Evaluating Production of Five Leafy Greens under Opaque and Thin Film Semitransparent Photovoltaic Arrays

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KEYWORDS. green roof, renewable energy, rooftop agriculture, solar panel, urban agriculture

ABSTRACT. Combining green roofs with solar modules can protect plants and produce energy in cities. Growing crops in this system is called rooftop agrivoltaics (RAV) and can complement current urban agriculture efforts. We evaluated a group of five leafy green crops (arugula, kale, lettuce, spinach, and Swiss chard) under different solar modules over 2 years at two locations. Data measurements were taken for fresh and dry weight (FW and DW, respectively), stomatal conductance (SC), plant size at harvest (PSH), and microclimate data. Treatments included a polycrystalline opaque silicon module, a cadmium telluride (CdTe) frameless opaque module, a 40% semitransparent CdTe module, and a full sun control. Four of the five leafy greens produced higher FW and DW under the 40% semitransparent modules compared with other treatments and the full sun control, except spinach. Most species also produced larger PSH under the photovoltaic (PV) module treatments compared with the full sun control. Leafy greens under the module treatments resulted in lower SC; however, lettuce and Swiss chard grown under the semitransparent module treatment produced higher SC compared with all other treatments. This research shows that incorporating photovoltaics on rooftop gardens influences the yield and SC of select leafy green crops. Although FW and DW mostly decreased under the deep shade treatments (opaque module, frameless module, and bifacial module) SC decreased, possibly due to less solar radiation on the leafy greens, reducing water use. Understanding the growth characteristics and growing environment of high-value crops like leafy greens will increase understanding of what food crops are suitable for RAV systems.

Green roofs can provide resiliency and ecosystem benefits in cities. They can extend the life of a roof by protecting it from direct solar radiation and buffering it from extreme temperature fluctuations (Calheiros and Stefanakis 2021). Green roofs also delay stormwater runoff by up to 12 min, depending on the characteristics of the layers used on the green roof (Salerno 2023). They also provide habitat for fauna, such as birds and arthropods, providing nesting, resting, feeding, and breeding sites in an urban environment (Ruszkowski and Bousselot 2024).

Agrivoltaics, a contraction of agriculture and photovoltaics (PV), where agriculture is combined with photovoltaic arrays (Barron-Gafford et al. 2019; Uchanski et al. 2023), is another system that can be used on rooftops. Using rooftop space for food and energy production is effective land use and can be a means to contribute to the urban ecosystem. The PV modules provide protection for the crops from environmental stressors, as well as lower temperatures and lower evapotranspiration rates (Uchanski et al. 2023). Prior studies have shown that there is no significant difference in perennial plant growth between full sun and under solar modules, and there was higher plant overwinter survivability under PV compared with full sun (Hickey 2023). This combination can also create more efficient energy production than with unvegetated substrate. Others have noted increases in the power output of the PV by 8.6% (Gupta et al. 2017).

Today, there are numerous types of PV modules available for use. The most common of these systems are silicon modules, usually in single or polycrystalline forms. Single crystalline silicon modules are highly efficient compared with the polycrystalline variety; however, the materials used to create the single crystalline silicon module are scarce and expensive to use (Rabaia et al. 2021). Silicon solar cells have been studied since the 1950s, and since then have had many iterations with different materials used to gain efficiency (Bosio et al. 2020).

One of the newer technologies is CdTe thin film photovoltaics, which are highly efficient PV cells. They are more efficient than the single crystal materials that have been used in the past (Bosio et al. 2006) with a theoretical efficiency of more than 32% (Romeo and Artegiani 2021). CdTe modules can be made thinner, which reduces manufacturing costs, lower costs per watt, and fewer materials are needed for the racking systems (Aghaei and Yaghobi 2011). CdTe also has a bandgap of 1.5 eV, which is very nearly ideal for photovoltaic energy conversion (Bosio et al. 2020; McCandless and Sites 2011). The bandgap is the minimum amount of energy required to excite an electron from the valance band into the conduction band (Smith and Nie 2009).

CdTe modules have also produced comparable energy yields to silicon-based PV. Using CdTe thin film PV on green roofs can theoretically increase power generation. Semitransparent modules combine the benefits of visible light transparency and light conversion into electricity (Sun and Jasieniak 2017). These can be created in multiple ways, including physical spacing of the solar cells within the module until the desired transparency is reached, wavelength selective solar cells that contain compounds that selectively absorb ultraviolet and/or near infrared light, thin film photovoltaics that are screen printed onto glass, and thin films deposited onto glass and laser ablation to create space (Pulli et al. 2020). Using the semitransparent PV modules with the CdTe thin film PV modules may increase power output, while providing enough sunlight for plants to grow under the panels. However, evaluating the ideal transparency levels for crop growth and energy production needs to be studied.

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Characterizing rooftop agrivoltaics (RAV) is necessary to understand how agrivoltaics and green roof systems can be integrated. Due to the harsh environments of rooftops, special care must be taken when choosing suitable plants for green roofs (Rayner et al. 2016; Seyedabadi et al. 2021). Leafy greens were chosen because of similar growing conditions, such as a daytime temperature of 15 to 24 °C, with regular irrigation (Ryder 2012), and relatively high market value. For example, in 2022, lettuce was the most widely consumed leafy green in the United States, which totaled $1.25 billion in sales (USDA ERS n.d.). With results found in agrivoltaics at-grade (Barron-Gafford et al. 2019; Liu et al. 2023; Widmer et al. 2024), we predicted that different modules would have different impacts on the environment below the modules. This would result in differences in crop growth, yield, and evapotranspiration. Our objectives for this study were 1) to evaluate the environmental conditions for crop growth under solar modules, such as substrate moisture content and temperature; 2) to explore the growth and yield of leafy greens, specifically arugula, kale, lettuce, spinach, and Swiss chard; and 3) evaluate SC of leafy greens to observe the patterns of water use in RAV systems, especially in urban settings.

Materials and methods

Following the methods of Uchanski et al. (2023), we evaluated leafy greens in a simulated rooftop agrivoltaic system installed at the Foothills Campus of Colorado State University, west of Fort Collins, CO, USA (40.586318–105.147377). The green roof system is 17 m × 8.7 m × 15 cm deep and contains a 20-mil root barrier and Extenduct drainage/water retention layer, supplied by Green Roof Solutions (Glenview, IL, USA). The substrate is composed of 60% expanded shale aggregate, 20% compost, 10% vermiculite, and 10% peatmoss, by volume.

This study evaluated leafy green production under three PV module treatments and full sun conditions. Similar to Uchanski et al. (2023), the PV module treatments included deep shade under opaque silicon polycrystalline framed solar modules, opaque CdTe frameless modules, which allows more light through due to the ~10-cm space between the panels, and 40% semitransparent CdTe thin film solar modules (Fig. 1). The modules were mounted to a standard ground-mounted racking system angled at ~35 degrees due south. The front edge of the modules was 35 cm (14 inches) above the substrate and the back edge is 122 cm (48 inches) above the substrate. Irrigation was supplied by 1.5 lph (0.4 gph) drip emitters spaced at 15-cm (6-inch) intervals and lines were spaced 30 cm (12 inches) apart (Netafim, Tel Aviv-Yafo, Israel). The plots were initially irrigated once a day at 7 AM, running for 30 min. Irrigation was increased

Fig. 1. Solar modules used in this project. Left to right: A, 40% semitransparent cadmium telluride (CdTe) frameless solar modules; B, opaque CdTe frameless; C, opaque polycrystalline silicon module; and D, full sun control. Photo: Matt Staver.

to twice a day at 7 AM and 3 PM, running for 30 min on May 20, 2022.

Growing conditions were continuously monitored using HOBO H21-USB micro station data loggers (Onset Computer Corporation, Bourne, MA, USA) every 15 min. Module surface and air temperatures [measured at 30 cm (12 inches) above the surface with solar shield] were measuredusing HOBO 12-bit temperature smart sensors. Substrate moisture content was measured using an ECH20 EC-5 Soil Moisture Sensor (Meter Group, Pullman, WA, USA).

Arugula (*Eruca sativa* ‘Standard Arugula’), kale (*Brassica oleracea* ‘Winterbore’), lettuce (*Lactuca sativa* ‘Salvius’), spinach (*Spinacia oleracea* ‘Space’), and Swiss chard (*Beta vulgaris* ‘Charbell’) were obtained from Johnny’s Selected Seeds (Winslow, ME, USA). Seeds were planted with PRO-MIX BX media (Premier-Tech, Rivière-du-Loup, QC, Canada) in 50-cell plug trays (Johnny’s Selected Seeds) on 5 Apr 2022, 4 May 2022, 12 Jul 2022, and 11 Apr 2023 in Plant Growth Facilities and The Horticulture Center at Colorado State University. Each cell is ≈131 cm^3. Once seeds germinated and were viable for transplantation, they were transplanted into randomly selected treatments on 3 May 2022, 21 Jun 2022, 9 Aug 2022, and 9 May 2023. Five of the same species of leafy green were planted in single rows, as shown in Figs. 2 and 3. The location of each species was randomized using an online number generator. Each number, 1 to 4 represented a treatment. Then, numbers 1 to 5 represented which species would be planted. Finally, numbers 1 to 5 represented the location within the treatment. The substrate was amended at transplanting using EcoGro compost (A1 Organics, Eaton, CO, USA).

Fig. 2. Lettuce planted in row. Each leafy green was planted in one row. The location of each row was randomized under each treatment, during each block.

The leafy greens were harvested and replanted every 42 d after transplanting on 14 Jun 2022, 2 Jul 2022, 20 Sep 2022, and 20 Jun 2023. The FWs were taken after harvest and were placed in brown paper bags. They were transferred into a drying oven at 70 °C and dried for 72 h. They were then weighed to find the DW. SC was collected at 12 PM using an SC-1 Leaf Porometer System (Meter Group, Pullman, WA, USA). Leaves for SC were selected at midcanopy. PSH was measured using the height and two widths. Height was measured from soil level to the tallest point. Width was measured by measuring at the widest part of the canopy of the plant, and then directly 90° perpendicular. FW, DW, SC, and PSH were collected at every harvest.

Statistical analysis was completed using R Studio version 4.1.2 (RStudio, Inc., Boston, MA, USA) for each vegetable type and response variable (FW, DW, SC, and PSH) through a three-way analysis of variance and using Tukey’s method for a pairwise mean comparison. The planting rounds were a blocking variable, repeating the study at multiple time points through the growing season. Due to the fixed location of the solar arrays, this is a physically unreplicated study and instead blocked over time as the form of replication. Because there is a separate analysis for each leafy green species, each leafy green species was a stand-alone study.

Results and discussion

The light penetrating through the semitransparent module resulted in higher productivity for some leafy greens, while protecting the plants from intense, direct solar radiation (Hudelson and Lieth 2021). The leafy greens were more likely to survive transplantation under PV module treatments, specifically the semitransparent CdTe treatment. The leafy greens in the full sun control frequently dried out, killing the plants after transplant.

HOBO MICROCLIMATE DATA. The mean air temperature under the PV module treatments and the full sun control were similar (Table 1). The max air temperatures under full sun control did reach past 40 °C in July and August, whereas the air temperature under the PV module treatments remained below 40 °C.

There was higher mean substrate moisture content under the PV module treatments in May and September compared with the full sun (Fig. 4). During June, July, and August, the semitransparent module treatment had the lowest substrate moisture content compared with the other PV module treatments and full sun control. This could be due to the higher plant productivity under the semitransparent module treatments compared with all other treatments (Figs. 5 and 6).

FRESH WEIGHTS. The study revealed that leafy greens planted under the PV treatments resulted in greater FW compared with the full sun control across most species (Fig. 5). There was a significant difference in FW in arugula among semitransparent module treatments, opaque module treatments, and full sun control. Arugula had a greater mean FW of 42.39 g ($P \leq 0.05$) under the semitransparent module treatment, whereas under the opaque module treatment and full sun control, the mean FW was 2.66 g and 18.66 g, respectively. Kale under the semitransparent module treatment produced a greater FW than the full sun control. The mean FW of kale under the semitransparent module treatment was 38.84 g, and under full sun was 12.09 g ($P \leq 0.05$).

Lettuce grown under the semitransparent PV module treatment produced higher FW compared with the other PV module treatments and full sun control ($P \leq 0.05$). The mean FW of lettuce was greater than the other PV module treatments and full sun control, resulting in a mean FW of 94.5 g. Under the opaque module treatment, the mean FW was 31.97 g, the frameless module treatment was 51.96 g, and the full sun control was 50.09 g. In lettuce, a reduction in PAR by 0.9% was found to enhance yield in greenhouse conditions (Stagnari et al. 2015). Spinach, however, did not exhibit statistically significant differences in FW across treatments. Spinach

Fig. 3. Planting of a block. As shown, a single species was planted in one row with five plants. Each leafy green was randomly assigned a location in each treatment and was randomly reassigned between each block. Photo: Hord, Coplan, Macht.

growth is hindered by temperatures exceeding 25 °C (Tai et al. 2020). Average air temperatures under the PV modules and full sun were below 25 °C; however, the air temperatures did fluctuate above 25 °C frequently, peaking at 40.34 °C in the full sun control (Table 1). The higher temperatures could have influenced the growth of spinach, resulting in no significant differences between treatments.

Dry weight. Net primary production is correlated with aboveground DW (Smart et al. 2017). Leafy greens grown under the semitransparent PV module treatment produced higher DW compared with the other PV module treatments and the full sun control (Fig. 6). The mean DW under the semitransparent module treatment was 4.47 g. Under the opaque and frameless module treatments, and full sun control, the mean dry weight was 1.41 g, 0.93 g, and 2.08 g, respectively ($P \leq 0.05$).

Differences were also found in kale DW between the semitransparent module treatment and the opaque module treatment. The mean DW under the semitransparent module treatment was 4.32 g and under opaque module treatment was 1.6 g ($P \leq 0.05$). There was no significant difference found between the full sun control plot and the PV module treatments.

Lettuce produced a higher DW when grown under the semitransparent module treatment compared with the other PV module treatments and full sun control ($P \leq 0.05$). The mean dry weight under the semitransparent module treatment was 5.88 g. The mean dry weight under the frameless module treatment was 3.1 g. There was no significant difference found between the full sun control and PV module treatments.

Swiss chard grown under the PV module treatments produced higher DW compared with the full sun control ($P \leq 0.05$). The mean dry weight for the opaque module treatment was 1.25 g. The mean dry weight was 0.51 g in the full sun control. Swiss chard had higher dry weights under the opaque module treatment compared with the other treatments and the full sun control. A study done by Ria et al. (2023) measured growth and productivity in Swiss chard under reduced sunlight intensity at 45%, 55%, and 80% in urban areas. The study showed that the 55% shade intensity resulted in higher leaf dry weight of 6.21 g. The second highest was under 0% shade intensity with 4.47 g. There was a 72% growth reduction between the plants grown in the 55% shade intensity and 0% shade intensity. Compared with our study, the Swiss chard grown in the full sun control plot had the lowest dry weight compared with the opaque module treatment, frameless module treatment, and the semitransparent module treatment. One difference between the studies is the climate in which the plants were grown. Ria et al. (2023) grew the plants in a tropical climate and our study took place in a semiarid environment. The difference in moisture availability and

Table 1. The minimum (Min), maximum (Max), and mean air temperatures (°C) under the opaque module treatment, frameless module treatment, semitransparent module treatment, and full sun control.

		Opaque	Frameless	Semitransparent	Full Sun
May	Min	1.23	0.14	0.22	−0.14
	Max	37.15	34.10	33.24	34.02
	Mean	13.75	14.70	14.89	15.03
June	Min	5.90	5.72	2.88	2.69
	Max	37.51	38.14	37.62	38.84
	Mean	20.94	20.91	20.99	21.11
July	Min	11.71	11.52	11.54	11.64
	Max	39.52	39.07	39.43	40.34
	Mean	24.01	23.95	22.09	24.30
August	Min	11.10	10.96	11.08	10.59
	Max	39.52	39.07	39.43	40.34
	Mean	21.77	21.89	22.00	22.13
September	Min	5.80	5.36	5.64	5.49
	Max	37.10	36.63	37.54	38.23
	Mean	19.05	18.99	19.43	19.53

light intensity between the different climates could have had an influence in the relative success of the leafy greens.

Root zone temperatures maintained below 20 °C can result in higher dry matter in spinach (Wang et al. 2022). The average substrate temperatures were ∼20 °C between June through August under the module treatments and the full sun control, and the max temperatures under the module treatments were above 20 °C (Table 1). With the substrate temperature fluctuating above 20 °C throughout the growing season, this could have influenced a reduced dry weight in spinach, resulting in no significant differences in dry weight for spinach under the module treatments or full sun control.

Plant size at harvest. Most species grown under the module treatments resulted in higher PSH compared with the full sun control. PSH was greater in arugula grown under the semitransparent module treatment compared with the other module treatments and the full sun control (Fig. 7). Arugula grown under the semitransparent module treatment produced a larger PSH of 22.2 cm compared with the PV module treatments ($P \leq 0.05$). Arugula grown under the opaque PV module treatment produced a PSH of 15.9 cm. Arugula grown under the frameless PV module treatment produced a PSH of 17.0 cm. Arugula grown under the full sun control produced a PSH of 7.9 cm.

Lettuce grown in the full sun control had reduced PSH compared with all PV module treatments. Under the opaque module treatment, the mean PSH was 17.77 cm, under the frameless module treatment, the mean PSH was 20.66 cm, and under the semitransparent module treatment the mean PSH was 18.66 cm. In the full sun control plot, the mean PSH was 9.67 g ($P \leq 0.05$).

Spinach grown under the frameless PV module treatment resulted in a larger PSH compared with the other PV module treatments and the full sun control ($P \leq 0.05$). Spinach grown under the frameless PV module produced a PSH of 10.31 cm. Spinach grown under the semitransparent module treatment resulted in a PSH of 8.16 cm. Spinach grown under the opaque module treatment resulted in a PSH of 5.91 cm. Spinach grown in the full sun control had a PSH of 5.89 cm.

PSH was greater in Swiss chard under the module treatments compared with the full sun control ($P \leq 0.05$). Under the opaque, frameless, and semitransparent module treatments, Swiss chard produced a PSH of 12.59 cm, 16.59 cm, and 14.25 cm, respectively. The Swiss chard grown in the full sun control plot resulted in a PSH of 7.11 cm.

In a study by Maseko et al. (2019), the plant height for Swiss chard increased at higher water availability. There was higher substrate moisture content under the opaque module treatment and the frameless module treatment (Fig. 4). The increased substrate moisture under the module treatments may have a positive influence on most of the leafy greens, resulting in larger PSH.

Stomatal conductance. SC is influenced by soil water supply and atmospheric evaporative demand (Liao et al. 2022). SC is used as a proxy for water use, because stomata control gas exchange (Buckley 2019). Significant differences in SC were found in plants between the module treatments and full sun control for some of the species (Fig. 8). SC in arugula grown under the opaque module treatment was significantly reduced compared with arugula grown in the full sun control. The mean SC under the opaque module

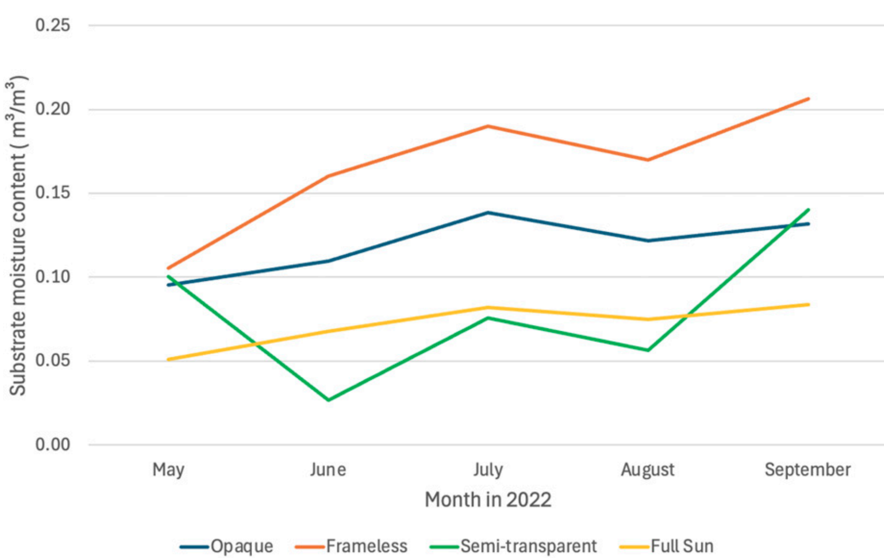

Fig. 4. Substrate moisture content (m^3/m) under silicon opaque module treatment, cadmium telluride (CdTe) thin film opaque frameless module, 40% semitransparent CdTe thin film module, and full sun control plot. The substrate water content was averaged each month for the growing season in 2022.

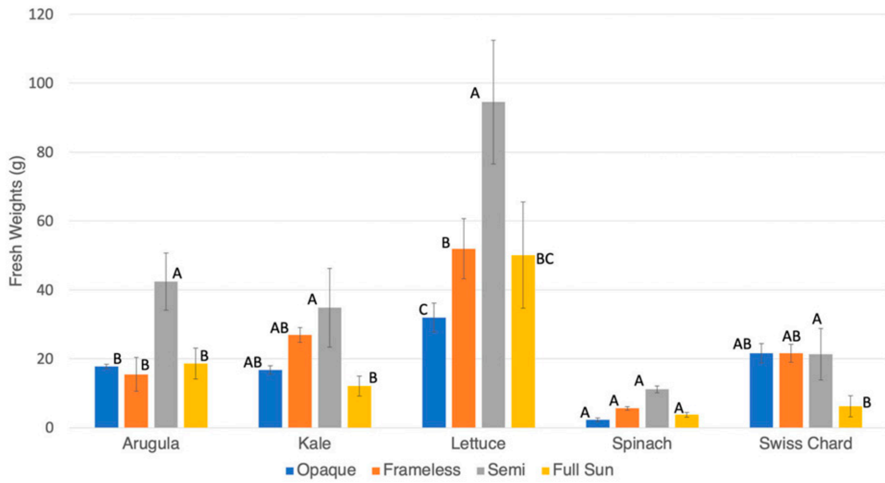

Fig. 5. Fresh weights (g) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, cadmium telluride (CdTe) thin film opaque frameless module, 40% semitransparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

treatment was 397.99 mmol/m^2/s. Under the full sun control, the mean was found to be 888.1 mmol/m^2/s ($P \leq 0.05$). Arugula has a reduction in water use efficiency if exposed to drought stress (Mangarotti et al. 2020). Because the plants were in shade, there was less direct solar radiation reducing water loss in arugula.

SC in lettuce grown under the opaque module treatment was significantly reduced compared with lettuce grown in the full sun control ($P \leq 0.05$). The mean SC under the opaque module treatment was 379.23 mmol/m^2/s. The mean in full sun control was 590.86 mmol/m^2/s. A study by Elamri et al. (2018) indicated a decrease in water demand in lettuce by 20% under agrivoltaics that included two tracking PV modules, two fixed PV modules, and a full sun control plot. The lettuce grown under the opaque module treatment in our research indicates a 38% decrease in SC compared with the full sun plot.

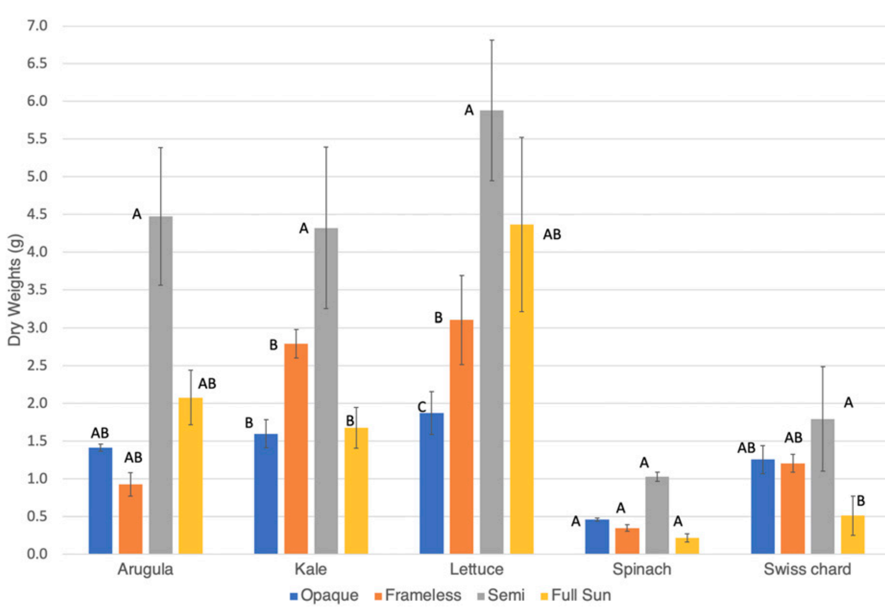

Fig. 6. Dry weights (g) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, cadmium telluride (CdTe) thin film opaque frameless module, 40% semitransparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

SC was higher in Swiss chard grown under semitransparent module treatment compared with both the opaque module treatment and frameless module treatment, and full sun control ($P \leq 0.05$). SC of Swiss chard grown under the semitransparent module treatment was 343.26 mmol/m^2/s. Swiss chard grown under the opaque module treatment, resulted in an SC of 130.53 mmol/m^2/s. The Swiss chard grown under the frameless module treatment resulted in an SC of 271.77 mmol/m^2/s, whereas the Swiss chard grown in the full sun control produced an SC of 283.34 mmol/m^2/s.

There were no significant differences produced in kale or spinach under the PV module treatments compared with full sun control. High temperatures can influence water use efficiency, photosynthesis, and plant weight (Sehgal et al. 2022). The average air temperature did not change drastically between the module treatments and the full sun control (Table 1). However, the maximum temperatures were close to 40 °C under the PV module treatments and were over 40 °C in the full sun control. The higher temperatures could have influenced the SC in kale and spinach, resulting in no significant differences between the PV module treatments and the full sun control. In spinach, root zone temperatures were found to influence dry matter production (Wang et al. 2022) and substrate moisture stress can reduce the growth of leafy greens (Maseko et al. 2019). Root zone temperature and substrate moisture content could have influenced the SC of spinach and kale, producing no significant differences between the module treatments and the full sun control.

In conclusion, leafy greens may experience growth and yield benefits when grown under the shade conditions of some PV systems on simulated green roofs. The plants are protected from direct solar radiation and transpire less under the modules. Some leafy greens produced higher FWs under the 40% semitransparent modules compared with other treatments and the full sun control. This may indicate that the partial shading from the 40% semitransparent module benefits certain species of leafy greens. Fully characterizing rooftop agrivoltaics is necessary to understand this system and how different solar modules influence crop

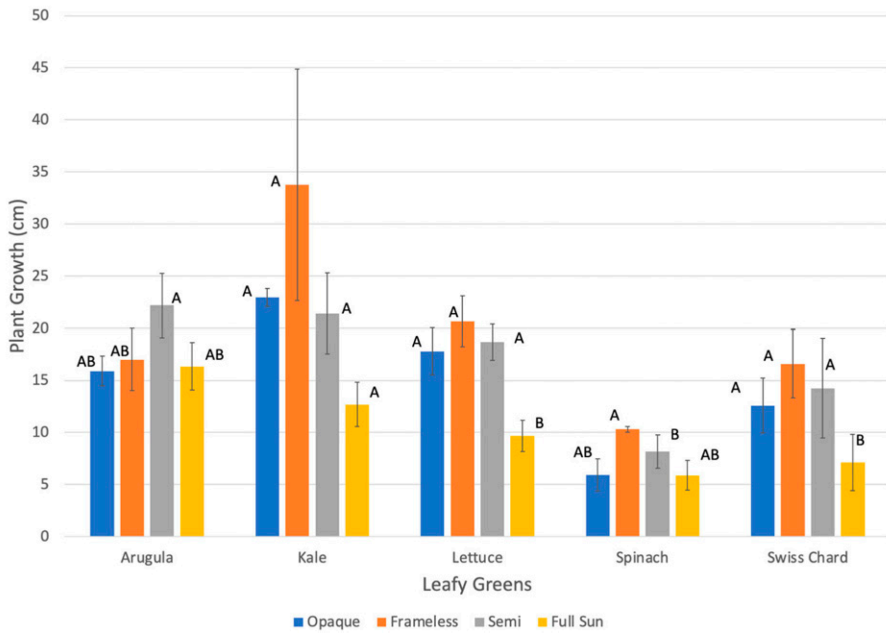

Fig. 7. Plant size at harvest (cm) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, cadmium telluride (CdTe) thin film opaque frameless module, 40% semitransparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

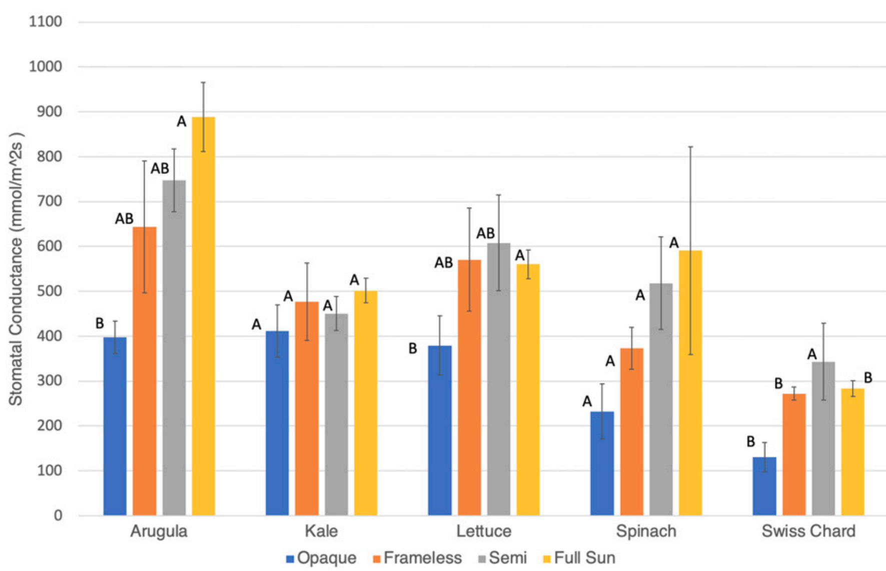

Fig. 8. Stomatal conductance (mmol/m^2/s) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, cadmium telluride (CdTe) thin film opaque frameless module, 40% semitransparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

production. RAV can produce renewable energy and food in the same location, creating a food-energy-water nexus that can aide resiliency within urban areas.

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