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Enhancing Lettuce Yields Using Quantum Dot Films

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Abstract. The spectral distribution and intensity of light are critical for crop growth. One strategy is to use spectral shifting filters to passively control both the intensity and the color of transmitted sunlight, and target critical spectral ranges for optimizing photosynthesis. Copper indium sulfide/zinc sulfide (CIS/ZnS) quantum dot films have been commercially developed as spectral shifting films for greenhouses. By downshifting blue light to green and red light through photoluminescence (PL), these CIS/ZnS films increase the transmission of more useful photons for photosynthesis. Yet, a complete understanding of how film properties impact crop yield has yet to be established. In this work, we simulated CIS/ZnS quantum dot composites at various quantum dot concentrations to determine the influence of spectral shifting on lettuce yields. At the highest concentration of quantum dots, lettuce yields increased by up to 30% relative to plants grown under the standard solar spectrum. However, increasing the amount of PL that escaped the film either by increasing the outcoupling efficiency or the PL quantum yield did not further increase yields due to the transmission of more green light. Therefore, to maximize lettuce yields, CIS/ZnS films should strongly absorb blue light without increasing the transmission of green light, favoring high concentrations of quantum dots and lower outcoupling efficiencies.

Keywords: Spectral Shifting, Quantum Dots, Sunlight Filter, Crop Modelling

1. Introduction

Wavelength-selective agrivoltaic systems ensure the effective sharing of sunlight for both photosynthesis and energy generation [1]. Semi-transparent, colored solar cells or colored sunlight filters, paired with opaque solar cells, allow for targeted spectral manipulation, directing wavelengths of light better suited for crop production toward plants while other wavelengths are used for energy generation. Alternatively, these semi-transparent, colored films can be used to tune transmitted sunlight without generating electricity, thereby reducing the need for supplemental lighting [2]. Spectral shifting materials make use of abundantly available sunlight to target critical wavebands of light for plant growth, namely blue (λ = 400 – 500 nm), green (λ = 500 – 600 nm), red (λ = 600 – 700 nm), and far-red or near infrared (λ = 700 – 750 nm) light. The balance of these colors in the extended photosynthetically active radiation (ePAR) range of light strongly impacts crop yield, morphology, and nutrition [3]. Because not all wavelengths of light contribute to biomass accumulation equally, sunlight filters can improve photosynthetic efficiency by shifting less useful photons into more useful spectral ranges.

Quantum dots (QDs) are attractive materials for spectral shifting films in agriculture due to their size-tunable optical properties and resistance to photobleaching [4]. QDs absorb higher-energy photons and downshift them to lower energies through photoluminescence (PL). Although a vast library of QDs has been reported in the scientific literature, few QD materials have been implemented in agricultural applications at scale. Copper indium sulfide/zinc sulfide core/shell (CIS/ZnS) QD films have been commercialized for greenhouses and have been reported to increase crop yields for a variety of crops, such as lettuce, tomato, and basil, due to both spectral shifting and improved diffusion of light throughout the greenhouse [5], [6], [7]. Here, we use CIS/ZnS QDs as an exemplary system to understand the impact of spectral shifting on biomass accumulation.

In this paper, we used simulations to deconvolute the impacts of QD concentration, PL quantum yield, and the extent of PL outcoupling in CIS/ZnS spectral shifting films on crop growth. By using lettuce as a model crop, we established trends in lettuce yields as a function of the transmitted spectrum through the film. We found that QD concentration was the dominant parameter for controlling spectral shifting, directly controlling lettuce dry weights. At the highest QD concentrations, or the greatest extent of spectral shifting, lettuce yields increased by 30% relative to crops grown under the standard solar spectrum. However, increasing the outcoupled PL radiation resulted in decreased yields due to additional transmitted green light. These results indicate the importance of optimizing the transmitted spectrum for maximizing lettuce crop yield.

2. Simulation Approach

We combined an optical model [8] with a spectrum-dependent biomass accumulation model [9] to determine the impact of spectral shifting on lettuce yields. We first calculated the transmission of light under CIS/ZnS films at different QD loadings. The CIS/ZnS QD spectra were extracted from the literature [5] using WebPlotDigitizer [10]. We assumed that the CIS/ZnS QDs were embedded in a polymer of refractive index 1.5 to form a spectral shifting film. Figure 1 shows a schematic of the CIS/ZnS spectral shifting film over a lettuce plant. Because CIS/ZnS absorbs ultraviolet (UV), blue, and green light, the transmitted fraction of light in this spectral range will decrease, indicated by the smaller arrows beneath the film. Since the PL spectrum is centered at approximately 600 nm, there will be increased transmission of both green and red light due to the PL outcoupling from the bottom of the film.

We assumed 150 µm thick films that were coated on greenhouse glass. Absorption in a single pass through the film was calculated using the Beer-Lambert Law. The transmitted light considered sunlight absorption and the three factors that controlled the amount of PL that reached the plant below: the QD concentration, the outcoupling efficiency for luminescence, and the CIS/ZnS PL quantum yield (PLQY). The QD concentration was represented by the optical density of the film at 400 nm, where OD = αtc, where α is the absorption coefficient, t is the thickness of the film, and c is the concentration. The outcoupling efficiency describes the fraction of PL that escaped the film. Assuming both the film and greenhouse glass had refractive indices of 1.5 and were in air, 12.5% of PL escaped out of the bottom surface. Texturing techniques [11], [12] or scattering additives [13] can be used to increase the film outcoupling efficiency. Lastly, the PLQY describes the ratio of photons emitted by the QD to those absorbed. Unless stated otherwise, the PLQY of CIS/ZnS QDs was 85% [5]. We then integrated the transmitted spectrum in the blue, green, red, and far-red color ranges to calculate the transmitted color fractions. For example, the blue color fraction is given by:

$$F_{Blue} = \frac{\int_{400}^{500} T(\lambda)d\lambda}{\int_{400}^{750} T(\lambda)d\lambda} \qquad (1)$$

where F_{blue} is the fraction of blue light in the transmitted spectrum $T(\lambda)$, calculated as the ratio of light integrated in the blue spectral range from 400 – 500 nm to light integrated in the total ePAR range of 400 – 750 nm.

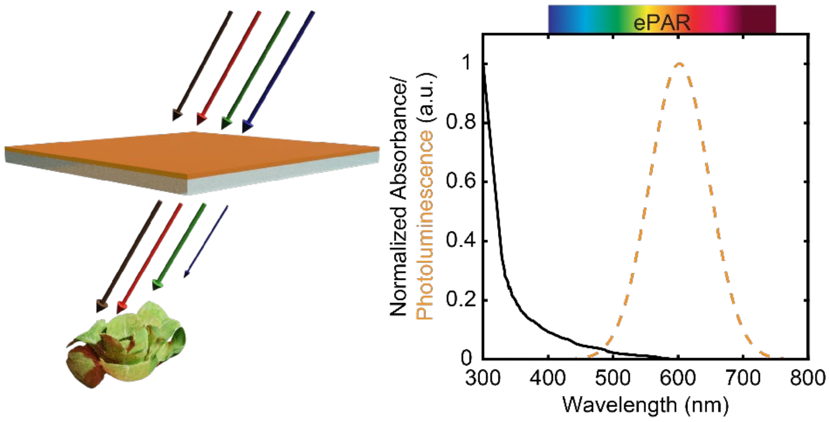

Figure 1. *Schematic of a spectral shifting quantum dot film used to increase lettuce growth. The film contained copper indium sulfide/zinc sulfide (CIS/ZnS) quantum dots that primarily absorb UV and blue light and have orange photoluminescence (PL), as demonstrated by their absorbance (black solid line) and PL (orange dashed line) spectra [5]. The extended photosynthetically active radiation (ePAR) range, important for crop growth, is shown as a colored bar for visual reference.*

The temperature-, spectrum-, and light intensity-dependent biomass model used dry weight as the primary state variable. The dry weight refers to the plant's non-water components, including plant tissue and starches [14]. We assumed that the plant temperature was 24 °C during the day and 19 °C at night. Using Bibb lettuce as a model crop, we calculated the growth of lettuce over a 35-day harvest cycle. To isolate the influence of spectral shifting, we assumed the light intensity remained constant among the varying films simulated here. The accumulated amount of light the plant received in a day was 19.2 mol $\cdot$ m^{-2} $\cdot$ d^{-1} in alignment with the ideal light intensity for lettuce growth [15]. Because the model developed by Abedi et al. considered far-red light, this light intensity was adapted to consider far-red light as well.

3. Results and Discussion

We first investigated the role of QD concentration in the film on lettuce dry weight. Figure 2 illustrates the benefits of implementing CIS/ZnS films to enhance crop growth. Figure 2(a) shows that at OD_{400} above 1.3, the lettuce yield increased beyond that grown under the standard solar spectrum (12.5 g). At the highest optical densities, or the greatest reduction in transmitted blue light, yield increases of up to 30% were achieved. Because the transmitted light intensity was controlled, the improvements to lettuce yield could be attributed to increases in the quantum use efficiency, as shown in Figure 2(b). This parameter describes the plant's ability to convert light energy to chemical energy, with higher values indicating better light utilization. Through spectral shifting, the quantum use efficiency increased up to 7.5×10^{-5} g/J from 3.3×10^{-5} g/J for lettuce grown under the standard solar spectrum. The trends in the dry weight shown in Figure 2(a) closely mirrored the trend in the quantum use efficiency shown in Figure 2(b), suggesting that optimizing the transmitted color fractions towards those ideal for lettuce growth also optimized crop yield.

To better illustrate the impact of spectral shifting on the transmitted color fractions, Figure 2(c) shows the transmitted spectrum under CIS/ZnS films of increasing OD_{400}. With increasing OD_{400}, the transmitted light in the blue spectral range of 400 – 500 nm decreased while the transmitted light in the red spectral range of 600 – 700 nm increased beyond that of the incident solar spectrum. These shifts as a function of OD_{400} are plotted in Figure 2(d). As the OD_{400} increased, the fractions of transmitted blue and green light decreased. Simultaneously, the transmitted fractions of red and far-red light increased. This combination improved the quantum use efficiency, which subsequently increased the dry weight.

These findings align with experimental growth trials conducted by Kang et al. [7]. They grew green leaf lettuce cv. Rex under CIS/ZnS films of both low and high QD loadings. Lettuce grown under the high concentration film had higher shoot dry and fresh weights compared to those grown under the film with the lower QD concentration despite a reduction in the light intensity. The greater spectral shifting under the higher QD concentration film enhanced leaf expansion and radiation capture. As the model employed in this work was based on experimental growth trials that also indicated higher red light fractions increased crop yield, utilizing films with high QD concentrations to increase transmitted red and far-red light will increase lettuce yield.

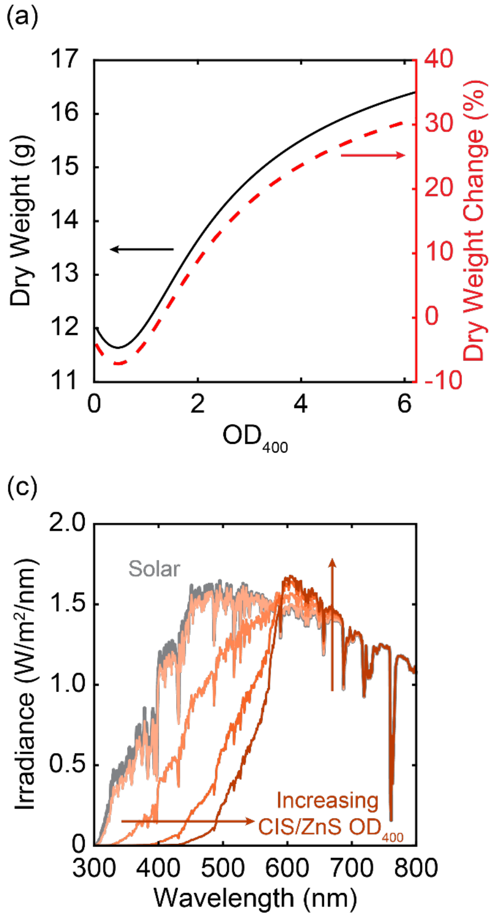

Figure 2. *(a) Simulated dry weight of lettuce grown under copper indium sulfide/zinc sulfide (CIS/ZnS) films at various optical densities at 400 nm (OD_{400}) in units of grams (black solid line) and percent change relative to lettuce grown under the standard solar spectrum (red dashed line). (b) Calculated quantum use efficiencies for lettuce under CIS/ZnS films at various OD_{400}. (c) Transmitted spectra under CIS/ZnS films with increasing OD_{400} (colored lines) compared to the standard AM1.5G solar spectrum (gray line). (d) Transmitted blue, green, red, and far-red color fractions under CIS/ZnS films at various OD_{400}.*

To further explore opportunities to enhance yield, we also studied whether increasing the intensity of emitted QD PL would increase yield. Figure 3 demonstrates that increasing the PL outcoupling efficiency beyond the standard 12.5% outcoupling efficiency used in Figure 2 did not further increase yield. Figure 3(a) shows that as the outcoupling efficiency increased for a given OD_{400}, the change in lettuce dry weight generally decreased. The greatest yield enhancements occurred at the highest OD_{400} and the lowest outcoupling efficiency. This behavior could be understood from the color fractions plotted in Figure 3(b). As the outcoupling efficiency increased from 25% to 100%, the transmitted green color fraction increased at the expense of the far-red color fraction. Because half of the PL from CIS/ZnS QDs lies in the green spectral range, increasing the outcoupling efficiency increased the amount of transmitted green light, which is not as beneficial for biomass accumulation as red light.

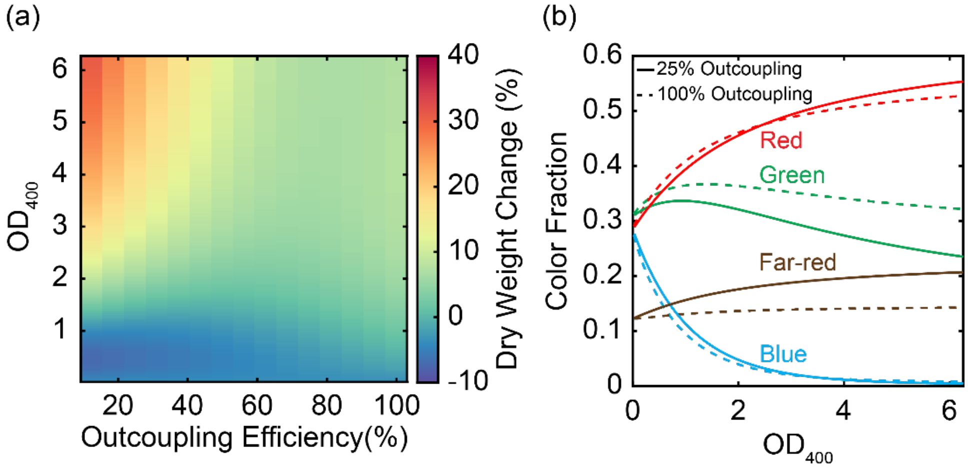

Figure 3. *(a) Change in lettuce dry weight as a function of film outcoupling efficiency and optical density at 400 nm (OD_{400}). (b) Transmitted color fractions as a function of film OD_{400} for films with 25% (solid lines) and 100% (dashed lines) outcoupling efficiencies.*

We also varied the PLQY to understand its role in the enhancement of lettuce yield through spectral shifting. Figure 4 illustrates the impact of both OD_{400} and the PLQY on the change in lettuce dry weight, assuming the outcoupling efficiency was maintained at 12.5%. Varying the PLQY broadly from 0% to 100% did not significantly change yields at lower OD_{400}, as illustrated in Figure 4(a). However, at high OD_{400}, reducing the PLQY increased yields. Because CIS/ZnS QDs have both green and red PL, increasing the PLQY increased the green fraction. Figure 4(b) depicts the change in the transmitted color fractions as a function of OD_{400} for CIS/ZnS QDs with both 0% and 100% PLQY. At 100% PLQY, the green fraction increased at higher OD_{400} at the expense of the far-red fraction. As a result, the dry weight decreased. Therefore, somewhat counterintuitively, to maximize lettuce dry weight, films with higher OD_{400} and lower PLQYs should be employed.

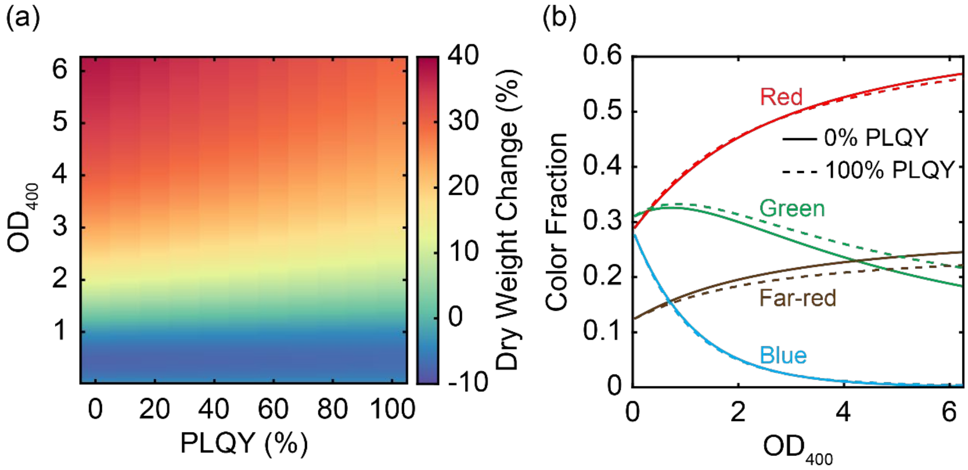

Figure 4. *(a) Change in lettuce dry weight as a function of the quantum dot's photoluminescence quantum yield (PLQY) and the film's optical density at 400 nm (OD_{400}). (b) Transmitted color fractions as a function of film OD_{400} for 0% (solid lines) and 100% (dashed lines) PLQY.*

4. Conclusion

This work highlights the utility of CIS/ZnS QD films for enhancing lettuce yield and indicates important research directions for the development of these films. At high OD_{400}, lettuce yields increased by up to 30% relative to plants grown under the solar spectrum at the same light intensity due to the benefits of spectral shifting. Quantum use efficiencies increased under CIS/ZnS films due to the reduction of blue light and the enhancement of both red and far-red light. However, counterintuitively, designing CIS/ZnS films to increase PL outcoupling, either through increased outcoupling efficiencies or PLQYs, decreased lettuce yields due to the transmission of additional green light. These findings suggest that for QD films, in practice, tailoring of the absorbance spectrum should be prioritized over optimizing the PL intensity. Furthermore, higher QD loadings should be employed to fully utilize the benefits of spectral shifting.

Data availability statement

Data will be made available on the Data Repository for U of M (DRUM) server. A DOI link will be added to this work.

Author contributions

K.Q.L.: Conceptualization, Methodology, Investigation, Software, Writing – original draft. N.J.E.: Methodology, Writing – review & editing. U.R.K.: Conceptualization, Methodology, Supervision, Funding Acquisition, Writing – review & editing. V.E.F.: Conceptualization, Methodology, Supervision, Funding Acquisition, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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