, red and far-red visible ranges to be provided to the lettuce plants and ideally filter the wavelengths exterior to these ranges.

The thin-film optical filter was fabricated using three common optical materials: Al_2O_3, ZnS and Ag [22-25, 54]. E-beam evaporation was used for the dielectric materials, and Ag was evaporated thermally within the same chamber. These techniques overcome the potential issues related to the possibility of target materials cross-contaminating during sputtering, as the plasma when sputtering fills the whole chamber and may cross-contaminate some of the target materials, as the shutters covering the materials do not fully seal the sources [55]. E-beam evaporation utilises crucibles that are exposed to the chamber volume individually. These crucibles are rotated into position from closed to open. Additionally, the deposition of material layers can be more accurate compared to sputtering, since the quartz sensor (layer

thickness monitor) is not affected by RF noise. The thin-film optical filter models and the corresponding fabrication results are discussed in the following sections.

The first design was an 18-layer thin-film filter designed using OptiLayer Pro with a single 14.5 nm-thick Ag layer. The dielectric materials utilized were MgF_2, and ZnS. The results of the simulation are shown in Figure 21. An 18-layer design is typically time-consuming and costly to fabricate, and is described here only for illustration purposes. Accordingly, an alternative filter using only 9 layers and the common materials Al_2O_3, ZnS and Ag was designed and fabricated.

The fabrication conditions of the nine-layered thin film filter were:

Tooling Factor (TF) of ZnS, Al_2O_3, and Ag were 77%, 95%, and 140%, respectively. The total desired thickness was 322 nm which was comprised of a symmetrical design, having Al_2O_3 outer layers, followed by alternating layers of ZnS, Ag, ZnS, with a central layer of Al_2O_3 and again followed by alternating layers of ZnS, Ag and ZnS. The desired thicknesses were also symmetrical around the central Al_2O_3 layer, and equivalent for the layers that were of the same material.

The comparison results of the measured data compared to the modelled data for the nine-layered thin-film filter design are shown in Figure 22. The low-emissivity transmission spectrum-shaping filter presented in Figure 23 will replace the current heat-mirror films employed in ClearVue solar windows [56], which will be installed into a pilot solar green house. Figure 23a illustrates a photograph of the thin-film filter filtering sunlight through a coated glass window. As can be observed, the green part of the visible spectrum is suppressed, as required, whilst the blue, red, and far-red components of the visible spectrum are being transmitted to the plants below. Note that, by using a higher number of layers, thin-film optical filters, which exhibit better correlation to the model in the green range of the visible spectrum, can be developed.

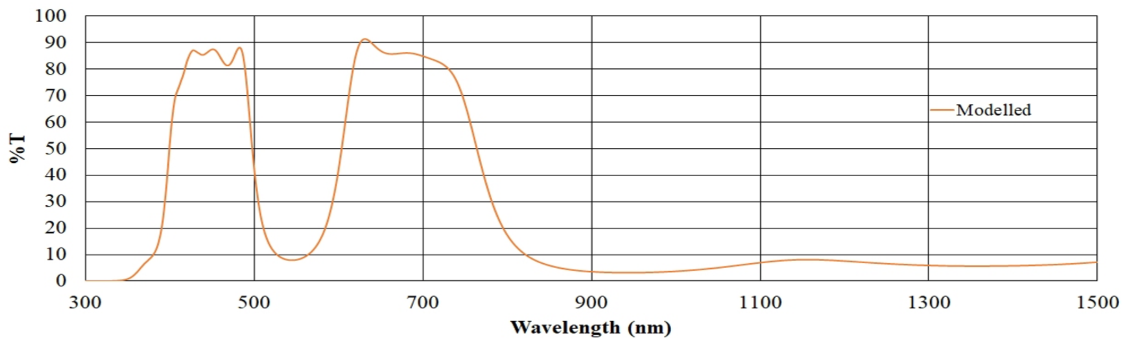


Figure 21. Simulated plot data from Opti-Layer Pro for an 18-layer thin-film filter design using MgF_2, ZnS and Ag.

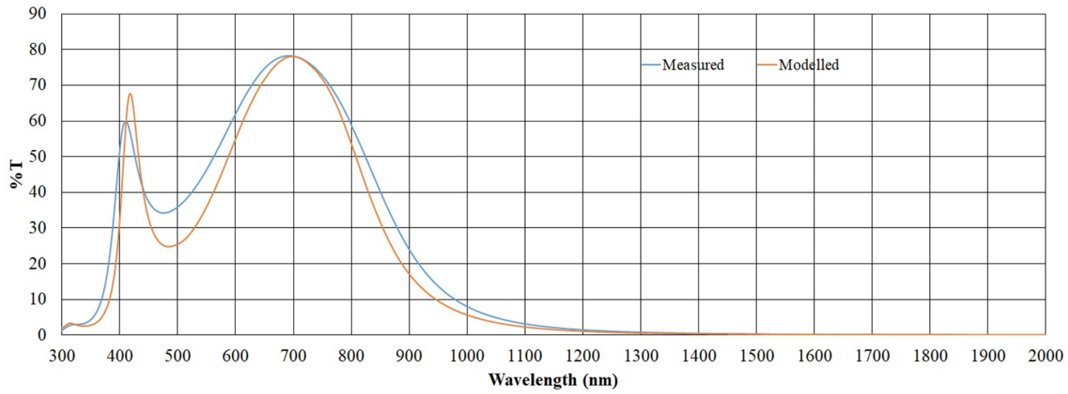


Figure 22. Simulated plot data from Opti-Layer Pro for a 9-layer thin-film filter design using Al_2O_3, ZnS and Ag, plotted with the transmission results obtained from a UV/Vis Spectrophotometer.

The design and manufacturing techniques used to prototype the 9-layer filter design of Figure 22 were adopted from ESRI's extensive prior experience with double-silver low-emissivity film designs, possessing high environmental exposure stability [57]. Figure 23 shows the visual appearance and color properties of a thin-film filter sample prototyped at ESRI, ECU, and also illustrates the spectral modification of natural sunlight's spectral contents, occurring on a normal-incidence transmission through this filter, in comparison with the spectral effects of a 6mm-thick ultraclear low-iron uncoated glass.

As distinct from all of the commercially fabricated low-emissivity double-silver film samples on glass substrates trialed by ESRI to date, the metal-dielectric designs (including that of Figure 22; Figure 23) can withstand exposure to moisture, water, and cleaning solvents. Figure 24 shows the environmental exposure stability test results, obtained using an air-filled laboratory box-furnace oven and an environmental test chamber.

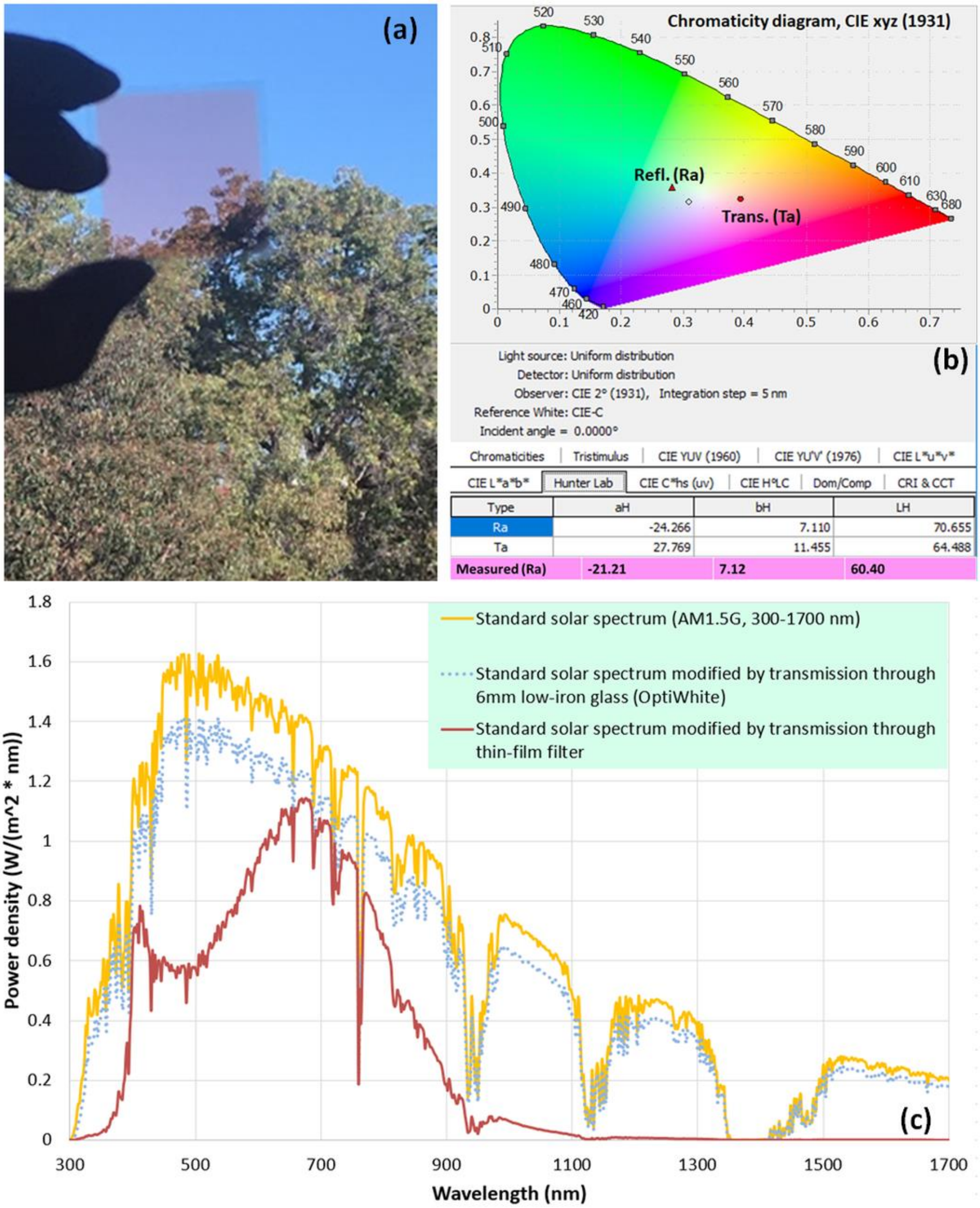


Figure 23. Thin-film filter on a glass substrate modifying the incoming natural sunlight. (a) filter image taken with the sample placed next to the glass of a conventional window; (b) filter chromaticity diagram, modeled in transmission and reflection; the measured reflected-colour Hunter Lab parameters (L, a, b) are also shown; (c) spectral modification of the natural sunlight (standard AM1.5G spectrum) on transmission through either the low-iron ultraclear 6mm glass, or through the thin-film filter design shown in Fig. 21.

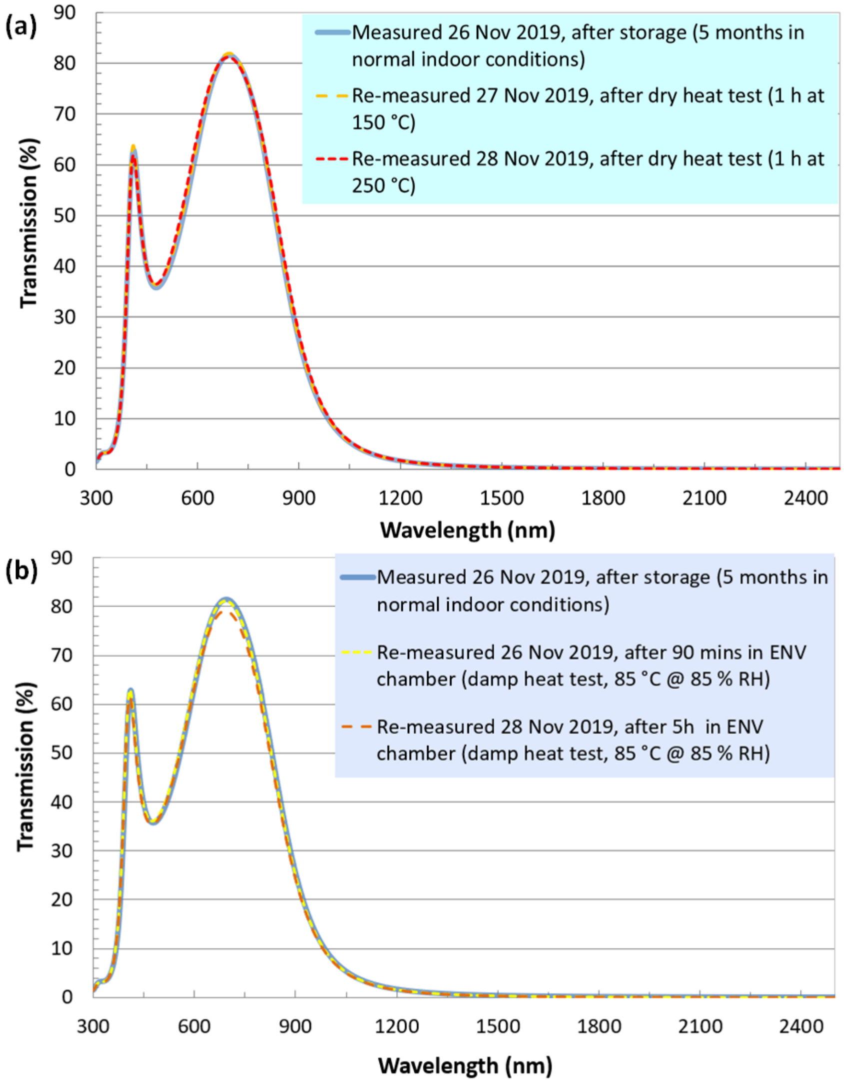


Figure 24. Environmental exposure test results obtained with the thin-film filter of Fig. 6(a), demonstrated by the stability of filter transmission characteristics. (a) dry heat exposure test results; (b) damp heat test results.

The following sequences of testing procedures were performed with the separately tested two glasscutter-separated parts of the filter sample shown in Fig. 24(a): (i) First dry heat exposure test, conducted at 150 °C, followed by another dry heat exposure at 250 °C, applied to the first pre-cut part of sample; (ii) first damp heat test run for 90 mins, followed by another damp heat test run for 5h, using the second pre-cut part of the same sample. No visible signs of sample surface degradation have been observed, and only minute spectral property changes were detected.

These features of double-silver metal-dielectric coatings on glass substrates will enable safe transport of future advanced greenhouse coating products from the coating manufacturing facilities, to the glass industry assembly factories, where the production of specific solar

window types will take place. A unique combination of advanced glazing system features can thus be realized - including the low thermal emissivity, heat shielding properties, custom-shaped transmitted colour and spectrum, and the suitability for use as components in photovoltaic energy-harvesting window designs.

2.8 CONCLUSIONS

A wavelength range of visible light can be optimized for obtaining improved biomass growth results from the sample plant *Lactuca sativa,* L. using energy-efficient LED light sources. Furthermore, dry biomass improvements in excess of 14% (compared to results obtained with white LED illumination) have been demonstrated in growth tent experiments that utilize a spectrally-optimised combination of LED illumination sources. Experimental results have confirmed the importance of providing blue, red and far-red visible wavelengths to plants for biomass productivity improvements. Even though several prior studies have also reported on the importance of these wavelength ranges for promoting plant growth productivity, our experiments have re-confirmed obtaining improved biomass production at relatively low optical power densities available from energy-efficient optical sources (compared to natural sunlight at weather conditions close to the NREL AM1.5G standard). These results have laid the foundation for the development of a prototype of a passive solar thin-film filter design suitable for use in existing low-emissivity energy-harvesting solar window products, for use in agricultural greenhouses. It can be expected that future lettuce growth experiments in advanced pilot greenhouses, which also use spectrally optimized solar windows, will reconfirm the biomass improvement results reported.

2.9 FUTURE WORK

The results of this research form the basis from which future work of developing a pilot greenhouse with glass panes having a thin-film filter coating, can be constructed. Further experiments utilising the sample plant of *Lactuca sativa*, L., can be performed, to compare the findings in this research conducted under LED lights, to those in natural sunlight conditions. Other sample plants such as tomato and capsicum can also be investigated, and suitable thin-film filter coatings developed for each sample plant.

3 Chapter Three - Conclusion and Future Work

The correlation between optimum growth of *Lactuca sativa*, L. (*L. sativa* - lettuce) plants and the optimum wavelength range of visible light has been investigated. The optimum wavelength range that maximises the yield of *Lactuca sativa*, L. has been determined, and a thin-film filter has been deposited onto a glass substrate, which provides the optimum illumination spectrum needed to substantially increase the lettuce plant yield within the constraints of this research.

During the course of the research, the following were conducted by way of ethically approved experiments;

Growing 90 lettuce plants (30 plants per grow tent) within 3 separate grow tents with a separate light treatment in each of the three tents (tent 1 having white light; tent 2 having red and blue visible light; and tent 3 having red, blue and far-red visible light). After 39 days, the lettuce plants were culled, and the wet and dry weights of the above ground growth taken and compared to the zero-biomass weight, to determine the biomass of each lettuce plant. These results demonstrated that the blue, red and far-red visible light illumination spectrum is the optimal light treatment that yields the highest biomass results.

Knowing the optimum illumination spectrum, a 9-layer thin-film filter was modelled using Opti-Layer Pro, and then fabricated in the laboratory using an E-beam Evaporation system. The thin-film filter comprised a central 50nm layer of Al_2O_3 and symmetrical and equivalent layers of 40nm ZnS, 21nm Ag, 40nm ZnS and 35nm Al_2O_3.

The main aims of this research project were to:

- determine the optimum wavelength range for *L. sativa* by growing *L. sativa* plants under LED lights in grow tents;
- develop a thin-film filter on a glass substrate;
- compare the theoretical and experimental transmissivity results for the thin-film filter;
- publish findings; and
- recommend further research that could not be conducted throughout this project.

These aims have all been met, as follows:

1. The optimum wavelength ranges for *Lactuca sativa*, L., which provided the greatest biomass results for the experimental conditions, were found to be 401-500nm (blue visible) and 601nm to 750nm (red and far-red visible).
2. Based on these ranges, a thin-film filter was developed that filters all wavelengths outside these ranges and passes the wavelengths within the specified ranges.
3. The transmission results of the thin-film filter were then compared for the theoretical and experimental results and found to be relatively close.
4. These findings were published in the MDPI publication – Sustainability in 2020:
    a. Thomas, J.A.; Vasiliev, M.; Nur-E-Alam, M.; Alameh, K. Increasing the Yield of *Lactuca sativa*, L. in Glass Greenhouses through Illumination Spectral Filtering and Development of an Optical Thin Film Filter. *Sustainability* **2020**, *12*, 3740.
5. The recommended future work that could not be conducted throughout this project involves building a greenhouse using the thin-film filter coating on the glass panes to compare the growth results for *Lactuca sativa*, L., from the LED results to those of natural sunlight; and developing new thin-film filters for other sample plants such as tomato and capsicum.

3.1 Additional Future Work

The results of this research form the basis from which further experiments using other sample plants, such as tomato, capsicum, basil and high-value herbs can also be conducted to determine suitable thin-film filter coatings for each sample plant. In addition, parameters, such as the nutrition quality of the plants grown under the LEDs, can also be compared to plants grown in a greenhouse using the thin-film filter coating, these parameters can be the fresh and dry root weights, the chlorophyll content of the leaves and other nutritional quality determining parameters.

In addition, the results of this experiment can be compared against an experiment using the same sample plant of *Lactuca sativa*, L., (lettuce) in a greenhouse with glass panes having the thin-film filter coating on each pane, so as to determine the efficacy of the results obtained here.

3.2 Addendum

The scientific name for the lettuce plant used in this research experiment is Lactuca sativa var. capitata.

References to ‘wet weight’ throughout this thesis are equivalent to stating the ‘fresh weight’.

4 Chapter Four - References

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