Final Report

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Title: Optimising LED lighting for maximum photosynthesis, yield and quality in strawberry

Strawberry production under LED lighting

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1. Industry summary

Light Emitting Diode (LED) lighting is rapidly replacing traditional High Pressure Sodium (HPS) lighting in horticultural glasshouse crop production. LED lights are more efficient and produce less radiant heat allowing for positioning of the lamps closer to the plants and thus enabling plants to be exposed to higher light intensities. Strawberries are a high-value crop that has the potential to be profitably grown under supplementary lighting. The relationship between increased light intensity, plant light-use efficiency, and yield needs to be explored to best utilise these technological advances in strawberry. Here the effect of a range of light intensities from LED lamps on plant photosynthetic rate and yield of a premium Junebearer strawberry variety was explored using a novel light gradient approach. A supplementary lighting gradient from 0 to 360µmol was established using a bank of high intensity LED lamps. Photosynthetic rate and yield per plant increased curvilinearly with increased light intensity up to 360µmol. The supplementary light intensity did not affect fruit ripening time. Results are discussed in the context of optimising the economic use of LED lighting for out-of-season strawberry production.

2. Introduction

The UK has a large demand for out of season strawberries with imports valued at £166m per annum (DEFRA, 2020). Supplementary-lit greenhouse production systems are a local alternative to importing fruit (Craver and Lopez, 2016; Lu and Mitchell, 2016). The quantity of light a crop intercepts is the predominant driver of yield in greenhouse crops (Xin et al., 2019). Supplementary lighting is required for effective winter production because of low natural light levels. High Pressure Sodium (HPS) lamps have been principally used to provide supplementary illumination in greenhouses. However, HPS lamps have low energy efficiency, producing excess radiant heat. Modern horticultural LED lighting has a higher efficiency and produces less radiant heat allowing for positioning closer to plants producing higher irradiances (Singh et al., 2015). LED lighting is increasing the feasibility of out of season horticultural crop production. However, for economic viability, growers must be able to utilise the crop specific optimum lighting intensity for maximum production and minimum cost.

Photosynthesis is a fundamental yield determinant. Photosynthesis driven increases in assimilates often equates to linear crop yield increases (Long, Marshall-Colon and Zhu, 2015). Leaf photosynthetic rate increases with light intensity up to a saturation point above which light ceases to be a limiting factor (Chen et al., 2011; Xin et al., 2019). Increasing light intensity has a greater effect on photosynthesis at low photon flux densities than closer to saturation. Plant light use efficiency and light saturation point is dependent on specific crop type and abiotic environment

(Baker, Long and Ort, 1988; Lawlor and Mitchell, 1991). Both too low and high light photon flux densities can cause plant stress responses (Wu et al., 2016; Yang et al., 2019). Crop photosynthesis response curves are often constructed by applying set intensities to a single leaf rather than measuring acclimatised plants in situ, which may lead to errors in accuracy (Herrmann et al., 2020; Lin et al., 2020).

Supplemental lighting has a direct positive affect on yield in many protected horticultural crops (Paucek et al., 2020; Palmitessa, Pantaleo and Santamaria, 2021). However, yield increases may not be simply related to photosynthetic increases and can be limited by further biotic and abiotic factors. Physiological factors can limit yield due to finite flower expression, growth habit and diversion of assimilates away from fruit (Hytönen and Elomaa, 2011). Environmental factors such as temperature, photoperiod, water or nutrients, can alter resource partitioning to vegetative rather than reproductive growth (Hytönen and Elomaa, 2011).

The relationship between photon flux density (PFD) and yield needs to be established for effective production. At lower intensities, additional lighting has a close relationship with yield (Shibaeva et al., 2022), for example, lighting improves yield in strawberry with additional light from 30 to 130 µmol (Van Delm et al., 2016). Strawberry yield, flowering and growth improves with supplemental lighting (Nestby and Trandem, 2013; Hidaka et al., 2015; Nadalini, Zucchi and Andreotti, 2017). Furthermore, increasing light can reduce production time due to earlier flowering (Nanya et al., 2012; Van Delm et al., 2016).

Earlier crop production and faster harvesting time increases economic viability. Yield improvements are dependent on increased flower expression and subsequent fruit number and size. An increase in both is ideal as larger berries reduce picking time. Furthermore, crop earliness is determined by flowering time and fruit ripening time. Flowering is controlled by both photoperiod and temperature whilst ripening is predominantly controlled by temperature (Sønsteby and Hytönen, 2008; Han et al., 2015). How light intensity interacts with these yield determining factors is important for crop lighting feasibility analysis.

This study explores the relationship between photon flux density, photosynthetic rate, fruit yield, ripening and berry size.

3. Materials and methods

A lighting gradient was established, with a 16hr lighting period, using three inclined, high intensity LED lamps (500w Crown High Bay LED Grow light, Philips, see appendix for light spectrum) placed at one end of a glasshouse bench (see appendix for experimental set up image). Natural light was reduced by 30%. Premium Junbearer strawberry tray-plants were planted in September 2019 in 11 rows of 6 replicate plants, giving a total of 66 test plants, with guard rows each end of the gradient. The experiment continued until May 2020. A standard commercial strawberry mix (Strawberry Special, Solufeed Ltd., Barnham, UK) was used to fertigate plants with additional potassium (Solupotassse, Solufeed Ltd., Barnham, UK) added at fruiting. The pH and EC were set at 5.5 and 1.8 mS/cm respectively and plants were irrigated to give a 10-20% daily run-off. Glasshouse temperature was set at 22°C/13°C day/night (average temperature of 17.3°C achieved) with a relative humidity of 60/90% day/night. Bees were introduced every six weeks for pollination.

Photosynthetic rate was recorded in the dark period with the LED lamps switched on so that illumination was only from the light source. Measurements were carried out on one leaf per test plant using an infra-red gas analyser (LCpro-SD portable photosynthesis system, ADC BioSientific Ltd, Hoddesdon, UK). For each recording, the chamber was held in place for at least two minutes. Fruit was harvested at commercial ripeness once a week. Newly open flowers were marked and dated to assess ripening time. Comparative images of one example plant from each light intensity row were taken at fruiting. A non-rectangular hyperbola was fitted to photosynthetic light response data (Ye, 2007). A 4 -parameter logistic curve was fitted to yield data as a function of light intensity using Genstat 19th edition.

4. Results

Photosynthetic rate increased curvilinearly with light intensity without reaching a saturation point (Figure 1). The compensation point, where CO_2 released from dark respiration equalled that used in photosynthesis, occurred at 5 µmols m-2 s-1 PFD.

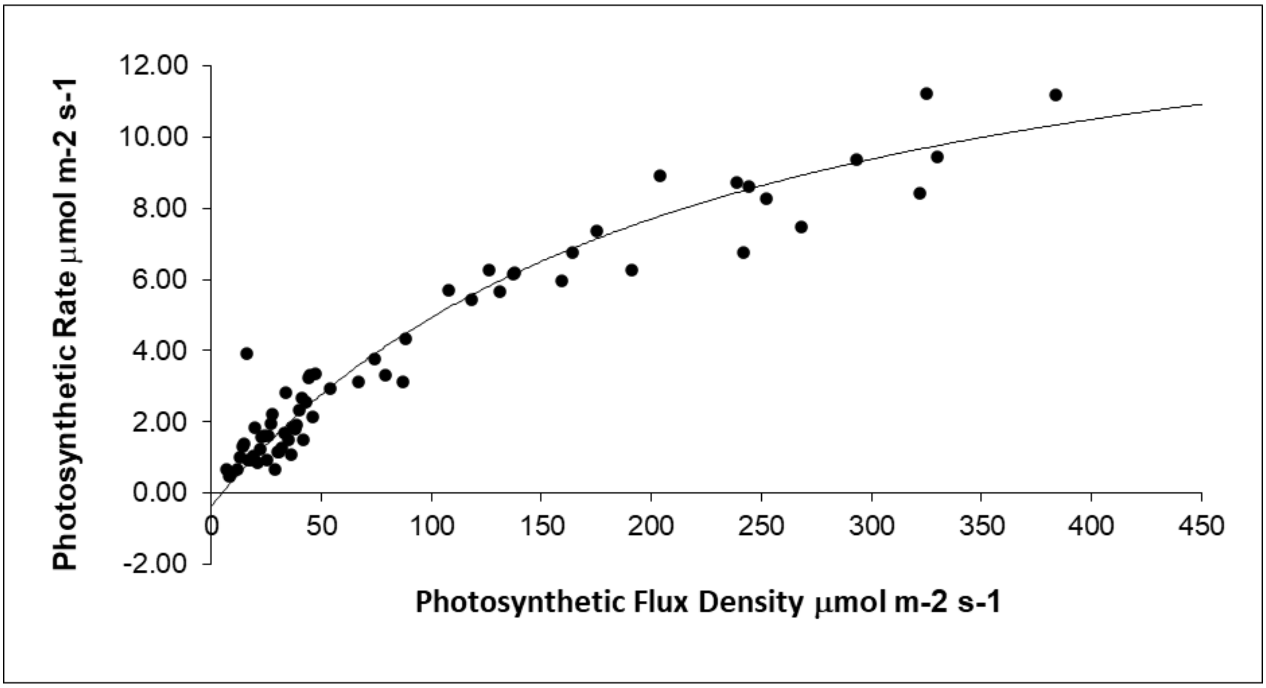


Figure 1: Night Photosynthetic rate of 66 test plants growing in a photon flux density gradient. Curve fitted using photosynthesis curve equation 11 (Ye, 2007).

Fruit yield increased significantly with increased light intensity with more variation at higher intensities ($p<0.001$). Fruit yield reached a maximum of 927g at 389µmols m-2 s-1 PFD, a daily light integral of 21.3 µmol m^{-2} s^{-1} (Figure 2). A fruit yield increase of 800g was seen at 200µmols m^{-2} s^{-1} PFD, whereas a further increase of only 130g, totalling 930g, is predicted at 400µmols m^{-2} s^{-1} PFD (Figure 2).

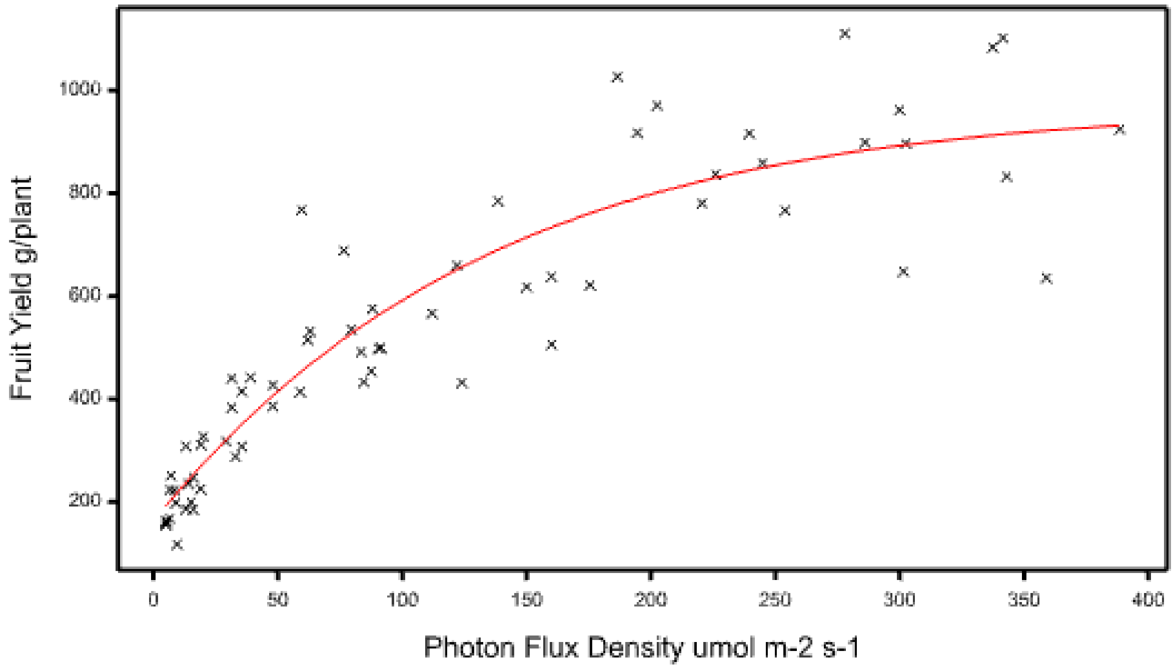


Figure 2: Effect of light intensity on individual test plant Strawberry fruit yield. Logistic regression curve fitted, accounting for 83.7 of variance. Predicted horizontal asymptote at 970g.

Fruit ripening time was not affected by variation in PFD (Figure 3A). Average berry size also did not show a trend with increased light intensity (Figure 3B).

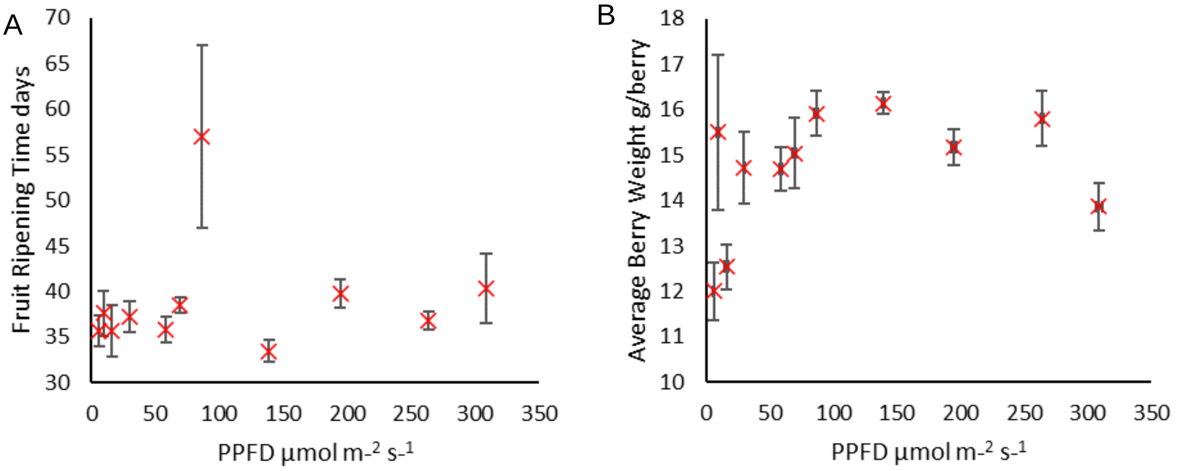


Figure 3: Effect of photosynthetic photon flux density on A) fruit ripening time and B) average berry weight. Vertical lines represent ±SEM.

Increased PFD showed an increase in overall plant and canopy size (Figure 4).

Figure 4: Sample plants from each row from low (30µmol, right) to high photon flux density (350 µmol, left).

Low supplementary light intensities reduced final petiole length. At 300µmols m^{-2}s^{-1} petioles reached their full length (14cm) after 16 days (growth rate 0.88cm/day), whereas at 100µmols m^{-2}s^{-1} petioles took 9 days (1.56cm/day) to reach the same length (Figure 5).

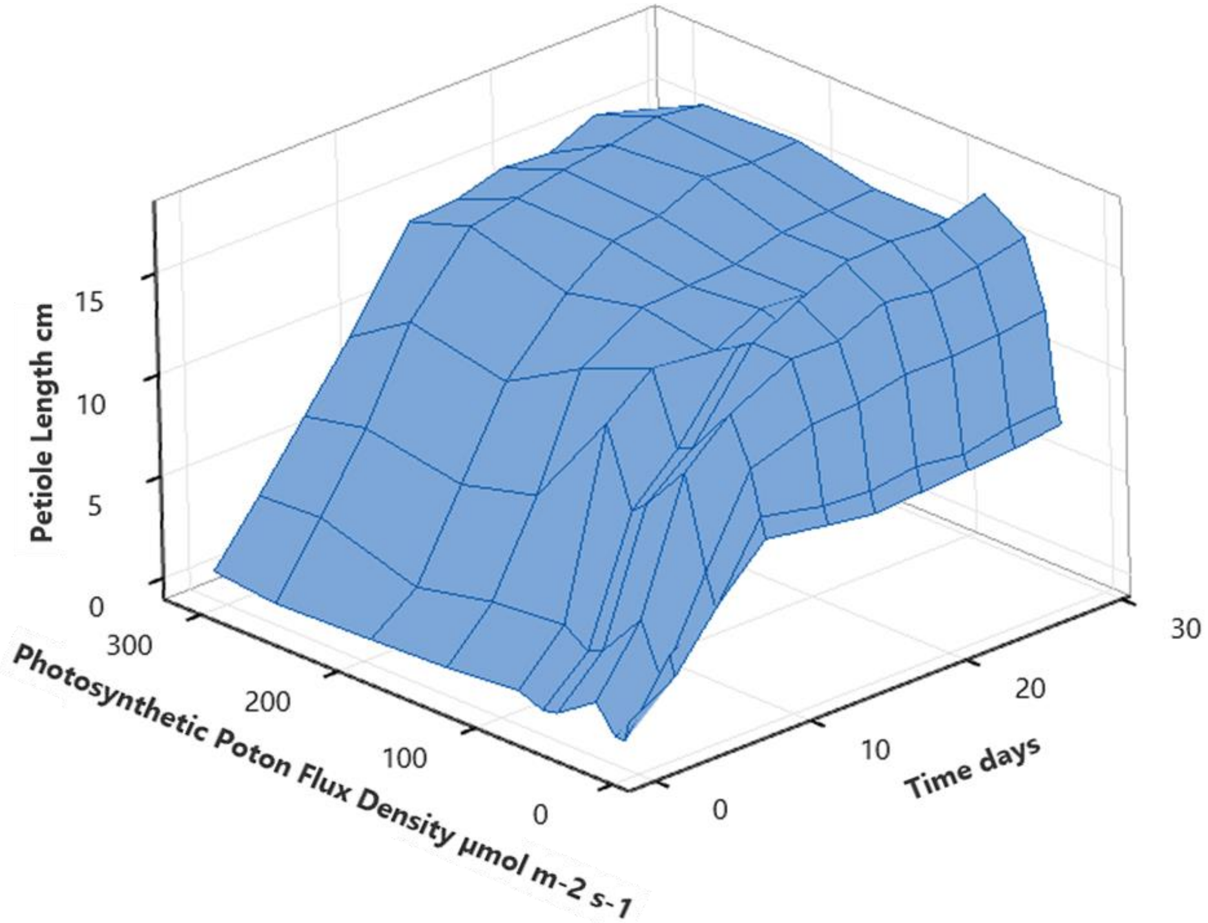


Figure 5: The relationship between PPFD and petiole extension over time. Time scale was measured from when newly emerging leaves are marked for petiole growth measurements.

5. Discussion

This study showed clearly that leaf photosynthetic rate in strawberry continues to increase up to 300µmol PFD without plateauing, indicating light is a limiting factor over this intensity range (Chen *et al.*, 2011; Xin *et al.*, 2019). The rate of increase in photosynthetic rate gradually decreased at higher intensities demonstrating a progressive decline in the effect of supplementary light as light intensity increased further (Chen *et al.*, 2011; Xin *et al.*, 2019). Strawberries low dark respiration rate shows the plants are not using much energy, increasing efficiency at low light levels. Here, photosynthetic rates were measured on in-situ leaves acclimatised to their light intensity (Herrmann, 2020). To analyse strawberries photosynthetic response completely experimentation with a higher maximum light intensity to incorporate the plant saturation point within the data needs to be conducted. Furthermore, canopy size increased in parallel to the rate of increase in leaf photosynthetic rate (Image 1) indicating that the overall rate of plant photosynthesis increased multiplicatively as light intensities increased.

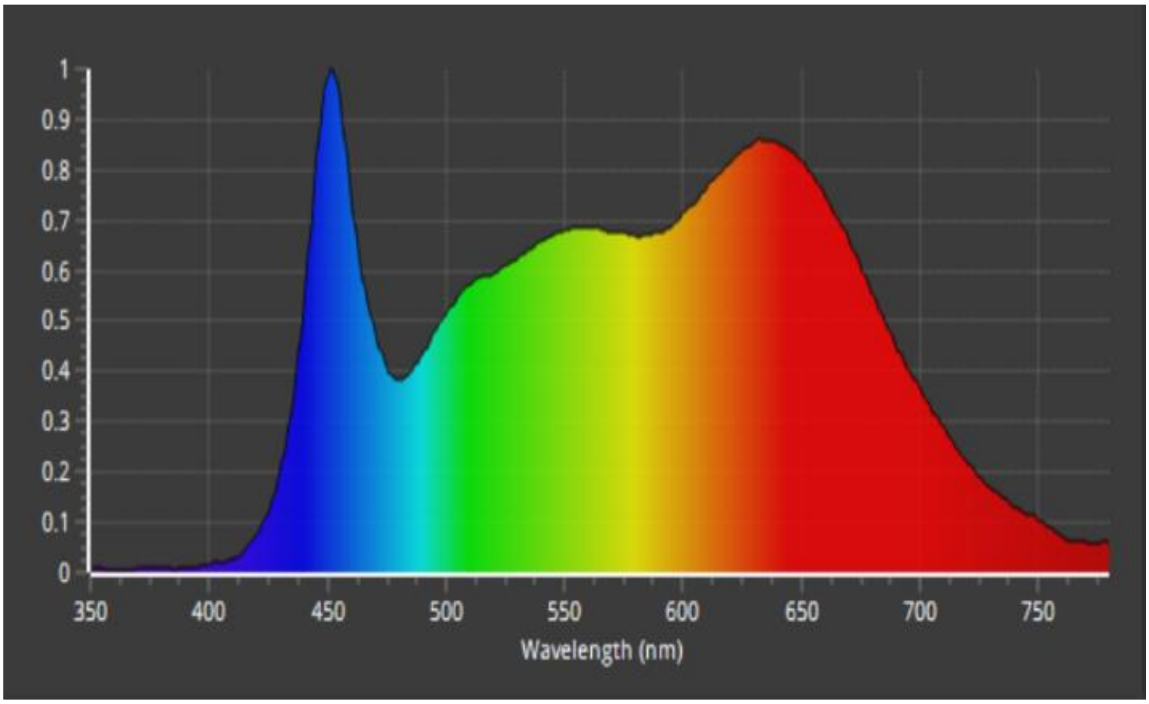
Fruit yield increased significantly with increasing light intensity with greater variation at higher intensities. This positive correlation between light and yield supports similar findings for other crops (Paucek *et al.*, 2020; Palmitessa, Pantaleo and Santamaria, 2021). However, yield reached 95% of the maximum potential yield at 370µmols PFD or a daily light integral (DLI) of 21.3. This suggests that additional supplementary lighting above 370µmols will have negligible effects on yield and supports findings of Shibaeva *et al.*, 2022, in cucumber and tomato, that lower DLIs are more efficiently used by plants and reduce production costs. High light intensities can benefit crops by penetrating into and driving photosynthesis in the lower canopy; however, lighting systems promoting even plant illumination can achieve this at lower intensities.

As well as high yields, faster yielding crops with more efficient harvesting times are more economically viable. However, in contrast to previous findings, increasing light intensity showed minimal benefit on crop earliness and showed no effect on fruit ripening time (Nanya *et al.*, 2012; Van Delm *et al.*, 2016). It may be that the increased rate of progress to fruiting under older supplementary lighting systems may have been due to higher plant temperatures under higher intensities, with less correlated seen in cooler LED systems. Ripening time was not significantly faster at high light intensities, indicating that this is predominantly determined by temperature and photoperiod (Han *et al.*, 2015) (Sønsteby and Hytönen, 2008). Yield increases seen at higher intensities were not due to an increase in average berry size Indicating increased flower expression or reduced flower abortion and waste fruit leading to a greater fruit number. Rate of growth and petiole extension was improved with increased light intensity.

5.1. Conclusion

This study showed a curvilinear relationship between both photosynthetic rate and fruit yield with increased supplementary illumination up to 350µmols PFD. Yield benefits plateau after 370µmols or 21.3 DLI suggesting that additional lighting above this will have negligible effects on strawberry yield. There was no effect of light intensity on berry size or ripening time. Increasing PFD increased canopy size.

6. Appendix



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