

The Potential of Photovoltaics in Greenhouses: Part II

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Agrivoltaic greenhouses have the potential to generate a secondary, passive income for greenhouse businesses. In “Potential of Photovoltaics in Greenhouses: Part I”, we explored the types of photovoltaic (PV) technologies that currently exist, and described potential strategies to incorporate PVs into greenhouse structures. Incorporating traditional opaque PVs into a greenhouse will create additional shading that could reduce crop quality and yield. However, light that is intercepted can generate electricity for use on site and/or potentially sold back to the grid. Thus, striking a balance between transmission of light sufficient for crop growth while capturing light to generate electricity is essential for commercial implementation.

Ideally, the shade created from PVs would provide some benefit to greenhouse crops. PV technologies designed for greenhouses should incorporate crop-centric principles that are not currently well defined, but could include maximizing photosynthetically active radiation (PAR, 400–750 nm) transmission, decreasing high-temperature stress, flexibility to grow various crops throughout the year, limiting undesirable extension growth for ornamentals, maintaining desirable leaf pigmentation, and/or not delaying crop production time.

One promising way to incorporate PV technologies into greenhouses is to incorporate newly emerging transparent solar panels as a one-to-one replacement for common rigid glazing materials such as glass, acrylic, or polycarbonate, thereby turning the entire greenhouse into one large solar panel. Semitransparent and transparent PV panels that absorb ultraviolet and near-infrared to generate electricity while maximizing transmission of PAR could be ideal. A collaborative research team at Michigan State University conducted a multi-year study to determine the effects of experimental PV panels on various greenhouse crops to inform future agrivoltaic greenhouse PV design.

Here, we highlight the effects of several experimental semitransparent and transparent PV panels on the growth of red-leaf lettuce. We selected this crop because of its short production cycle, commercial importance, and effects of light on leaf size, leaf pigmentation, and biomass.

Experimental Protocol

We constructed eight identical chambers, each approximately 10 square feet (1 m²), and placed them on separate benches inside a glass-glazed greenhouse (Figure 1). The roof of each chamber was constructed with a different experimental PV panel and angled 20 degrees south. The transmission spectrum for each experimental PV glazing material is displayed in Figure 2. We compared a conventional greenhouse material (clear acrylic plastic) to four semitransparent (moderate shade, heavy shade, CO575, and CO475) and three transparent (CO850, CO770, and CO700) experimental PV panels. Each wavelength-selective panel had a unique absorption cutoff (CO) ranging from 475 to 850 nm. The CO value for each treatment is approximately the wavelength (in nm) when light transmission is decreased by 50%. For instance, CO475 absorbed a large fraction of light between 500 and 600 nm, while CO850 absorbed wavelengths longer than 850 nm.

Red-leaf lettuce ‘Rouxai’ seedlings were grown from seed inside a controlled growth room for 14 days at 70 °F (21 °C) and a daily light integral (DLI; mol m⁻² d⁻¹) of 12 mol m⁻² d⁻¹. Once

seedlings had two fully expanded leaves, they were transplanted inside each chamber from May 28th to June 23rd (26 days) at a density of 1.5 plants ft⁻² (16 plants m⁻²). 15 plants per chamber were harvested for fresh mass and quality measurements.

Average air temperature and DLI were measured continuously in each chamber. The average DLI inside the chambers differed between treatments and ranged from 7 mol m⁻² d⁻¹ in the heavy shade treatment to 23 mol m⁻² d⁻¹ in the clear acrylic control chamber. The average air temperature inside each chamber was 73 °F (23 °C).

Results

Semitransparent PV trends: An average DLI of 7 mol m⁻² d⁻¹ (heavy shade) was too low to grow a commercially acceptable head of ‘Rouxai’ in 26 days. The low DLI caused elongated leaves, poor leaf color, and relatively low fresh mass (Figure 3). The moderate shade, CO575, and CO475 panels, which transmitted an average DLI of 10.6 to 13.1 mol m⁻² d⁻¹, produced ‘Rouxai’ with 10% to 26% less fresh mass and less red coloration than the high light, clear acrylic control. Interestingly, lettuce heads had greater fresh mass and longer leaves under the wavelength-selective CO475 and CO575 panels compared to the moderate shade treatment with a similar DLI. Similar results occurred in snapdragon, basil, and soybean. Thus, two different wavelength-selective PV panels could increase plant fresh mass compared to a non-wavelength selective PV panel, but this often comes at the expense of increased stem and/or leaf elongation. While lettuce fresh mass was lower under the semitransparent PVs compared to the clear acrylic control, semitransparent PV could still have applications as a greenhouse glazing in locations where the average DLI is greater than that of Michigan, or potentially as seasonal shading material for crops tolerant of lower DLIs.

Transparent PV trends: Plants in these treatments received the highest DLIs and ranged from 18.4 to 22.9 mol m⁻² d⁻¹. Lettuce fresh mass under the CO770 and CO850 panels was similar to under the clear acrylic, but greater than the CO700 panel. The CO700 panel had less transmission of far-red light than the CO770 and CO850 panels. Lower fresh mass under the CO700 treatment could result from 1) far-red light driving photosynthesis and/or increasing the capture of light; 2) imperfect absorption cutoffs that consequently decreased the average DLI, or 3) a combination of the two.

Identifying an optimal cutoff above 700 nm – where the light is no longer useful to plants – is a critical research and development consideration for transparent PVs used in greenhouses. Our results suggest a cutoff between 700 nm to 750 nm has a minimal effect on lettuce fresh mass, in comparison to a wavelength cutoff of 675 nm for transparent PVs in window glass for human vision (Lunt, 2012). However, these results should not completely dismiss the potential use of CO700 because it decreased plant height and increased stem diameter of snapdragon, resulting in more compact plants. This indicates there are other potential benefits of PVs, such as to inhibit extension growth of ornamentals when fresh mass is less of a concern. It also highlights the need for panels to be designed with crop-centric criteria (Stallknecht et al. 2023b).

General trends: Lettuce ‘Rouxai’ fresh mass increased as the average DLI inside each chamber increased, but in a non-linear manner (Fig. 3). In the most extreme case, lowering the DLI from 22.9 mol m⁻² d⁻¹ (clear acrylic) to 7 mol m⁻² d⁻¹ (heavy shade) decreased the average fresh mass of ‘Rouxai’ lettuce by 49%. In this study, biomass accumulation saturated around ~18 mol m⁻² d⁻¹. Similar to fresh mass, lettuce leaf color was progressively less red and greener when the average DLI was lower than ~18 mol m⁻² d⁻¹.

Overall, fresh mass and leaf color were primarily determined by the average DLI and secondarily by the PV panel transmission spectrum. Similarly, the average DLI was a more influential factor than transmission spectrum for snapdragon, basil, dwarf tomato, and petunia (Stallknecht et al. 2023a,b). Based on these collective responses, we conclude that transparent PV panels that provided $\leq 25\%$ shade were an acceptable replacement for a typical greenhouse glazing material during the spring in Michigan.

In summary, transparent PVs have the potential to be used as conventional greenhouse glazing materials, especially in high-light regions, and more seasonally in temperate climates such as in Michigan from late spring to early fall. However, in low-light regions, a decrease in the average DLI would likely have a detrimental impact on plant growth. Additional research is needed on a wider range of crops in different growing regions. Furthermore, the economics of PV panels will need to be explored once (semi-) transparent materials are commercial available.

References:

- Lunt RR. 2012. Theoretical limits for visibly transparent photovoltaics. *App. Phys. Lett.* 101(4).
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- Stallknecht EJ, Herrera CK, Sharkey TD, Lunt RR, Runkle ES. 2023b. Growth of snapdragon under simulated transparent photovoltaic panels for greenhouse applications. *J Env Hortic.* 41:170-179.

Authors and acknowledgments

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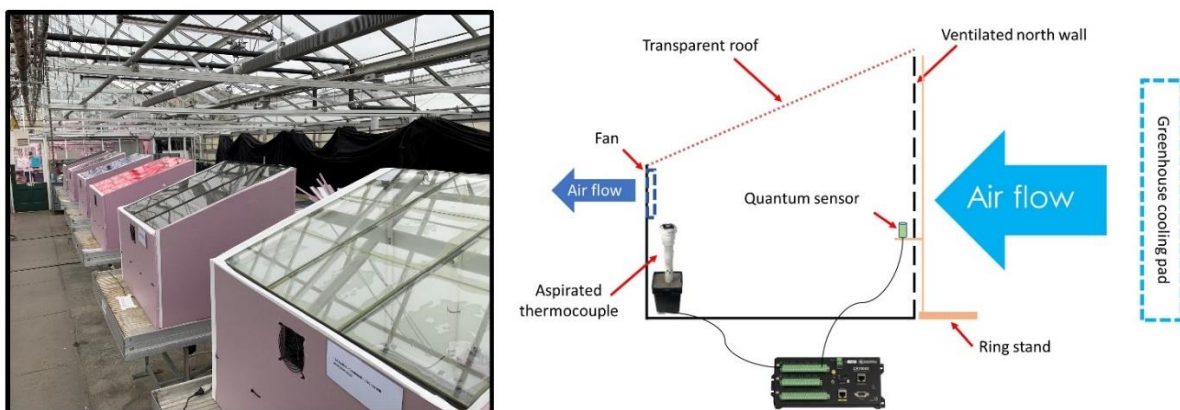


Figure 1. Picture of chambers with various experimental PV greenhouse glazing materials (left) and schematic of chamber design (right). Adapted from Stallknecht et al. (2023a)

Glazing material transmission:

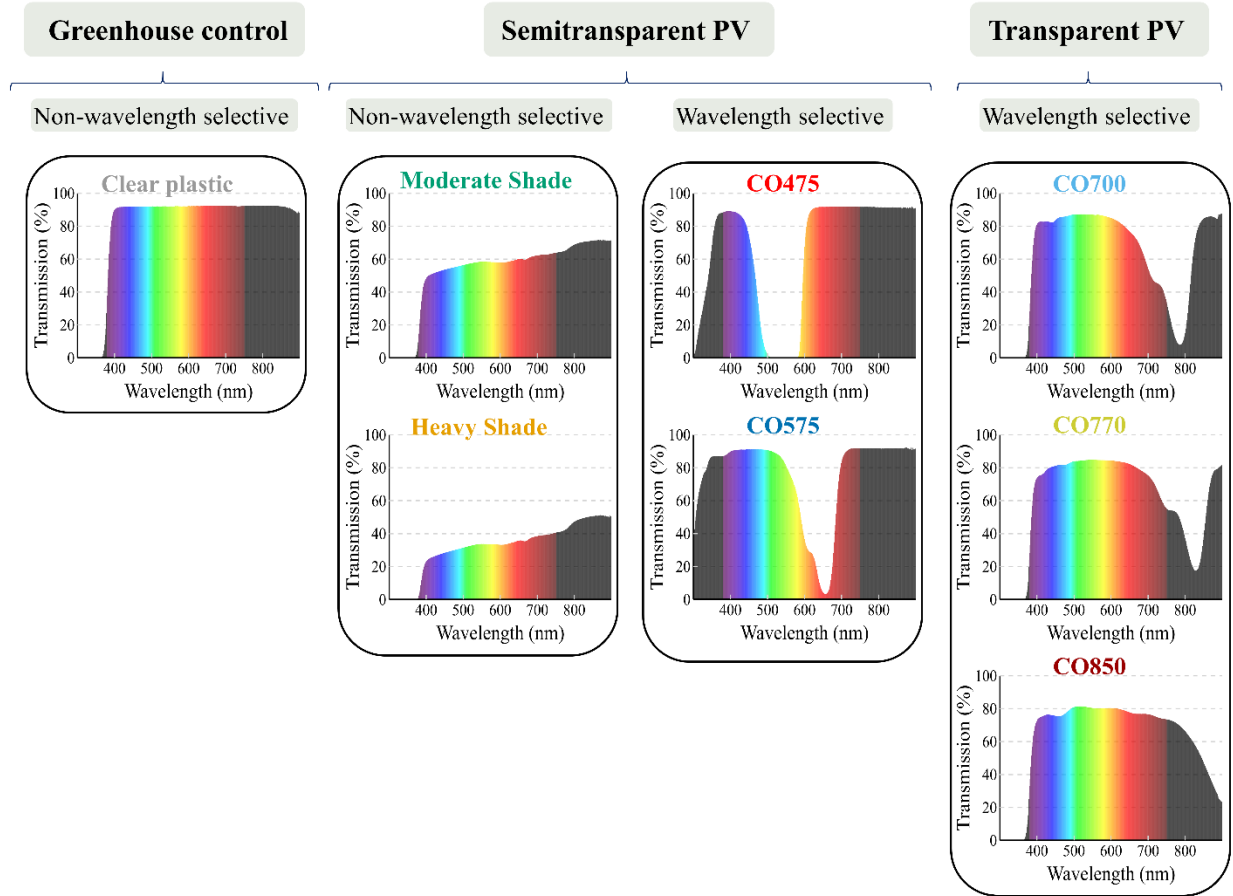


Figure 2. The transmission spectrum of each experimental photovoltaic (PV) panel.

Lettuce 'Rouxai'

26 days inside chambers | Natural photoperiod | 23 °C/73 °F

Glazing material:

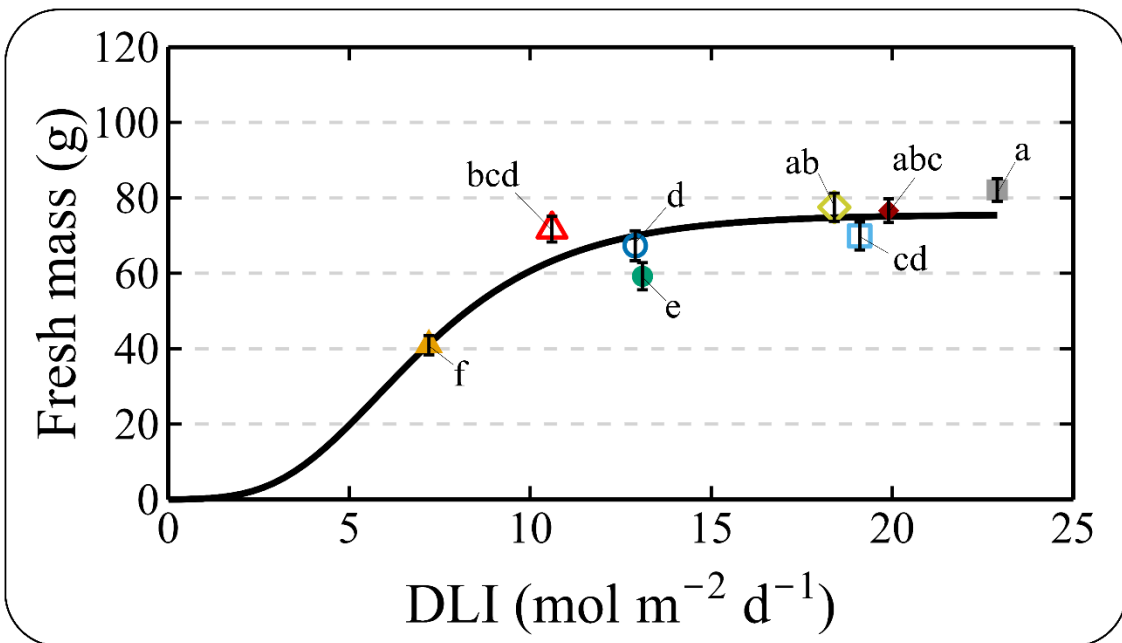
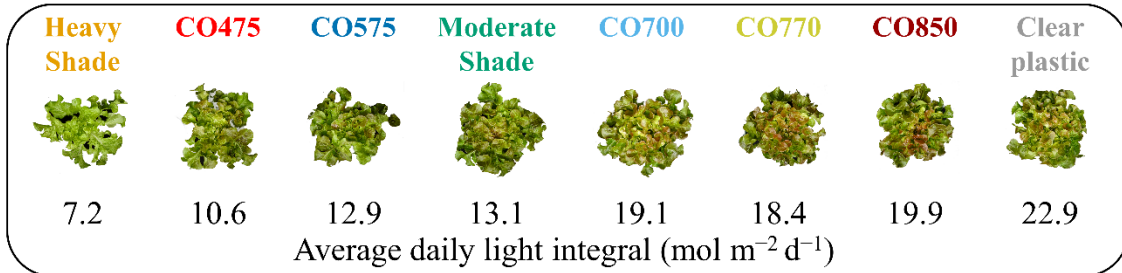


Figure 3. Lettuce 'Rouxai' growth under different experimental PV greenhouse glazings as a function of average daily light integral (DLI). Plot symbols indicate means ($n=15 \pm 95\%$ CI) and letters indicate significant difference using Tukey's HSD at $\alpha=0.05$.