THESIS

EVALUATING LEAFY GREEN PRODUCTION IN A COLORADO ROOFTOP AGRIVOLTAIC SYSTEM

Submitted by

Armando Villa-Ignacio

Department of Horticulture and Landscape Architecture

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2024

Master's Committee:

Advisor: Jennifer Bousselot

Mark Uchanski
Walajabad Sampath

Copyright by Armando Miguel Young Villa-Ignacio 2024

All Rights Reserved

ABSTRACT

EVALUATING LEAFY GREEN PRODUCTION IN A COLORADO ROOFTOP AGRIVOLTAICS SYSTEM

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 two years at two locations. Data measurements were taken for fresh and dry weight (FW, DW) stomatal conductance (SC), plant size at harvest (PSH), and microclimate data. At the Colorado State University Foothills Campus, the treatments included a polycrystalline opaque silicon module, a cadmium telluride (CdTe) frameless opaque module, and a 40% semi-transparent CdTe module. At CSU Spur, there was an opaque module and a bifacial module. Both sites included a full sun control plot. At the Foothills campus, for of the five leafy greens produced higher FW and DW under the 40% semi-transparent modules compared to other treatments and the full sun control, except spinach. Most species also produced larger PSH under the PV module treatments compared to the full sun control. Leafy greens under the module treatments resulted in lower SC, however, lettuce and Swiss chard grown under the semi-transparent module treatment produced higher SC compared to all other treatments. At CSU Spur, plant responses were also species specific with arugula, kale, and lettuce yielding higher FW and DW in full sun. Most leafy greens resulted in lower SC, except for lettuce, which had a higher SC under solar module treatments. Spinach had no difference in FW but lower DW in the opaque treatment compared to the full sun control, and lower SC under both treatments. There was a lower FW between the bifacial treatment and the full sun control in Swiss chard. This research shows that incorporating photovoltaics on rooftop gardens influences the yield and stomatal conductance of select leafy green crops. While 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.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor Dr. Jennifer Bousselot. Her guidance and support made this work possible. Without her, none of this would have been achieved.

I would also like to acknowledge my committee members, Dr. Mark Uchanski and Dr. Walajabad Sampath for their expertise and support.

Thank you to Dr. Maria Chavez, who's never ending support and commitment to helping us achieve our goals continues to inspire me. This would not have been possible without you.

To the entire Bousselot lab: Amanda Salerno, Kyle Ruszkowski, Thomas Hickey, Michael Guidi, Allisa Linfield, Eliza Gross, Brian Adams, and our interns, Tatianna Hall, Bjorn Thune-Larsen, Blake Gornick, Kathryn Braun, Rebekah Buena, Kaavya Ahuja, Maria Schonewise, and Kierra Hamlin. This project would not have been possible without all your contributions, friendship, advice, and support. I am immensely proud to call all of you colleagues and friends.

To my fellow HLA graduate students, thank you for your friendship, encouragement, and willingness to talk when times get tough. Special shout out to the basement office crew!

To Daniel Shaw and Mayank Mate, thank you for your expertise in PV systems that helped me so much writing this.

To my friends and family, specifically James Weaver, who has unselfishly volunteered to help me with the project, and my sister, Denise Ellis, DMA, who's determination, and passion continue to inspire me to achieve my goals.

TABLE OF CONTENTS

Chapter 1: The Synergy Between Green Roofs and Photovoltaic Modules

1.1 Introduction

Projections show that by 2050, 68% of the global population will reside in urban areas (United Nations, 2018). This growth will be accompanied by a surge in urban land development, with an expansion of urban land area by 78-171% by 2050 (Huang et al., 2019). Consequently, the United States faces the potential loss of an additional 18.4 million acres of farmland by 2040. This will be mostly driven by low-density residential construction, such as suburban neighborhoods, utilizing land for housing and not farmland for food production (Hunter et al., 2022).

Repurposing underutilized spaces in urban environments is a solution to offset some of the issues associated with rapid urbanization. Rooftops constitute between 40-50% of the total footprint in urban areas (Stovin, 2010), most of which could be repurposed into green roofs. Modern green roof technologies have been studied over the last fifty years and has shown positive environmental results for urban areas (Bousselot et al., 2020; Getter and Rowe 2006; Köhler et al., 2019; Lambert and Donihue, 2020; Manso et al., 2020; Obendorfer et al., 2007; Paithankar and Taji, 2020; Walters et al., 2022).

Photovoltaic (PV) green roofs present an innovative approach that increases the benefits of both technologies (Shafique et al., 2020; Uchanski et al., 2023). One advantage of this system is the mutual cooling effect. On the ground, or at-grade, research has shown that PV provides shade and protection from extreme weather for plants, while the plants cool the modules due to evapotranspiration (ET), thereby enhancing the efficiency of the module (Barron-Gafford et al., 2019; Dinesh and Pearce, 2016; Hui and Chan, 2011; Semeraro et al., 2024). Continued research has also shown an increase in energy production during elevated temperatures and reductions in substrate temperature (Lamnatou and Chemisana, 2015). Higher carbon sequestration has also been seen in PV green roofs, due to photosynthesis in plants and reduced building emissions by reducing energy demands (Getter et al., 2009; Jahanfar and Drake, 2018; Seyedabadi et al., 2021).

PV green roofs can be utilized in areas where building owners intend to optimize renewable energy and green spaces on top of buildings (Bousselot et al., 2020). Rooftop agrivoltaics (RAV) combines green roofs for food production and PV modules for electricity in a synergistic system for better land-use strategy in urban areas. RAV can provide an integrated solution to issues related to the food-water-energy nexus (Jing et al., 2022; Uchanski et al., 2023).

1.2 Green Roofs and Agrivoltaics

In North America, the National Renewable Energy Laboratory (NREL) identified approximately 770,000 hectares of rooftops, of which 32% are suitable for PV (Gangnon et al., 2016). These rooftops can supplement current energy production and urban agriculture systems by incorporating RAV (Baudoin et al., 2017; Walters and Stoelzle Midden, 2018).

Research on agrivoltaics at-grade has demonstrated its potential to enhance crop productivity, indicating a 60-70% increase through integrating crop and solar modules (Dupraz et al., 2011). Despite shade-induced delayed or reduced crop yield observed in lettuce, (Elamri et al., 2019) the implementation of agrivoltaics can provide protection for plants from environmental extremes, which can contribute to more resilient agricultural systems (Barron-Gafford et al., 2019). Hui and Chan (2011) reported that the integration of PV on green roofs reduced substrate and surface temperature and increased power output. This combination has been shown to enhance plant survival rates and increase biomass, particularly in perennial herbaceous plants (Jahanfar et al., 2019; Köhler et al., 2002).

Evapotranspiration (ET) is the process by which water moves from the soil to the atmosphere via evaporation and transpiration (USGS, 2018). By density, the coarse substrate used on green roofs does have a lower water holding capacity than soil (Uchanski et al., 2023). However, several studies have revealed that PV modules and crop integration in RAV systems can conserve water overall. The shade cast by solar modules can reduce water use by plants through a reduction in stomatal conductance, or an increase in water use efficiency (Elamri et al., 2018). Applied soil moisture has been shown to remain 15% higher in the substrate due to shading from PV modules (Klokov et al., 2023). In addition to shading, PV reduces solar radiation and wind, leading to reduced evapotranspiration (Jahanfar et al., 2020; Teng et al., 2022).

Additionally, the carbon uptake capacity of crops under PV increases compared to full sun control plots (Barron-Gafford et al., 2019). Shading from solar modules can create favorable microclimates for plant growth, providing greater carbon sequestration potential (Walston et al., 2022), and low-carbon energy production (Armstrong et al., 2016). Green roofs can also be used to sequester CO_2 from the atmosphere via photosynthesis of the plants grown on it (Shafique et al., 2020). Combining PV modules on green roofs in urban areas can reduce carbon emissions further by reducing energy demands (Jahanfar et al., 2018).

1.3 Light Interactions

Rooftop surfaces in urban areas have higher solar radiation levels due to the low slope design of most buildings (Redweik et al., 2013). While light is crucial for plant growth, excessive light can result in slow growth and lower yield (Liu et al., 2023). In at-grade agrivoltaic systems, there is an increased shading of plants compared to traditional systems. This shading, however, has been associated with trade-offs, particularly in environments with dryland conditions. The shade from the modules can decrease evaporation from the substrate, which can lead to soil moisture retention (Barron-Gafford et al., 2019). Crop selection can also influence PV modules, specifically tilted bifacial modules. Silver-leafed plants such as *Sedum sieboldii* can reflect more light onto the PV modules, increasing the albedo effect onto the underside of the tilted bifacial modules (Baumann et al., 2019; Lamnatou and Chemisana 2015a). An increase in albedo from the silver leaved plants can improve the output between 5-20% in bifacial PV modules (Uematsu et al., 2003).

1.4 Temperature

PV modules in cities can provide energy generation, as well as reflecting direct solar radiation, which may insulate the receiving building (Albatayneh et al., 2022). However, the higher heat on rooftops can be detrimental to the energy production of the PV modules, degrading at a rate of 0.55-0.95% per year (Kirmani and Kalimullah, 2017). RAV reduces temperatures on the PV module and increases energy production (Alonso-Marroquin and Qadir, 2023; Köhler et al., 2007; Schindler et al., 2016; Shafique et al., 2020).

Temperatures on rooftops are slightly cooler with less daily variation when shaded by the solar modules (Bousselot et al., 2017), resulting in a 1.3°C cooler ambient air temperature under the PV modules during the hottest time of the day (Uchanski et al., 2023). PV modules, however, must be placed close enough (between 60mm and 120mm) to the green roof to benefit from enhanced cooling from evapotranspiration, but not so close that wind cannot cool the space between modules and plants (Gupta et al., 2017).

Hui and Chan (2011) indicate that adding irrigation can enhance the cooling effect that green roofs produce. The additional irrigation increases moisture level in the soil and in the air, which can cool the PV modules through ET. The irrigation combined with the shade of the PV modules can reduce soil temperatures at-grade in agrivoltaics plots versus unshaded plots (Marrou et al., 2013; Uchanski et al., 2023).

1.5 Energy Production

Renewable energy production has become increasingly important in urban areas. Numerous cities and countries are setting targets for achieving net-zero carbon emissions by 2050 (O'Regan and Nyhan, 2023; Seto et al., 2050; United Nations, 2022). This will require radically reducing the production of greenhouse gas emissions from urban activities (Seto et al., 2021). Some examples include Colorado’s 2023 legislation, which aims to reduce carbon emissions by 50% by 2030 and 90% by 2050 (Greenhouse Gas Emission Reduction measures, 2023).

To meet these goals, major cities are implementing various plans, one of which includes more green infrastructure like green roofs (Set et al., 2021). This can be accomplished through incorporating more natural parks, planting more trees, and including more structures like living walls and green roofs. Integration of solar energy production with green roof agriculture also presents a solution that addresses the need for green spaces in cities.

Incorporating PV and green roofs has been shown to reduce module temperatures by up to 4°C, with midday temperatures potentially dropping by as much as 6°C (Hendarti et al., 2013). This cooling effect can enhance efficiency and power output of the PV modules (Hui and Chan, 2011). Improved power output from ET can be enhanced by aligning irrigation systems to also fall onto the PV modules. Cooling with water from irrigation can improve energy output by up to 5.6 %, and the irrigation can also clean the dust off the PV modules, improving energy output by up to 8.8% and efficiency by up to 11.86% (Mustafa et al., 2020). These benefits may vary based on location, crop selection, and module. However, further research is needed to understand the effects of different combinations of modules and crops (Barron-Gafford et al., 2019; Dinesh and Pearce, 2016; Klokov et al., 2023; Mamun et al., 2022)

Utilizing PV in agriculture is an efficient use of available land, combining food production, energy generation, and water management. As populations rise and urban areas grow, however, agricultural land will be difficult to acquire. Combining agrivoltaics with green roofs in RAV is an effective land use strategy in cities. Rooftops are an underutilized space and can be used to supplement current urban agricultural systems, as well as increase renewable energy production and water management. With various benefits including temperature regulation, RAV can supplement current systems to aid in creating resilient systems.

2. Evaluating Production of Five Leafy Greens Under Opaque and Thin-Film Semi-Transparent Photovoltaic Arrays

2.1 Introduction

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 differences (Calheiros and Stefanakis, 2021). Green roofs also delay stormwater runoff by up to 12 minutes, 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 utilized on rooftops. Utilizing rooftop space for food production can be a means to contribute to the urban food system. 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 significance difference in perennial plant growth between full sun and under solar module, and there was higher plant overwinter survivability under PV compared to 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 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 to 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 utilized to gain efficiency (Bosio et al., 2020).

One of the newer technologies is cadmium telluride (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, 2012). 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 shown comparable energy yields to silicon-based PV. Utilizing CdTe thin film PV on green roofs can theoretically increase power generation. Semi-transparent modules combine the benefits of visible light transparency and light conversion into electricity (Sun & Jasieniak, 2017). These can be created in multiple ways. 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 UV and/or near infrared light, thin film photovoltaics that are screen printed onto glass, thin films deposited onto glass and laser ablation to create space, and others (Pulli et al., 2020). Utilizing the semi-transparent 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.

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). 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. 3) Evaluate stomatal conductance of leafy greens to observe the patterns of water use in RAV systems, especially in urban settings.

2.2 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, Colorado (40.586318–105.147377) (Figure 1). The green roof system is 17 m x 8.7 m x 15 cm deep and contains a 20-mil root barrier and Extenduct drainage/water retention layer, supplied by Green Roof Solutions (Glenview, Illinois, USA). The substrate is comprised of 60% expanded shale aggregate, 20% compost, 10% vermiculite, and 10% peat moss, by volume.

Figure 1. Location of the simulated rooftop agrivoltaic site. Source: Google Maps.

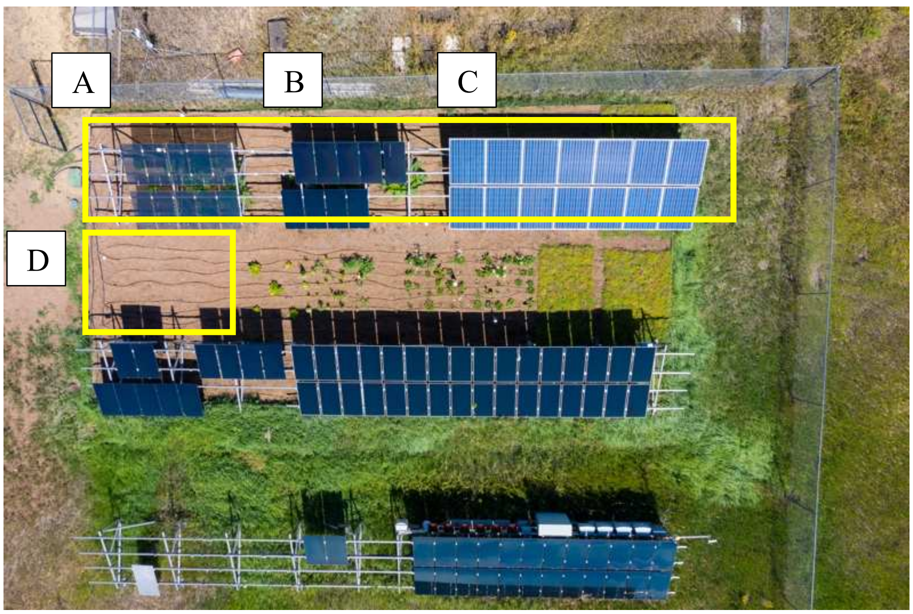

Figure 2. Solar modules used in this project. Left to right: A. 40% semitransparent CdTe frameless solar modules, B. opaque CdTe frameless, C. opaque polycrystalline silicon module, and D. full sun control. Photo: Matt Staver.

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, and 40% semitransparent CdTe thin film solar modules (Figure 2). The modules were mounted to a standard ground-mounted racking system angled at approximately 35 degrees due south. The front edge of the modules was 35 cm (14 in) above the substrate and the back edge is 122 cm (48 in) above the substrate. Irrigation was supplied by 1.5 lph (0.4 gph) Netafim drip emitters spaced at 15 cm (6 in) intervals and lines were spaced 30 cm (12 in) apart. The plots were initially irrigated once a day at 7 am, running for 30 minutes. Irrigation was increased to twice a day at 7 am and 3 pm, running for 30 minutes on May 20th, 2022.

Growing conditions were continuously monitored using HOBO H21-USB micro station data loggers (Onset Computer Corporation, Bourne, MA, USA) every 15 minutes. Module surface, and air temperatures (measured at 30 cm [12 in] above the surface with solar shield) are measured using HOBO 12-bit temperature smart sensors. Substrate moisture content was measured using 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, Maine, USA). Seeds were planted with PRO-MIX BX media (Premier-Tech, Rivière-du-Loup, QC, Canada) in 50 cell plug trays on 4/5/22, 5/4/23/22, 7/12/22, and 4/11/23 in Plant Growth Facilities and The Horticulture Center at Colorado State University. Once seeds germinated and viable for transplant, they were transplanted into randomly selected treatments on 5/3/22, 5/21/22, 8/9/22, 5/9/23. Five of the same species of leafy green were planted in single rows. The location of each species was randomized using an online number generator. Each number, 1-4 represented a treatment. Then, numbers 1-5 represented which species would be planted. Finally, numbers 1-5 represented the location within the treatment. The substrate was amended at transplanting using EcoGro compost (A1 Organics, Eaton, Colorado, USA).

The leafy greens are harvested and replanted every 42 days after transplanting on 6/14/22, 7/2/22, 9/20/22, and 6/20/23. The fresh weights (FW) 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 hours. They were then weighed to find the dry weight (DW). Stomatal conductance (SC) was collected at 12 pm using an SC-1 Leaf Porometer System (Meter Group, Pullman, WA, USA). Leaves for SC were selected at mid-canopy. Plant size at harvest (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 ANOVA analysis, 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. Since there is a separate analysis for each leafy green species, each leafy green species was a stand-alone study.

2.3 Results and Discussion

The light penetrating through the semi-transparent 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 transplant under PV module treatments, specifically the semi-transparent CdTe treatment. The leafy greens in the full sun control frequently dried out, killing the plants after transplant.

2.3.1 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, while 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 to the full sun (Figure 3). During June, July, and August, the semi-transparent module treatment had the lowest substrate moisture content compared to the other PV module treatments and full sun control. This could be due to the higher plant productivity under the semi-transparent module treatments compared to all other treatments (Figure 4, Figure 5).

Table 1. The min, max, and mean air temperatures (℃) under the opaque module treatment, frameless module treatment, semi-transparent module treatment, and full sun control.

		Opaque	Frameless	Semi-Transparent	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

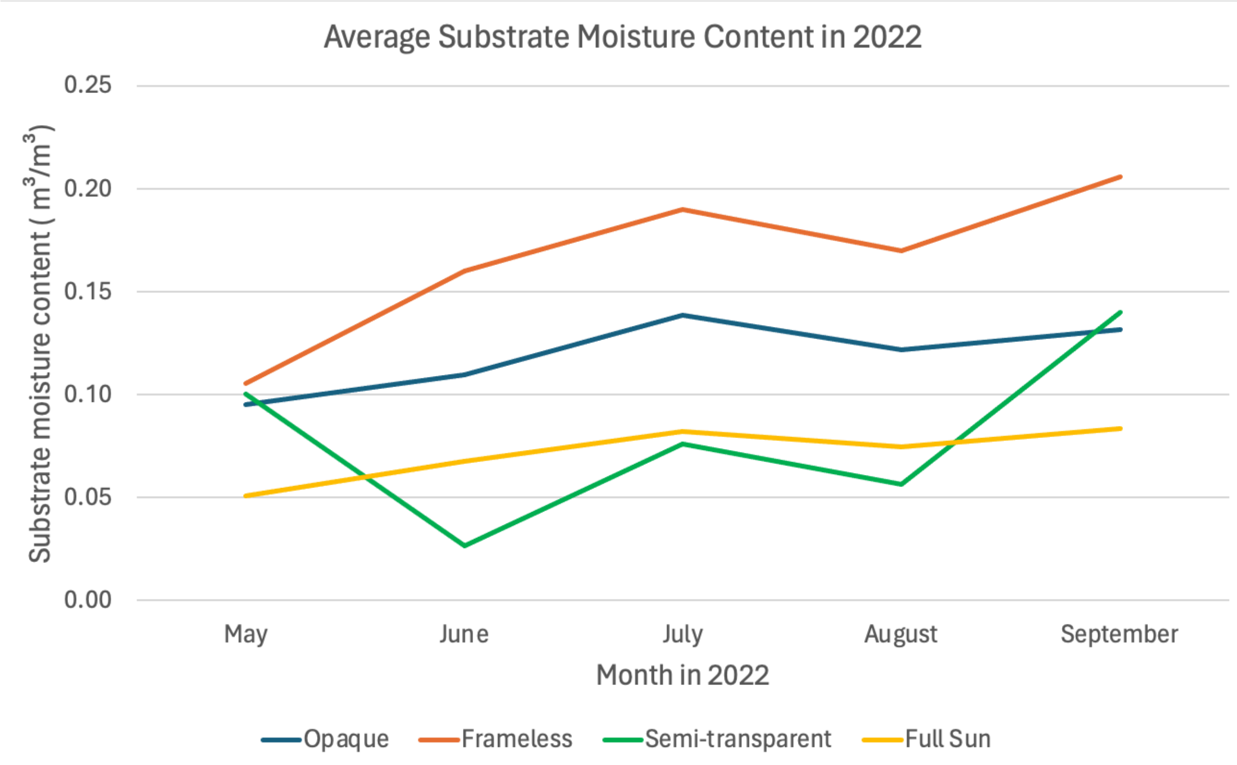

Figure 3. Substrate moisture content (m³/m) under silicon opaque module treatment, CdTe thin film opaque frameless module, 40% semi-transparent CdTe thin film module, and full sun control plot. The substrate water content was averaged each month for the growing season in 2022.

2.3.2 Fresh Weights

The study revealed that leafy greens planted under the PV treatments resulted in greater FW compared to the full sun control across most species (Figure 4). There was a significant difference in FW in arugula between semi-transparent 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 semi-transparent 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 semi-transparent module treatment produced a greater FW than the full sun control. The mean FW of kale under the semi-transparent module treatment was 38.84 g, and under full sun was 12.09 g ($p \leq 0.05$).

Lettuce grown under the semi-transparent PV module treatment produced higher FW compared to 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 in 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 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.

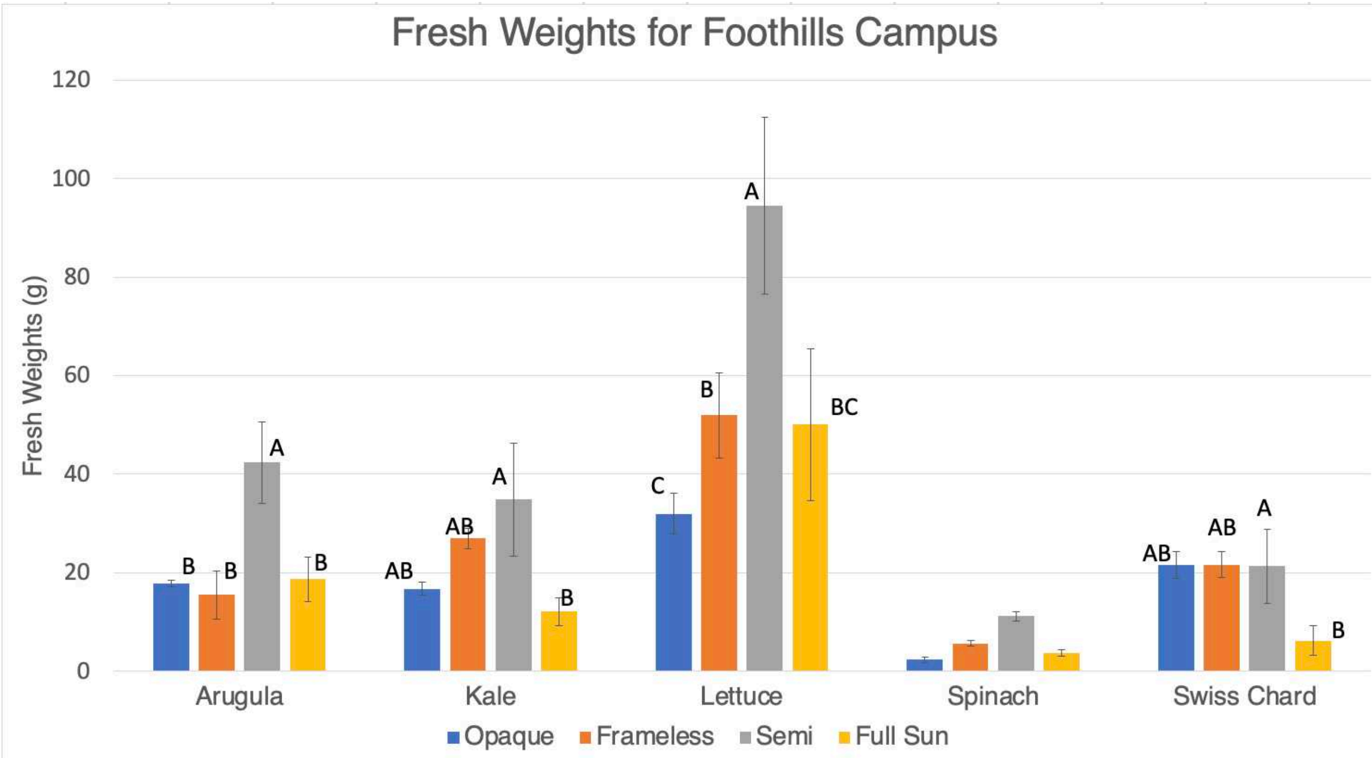

Figure 4. Fresh weights (g) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, CdTe thin film opaque frameless module, 40% semi-transparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

2.3.3 Dry Weight

Net primary production is correlated with above ground DW (Smart et al., 2017). Leafy greens grown under the semi-transparent PV module treatment produced higher DW compared to the other PV module treatments and the full sun control (Figure 5). The mean DW under the semi-transparent 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 semi-transparent module treatment and the opaque module treatment. The mean DW under the semi-transparent 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 semi-transparent module treatment compared to the other PV module treatments and full sun control ($p \leq 0.05$). The mean dry weight under the semi-transparent 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 to 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 to 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 to our study, the Swiss chard grown in the full sun control plot had the lowest dry weight compared to the opaque module treatment, frameless module treatment, and the semi-transparent module treatment. One major 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 semi-arid environment. The difference in moisture availability and 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 approximately 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 2). With the substrate temperature fluctuating above 20°C throughout the growing season, dry weight in spinach did not show any significant differences under the module treatments compared to the sun control.

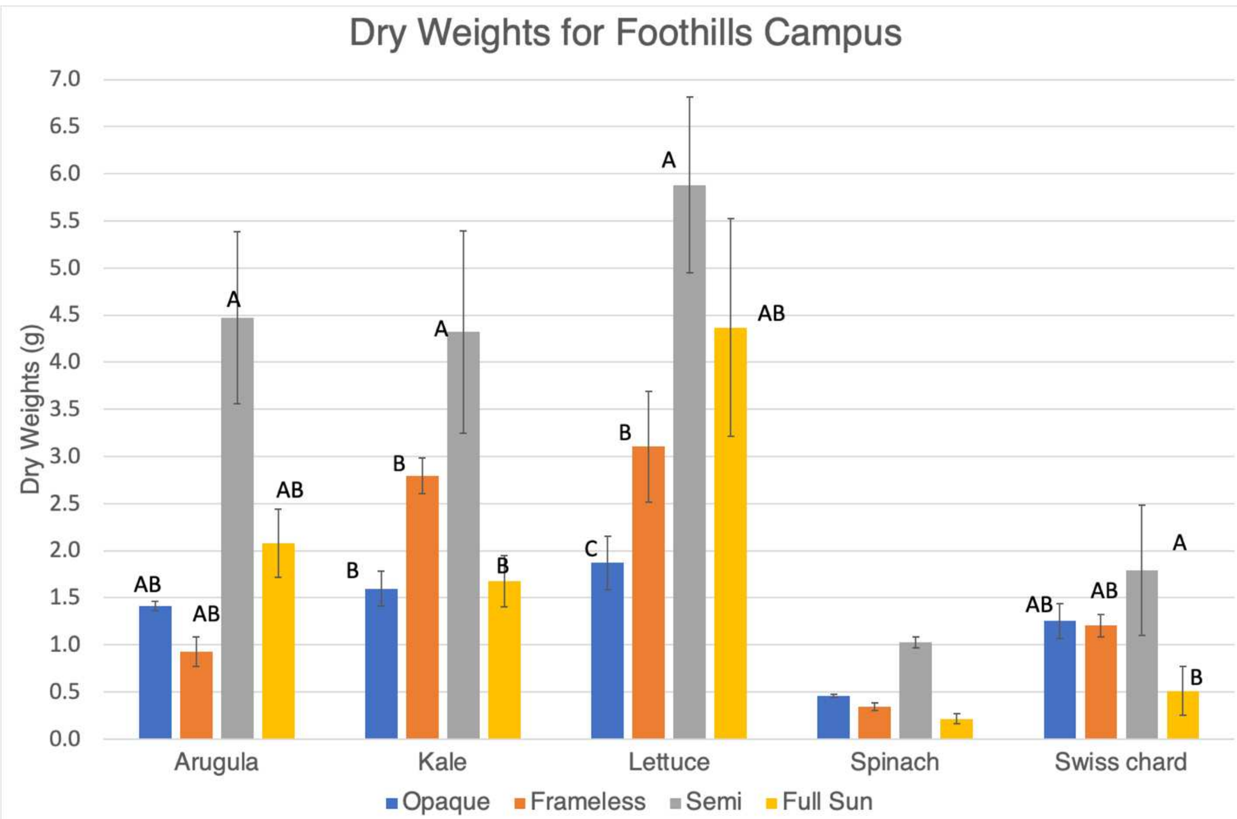

Figure 5 Dry weights (g) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, CdTe thin film opaque frameless module, 40% semi-transparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between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

2.3.4 *Plant Size at Harvest*

Most species grown under the module treatments resulted in higher PSH compared to the full sun control. PSH was greater in arugula grown under the semi-transparent module treatment compared to the other module treatments and the full sun control (Figure 6). Arugula grown under the semi-transparent module treatment produced a larger PSH of 22.2 cm compared to 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 to 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 semi-transparent 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 to 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 semi-transparent 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 to the full sun control ($p \leq 0.05$). Under the opaque, frameless, and semi-transparent 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 (Figure 3). The increased substrate moisture under the module treatments may have a positive influence on most of the leafy greens, resulting in larger PSH.

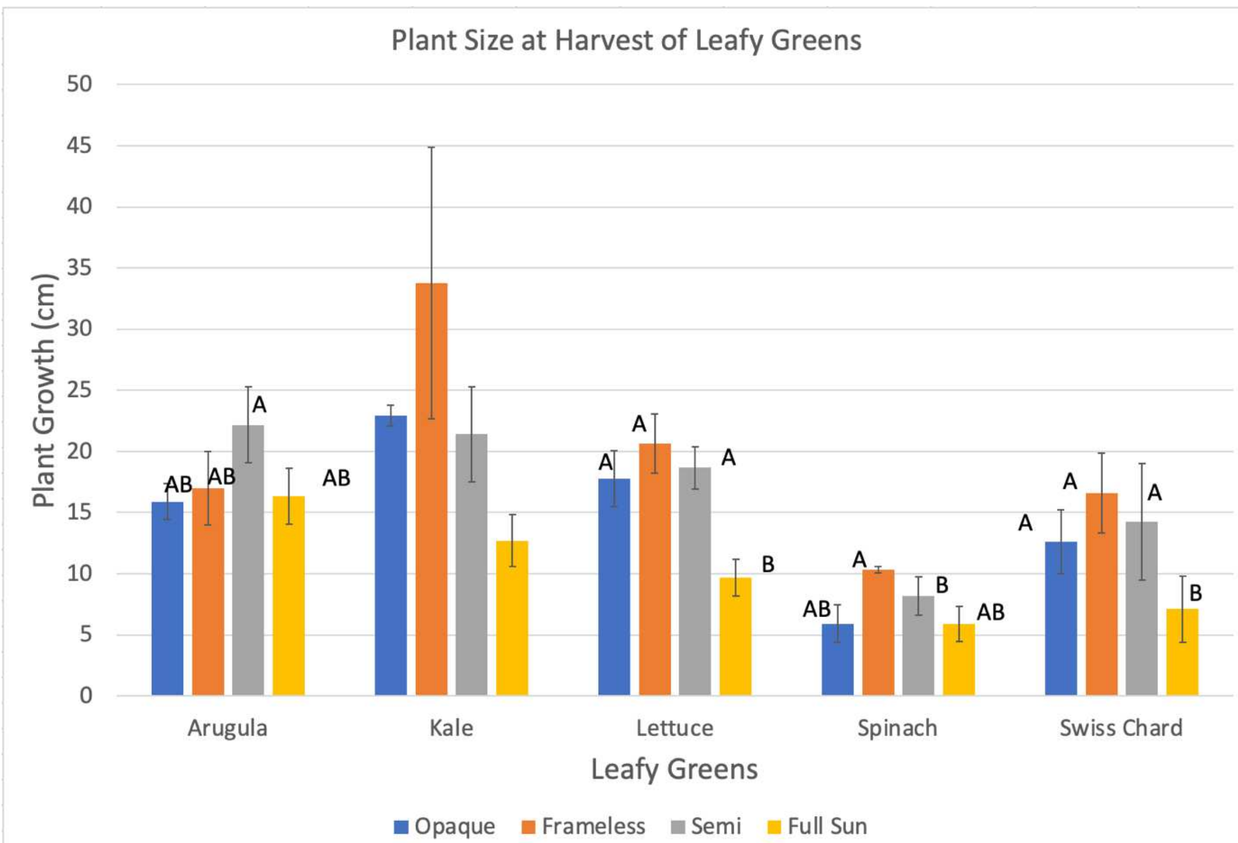

Figure 6 Plant size at harvest (cm) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, CdTe thin film opaque frameless module, 40% semi-transparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

2.3.5 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, since 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 (Figure 7). SC in arugula grown under the opaque module treatment was significantly reduced compared to arugula grown in the full sun control. The mean SC under the opaque module 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). Since 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 to 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 to the full sun plot, resulting in lower SC under the module treatments compared to full sun control. SC was higher in Swiss chard grown under semi-transparent module treatment compared to both the opaque module treatment and frameless module treatment, and full sun control ($p \leq 0.05$). SC of Swiss chard grown under the semi-transparent 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, while 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 to 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 max 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.

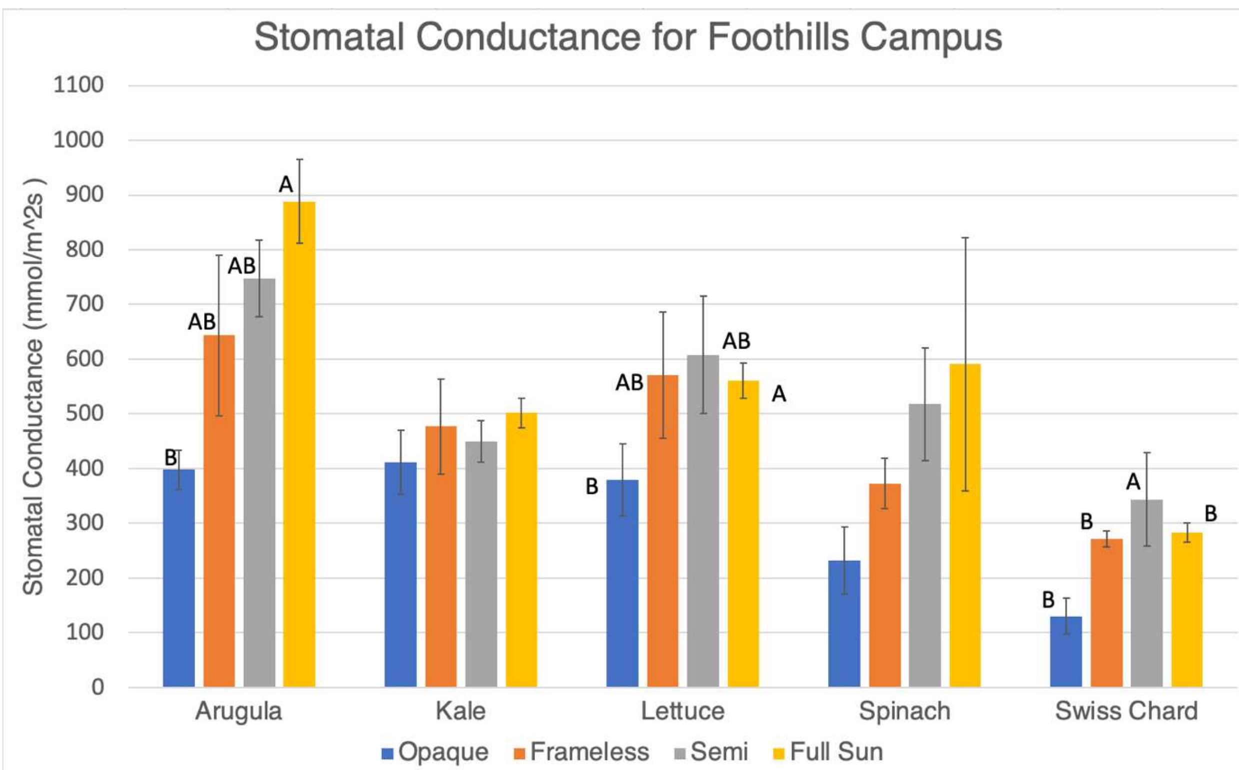

Figure 7 Stomatal conductance (mmol/m²/s) of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, CdTe thin film opaque frameless module, 40% semi-transparent CdTe thin film module, and full sun control plot. The letters signify significant differences found between treatments.

In conclusion, leafy greens may experience growth and yield benefits when grown under the shade conditions of PV systems on simulated green roofs. The plants are protected from direct solar radiation and transpired less under the modules. Some leafy greens produced higher FWs under the 40% semi-transparent modules compared to other treatments and the full sun control. This may indicate that the partial shading from the 40% semi-transparent module benefits certain species of leafy greens. RAV can produce renewable energy and food in the same location. Fully characterizing rooftop agrivoltaics is necessary to understand this system and how different solar modules influence crops.

3. Evaluating Leafy Green Production Under Two Silicon Modules in a Rooftop Agrivoltaics System

3.1 Introduction

Urban agriculture has the potential to enhance food production resiliency within urban areas (Ferreira et al., 2018; Langmeyer et al., 2021). One potential urban agricultural application is agrivoltaics. Agrivoltaics is the combination of food and energy production on the same land (Dinesh and Pearce, 2016). Rooftop agrivoltaics (RAV) is an option that can be utilized to supplement current urban agriculture systems. RAV is the combination of agrivoltaics and green roofs (Uchanski et al., 2023). Using green roofs for agrivoltaics in urban areas can utilize unused space. The depth of the green roof substrate determines what can be grown in the system. Extensive green roofs have a depth of less than 15 cm, while intensive green roofs have a substrate depth of greater than 15 cm (Raji et al., 2015). Whittinghill et al. (2013) reported that various crops can grow with a substrate depth of just 10.5 cm, including tomatoes, green beans, and cucumbers, producing adequate yield if suitable irrigation is provided. Water management is important due to the characteristics of the coarse substrate, high winds, and intense solar radiation on rooftops (Walters and Stoelzle Midden, 2018).

Combining green roofs with solar module s can influence both the PV modules and the plants. This can include decreased soil temperature and increased substrate moisture content due to shading and protection from environmental extremes. There is an increase in electricity production as well, due to module -plant interaction from evapotranspiration (Lamnatou and Chemisana, 2015). The most common PV modules are silicon-based. Silicon is non-corrosive and is chemically stable when manufactured into a thin layer of silicon oxide on the solar cell.

This acts as a passivating layer and reduces the number of recombination centers at the surface, improving performance of the silicon PV module (Ushasree and Bora, 2019). With agrivoltaics producing synergistic benefits at-grade (Barron-Gafford et al.,2019; Dupraz et al., 2011; Marrou et al., 2013; Valle et al., 2017; Wang and Sun, 2018; Wang et al., 2017), using RAV could have a similar effect.

In this study, we selected vegetative crops due to their relatively lower light requirement compared to fruiting crops. Vegetative crops also have a short harvest interval of 30 to 40 days. This allows multiple plantings and harvest through the growing season. Leafy greens also have a high market value. Lettuce was sold at an average of $0.61/lbs. and has sold more than 4.4 million lbs. in 2023 (Davis et al., 2024). In 2022, it was the most widely consumed leafy green in the United States, where leaf lettuce totaled at $1.25 billion (USDA-ERS, n.d.). Evaluating leafy green production in RAV is needed to determine if the system is feasible for urban agriculture. We hypothesize that the PV modules influence crop growth, yield, and evapotranspiration. Our objectives for this study are 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. 3) Evaluate stomatal conductance of leafy greens to observe the patterns of water use in RAV systems.

3.1 Materials and Methods

A rooftop agrivoltaics system was installed at the CSU Spur Campus in January 2023, in Denver, Colorado (39.78362573997075, -104.97355634232864). The system installed is the Urban Agriculture Garden Roof ® Assembly by American Hydrotech (Chicago, Illinois, USA).

The substrate is 45 cm (18 in) deep with LiteTop Growing Media, a proprietary substrate mix, also from American Hydrotech. Three treatments were included: 1.) full sun conditions (control), 2.) shade under opaque silicon polycrystalline framed solar modules, and 3.) shade under bifacial silicon solar modules. The modules are mounted to a standard ground-mounted racking system angled at approximately 44 degrees due east. The front edge of the modules is 2.13 m (84 in) above the substrate and the back edge is 2.97 m (117 in) above the substrate. Irrigation was supplied with overhead rotator sprinkler system, once daily during the growing season at 7 am for 7 minutes.

Growing conditions were continuously monitored every 15 minutes using HOBO H21-USB micro station data loggers (Onset Computer Corporation, Bourne, MA, USA). Solar module, surface, and air temperatures (measured at 30 cm [12 in] above the surface with solar shield) were measured using HOBO 12-bit temperature smart sensors. Substrate moisture content was measured using ECH20 EC-5 Soil Moisture Sensor (Onset Computer Corporation, Bourne, MA, USA. Solar radiation was measured continuously using an S-LIB-M003 Solar Radiation (Silicon Pyranometer) Smart Sensor (Onset Computer Corporation, Bourne, MA, USA).

The same varieties of leafy greens from chapter 2 were used in this study (arugula, kale, lettuce, spinach, and Swiss chard). A sedum mix mat was laid surrounding the research plots, supplied by Sempergreen (Culpeper, Virgina, USA). Leafy green seeds were germinated in 50 cell plug trays using Lambert LM-HP media (Lambert, Rivière-Ouelle, Québec, Canada) on 4/15/23, 6/1/23, 7/6/23, and 9/19/23 at the Terra Greenhouse at CSU Spur. Plants were transplanted from trays into randomized treatments on 4/28/23, 6/14/23, 8/5/23, 10/6/23. The randomization method was similar to Chapter 2. However, the numbers used for treatment randomization were 1-3. Compost was incorporated at the time of transplant using EcoGro compost (A1 Organics, Eaton, Colorado, USA).

Similar to chapter 2, the greens were harvested 42 days after transplanting on 6/9/23, 7/26/23, 9/16/23, and 11/7/23. The data collected at harvest included fresh weights (FW), dry weight (DW), stomatal conductance (SC), and plant size at harvest (PSH). DW was measured 72 hours after the leafy greens were dried at 70°C. SC was measured at 12 pm. Leaves selected for SC evaluation were at mid-canopy. 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.

Statistical analysis was completed using R Studio version 4.1.2 (RStudio, Inc., Boston, MA, USA) for each leafy green type and response variable (PSH, FW, DW, SC) through a two-way ANOVA analysis, using Tukey's method for a pairwise mean comparison. Due to the fixed location of the solar arrays, this is an unreplicated study and blocked over time as the form of replication. Since there will be a separate analysis for each leafy green, each leafy green will be evaluated as a stand-alone study.

3.2 Results and Discussion

3.2.1 HOBO Data

Similar to Uchanski et al. (2023) and Bousselot et al. (2017), we selected one date (August 31, 2023) of data to visualize to represent temperature during a typical growing day. There was a drop in air temperature for all treatments at approximately 7:04 am (Figure 8) because the sprinkler system turned on at 7 am. The temperature under the PV module treatments and the full sun control decreased due to the release of heat during evaporation of irrigation water. The full sun control plot experienced higher temperatures earlier in the day and begins to drop at around 16:30. Under the PV module treatments, peak temperature is reached around 17:19. Overnight, temperatures under the opaque module treatment are slightly higher than the bifacial module treatment and full sun control.

The substrate temperature under the PV module treatments increased before 12:04, and decreased right after, with temperatures lower than the full sun treatment (Figure 9). This could be due to the shade under the PV module treatments at midday, lowering the temperature of the substrate under the PV module treatments. After approximately 16:34, the substrate temperature in the full sun control decreased, while the substrate temperature under the PV module treatments gradually increased until 18:04, where it began to decrease again. The PV modules treatments are aligned facing east, therefore, later in the day, the area under the PV module treatments is exposed to direct western light, increasing the substrate temperature.

The substrate moisture content under the opaque module treatment was higher compared to the bifacial module treatment and the full sun control (Figure 10). The substrate in the bifacial module treatment had a higher moisture content for most of the day compared to the full sun control until 17:19. There was an increase of substrate moisture content in all treatments before 7:34, due to the irrigation at 7:00.

Lower solar radiation was measured under the PV module treatments compared to the full sun plot (Figure 11). There was a marked increase in solar radiation under the PV module treatments at approximately 16:34 under both PV treatments. There was also higher solar radiation under the opaque PV module treatment compared to the bifacial module treatment. This can be due to the white backsheet of the opaque module. Surfaces with higher albedo reflect more solar radiation (Oleson et al., 2010). Due to the white backsheet of the opaque module, the light is reflected off the white backsheet when there is direct sunlight under the PV module as the sun sets. The amount of solar radiation under the PV module would therefore increase.

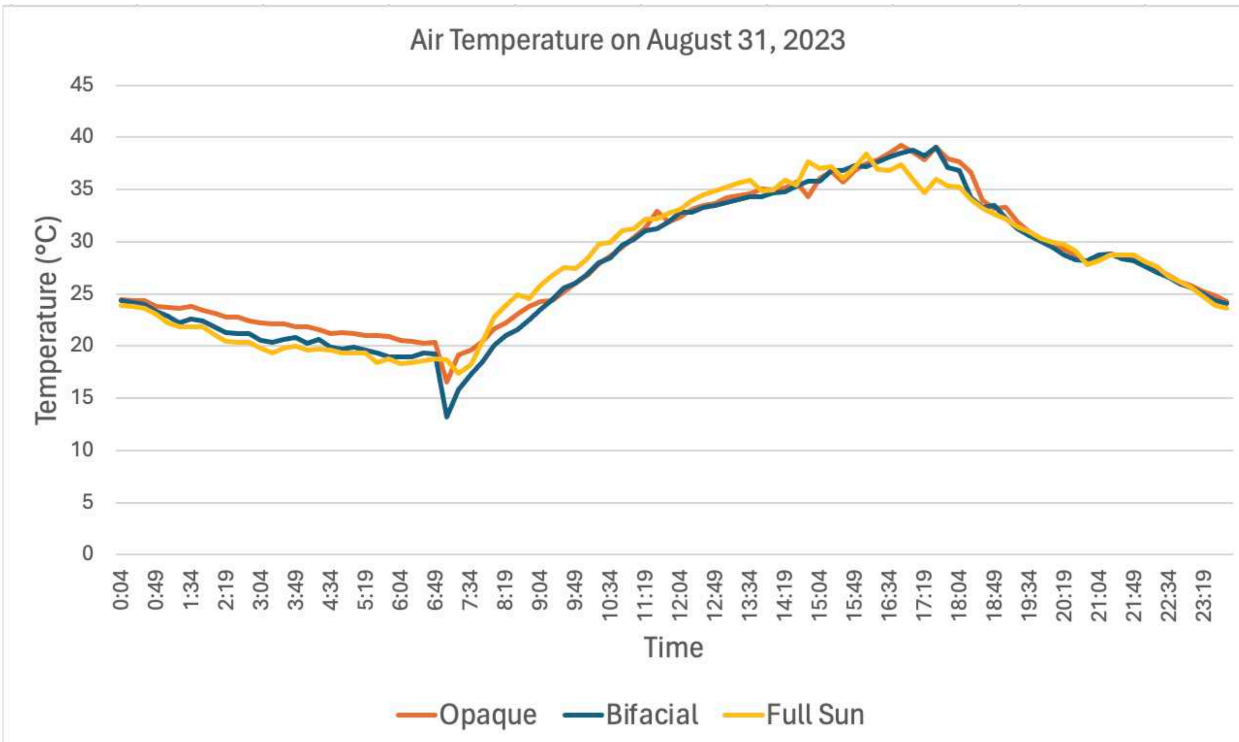

Figure 8. Air temperature under all three module treatments at CSU Spur on August 31st, 2023.

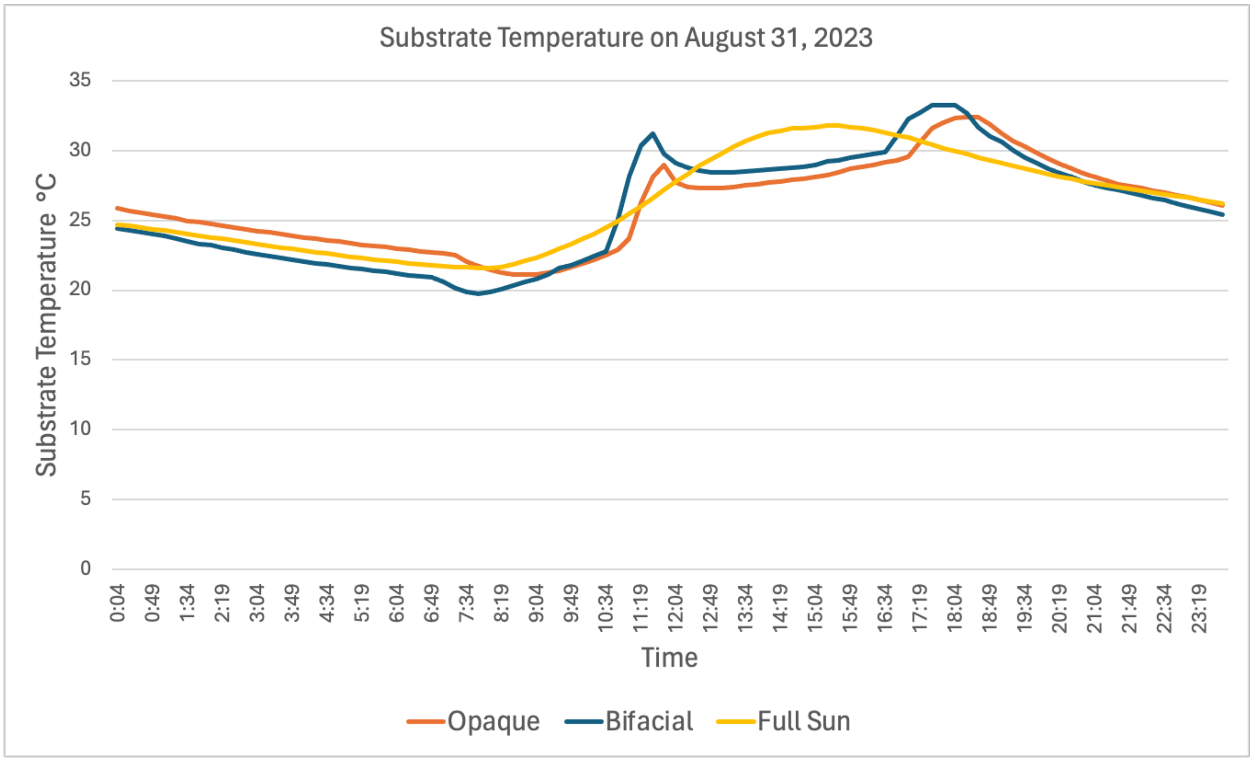

Figure 9. Substrate temperature under all three treatments on August 31, 2023, at CSU Spur.

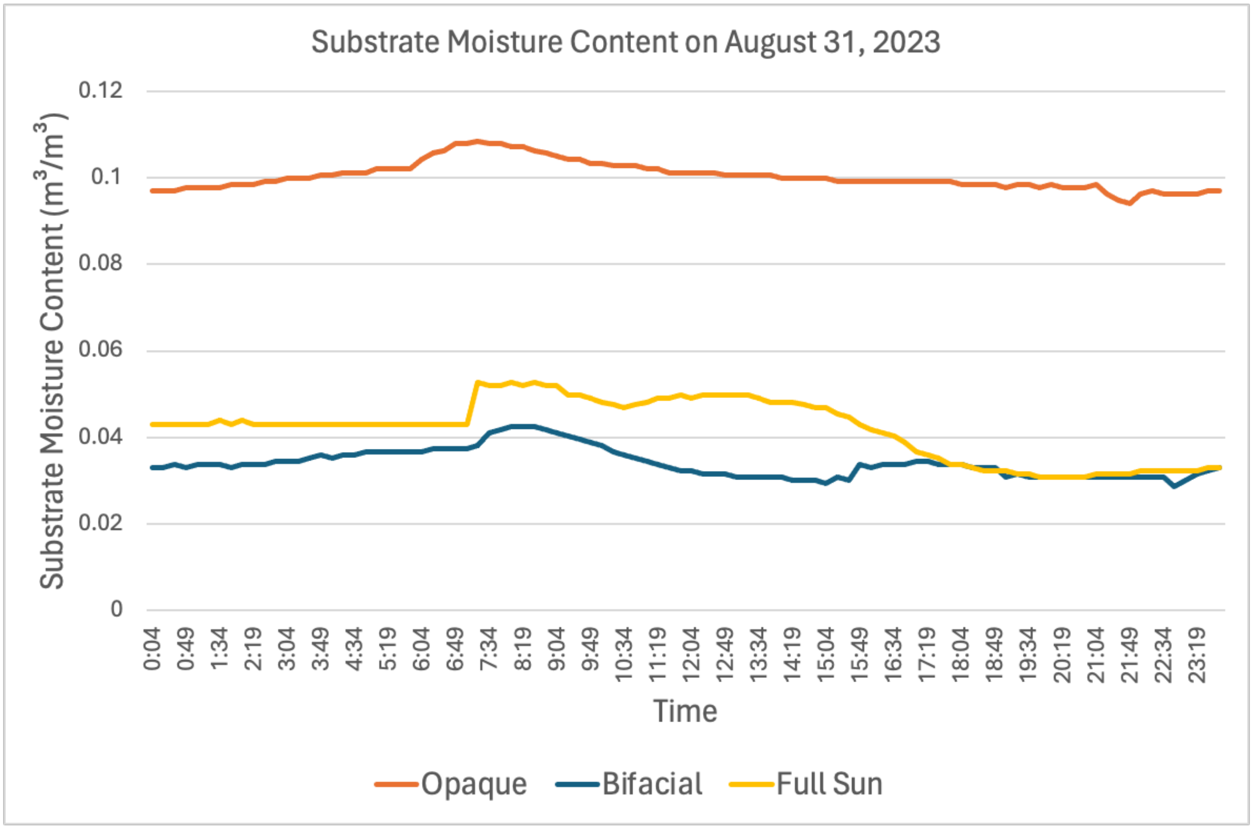

Figure 10. Substrate moisture content (m^3/m^3) under all three treatments at CSU Spur on August 31st, 2023.

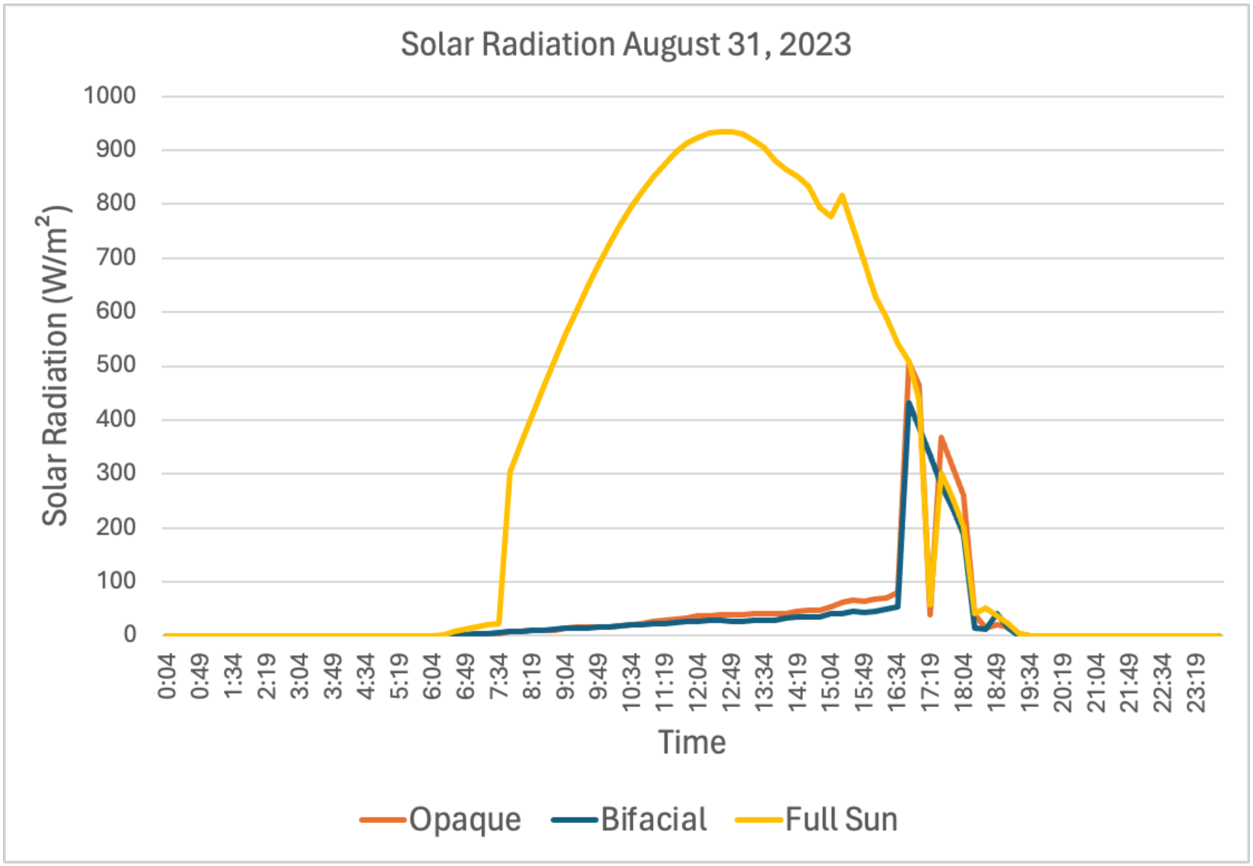

Figure 11. Solar radiation (W/m^2) under all three treatments at CSU Spur on August 31st, 2023.

3.2.1 Fresh Weight

The leafy greens grown under the full sun control produced higher FW across most species (Figure 12), except for spinach. Spinach growth can be reduced when temperatures exceed 25°C (Tai et al., 2020). The air temperature below the PV module treatments was above 25°C for extended periods of time (Figure 8). Spinach growth reduction can be due to the decrease in CO_2 assimilation rate that occurs when temperatures reach over 25°C (Tang et al., 2006). This reduces the rate of photosynthesis in spinach, reducing growth and overall size.

Arugula grown under full sun control resulted in a statistically higher FW of 288.17 g compared to either PV module treatment ($p \leq 0.05$). Arugula grown under opaque and bifacial module treatments were not statistically different from each other and resulted in a FW of 72.77 g and 62.20 g, respectively.

Kale grown in the full sun control resulted in a higher FW of 170.34 g compared to either PV module treatment ($p \leq 0.05$). Kale grown under opaque and bifacial module treatments were not significantly different from each other. Kale grown under the opaque module treatment resulted in a mean FW of 71.17 g and kale grown under the bifacial module treatment resulted in a mean FW of 57.33 g. Previous studies have also shown that higher light availability increases yield in kale (Ashenafi et al., 2022; Lefsrud et al., 2006). The solar radiation in the full sun control was higher compared to the PV module treatments, which increased yield of kale in the full sun control.

Swiss chard grown under the full sun control produced a FW of 175.08 ($p \leq 0.05$). FW of Swiss chard grown under the module treatments were not significantly different from each other. Swiss chard grown under the opaque module treatment resulted in a FW of 78.80 g, and Swiss chard grown under the bifacial module treatment resulted in a FW of 47.06 g.

Lettuce grown in the full sun control plot produced a FW of 189 g ($p \leq 0.05$). Lettuce grown under the opaque and bifacial module treatments were not statistically significant from each other. Lettuce grown under the opaque module treatment resulted in a FW of 71.69 g. Lettuce under the bifacial module treatment resulted in a FW 82.44 g. In lettuce, a decrease in PAR by 0.9% can enhance yield (Stagnari et al., 2015). The PAR readings under the full sun control plot were greater than the PV module treatments (Figure 11). The average solar radiation (W/m^2) for the opaque treatment was 34.77 W/m^2, and the average solar radiation found in the bifacial module treatment was 30.58 W/m^2. The average solar radiation found in the full sun control was 299.02 W/m^2. The opaque module treatment was 88.37% darker than the full sun control, and the bifacial module treatment was 89.78% darker than the full sun control. The PAR was reduced beyond the 0.9% recommended by Stagnari et al. (2015) which decreased productivity in lettuce under the module treatments.

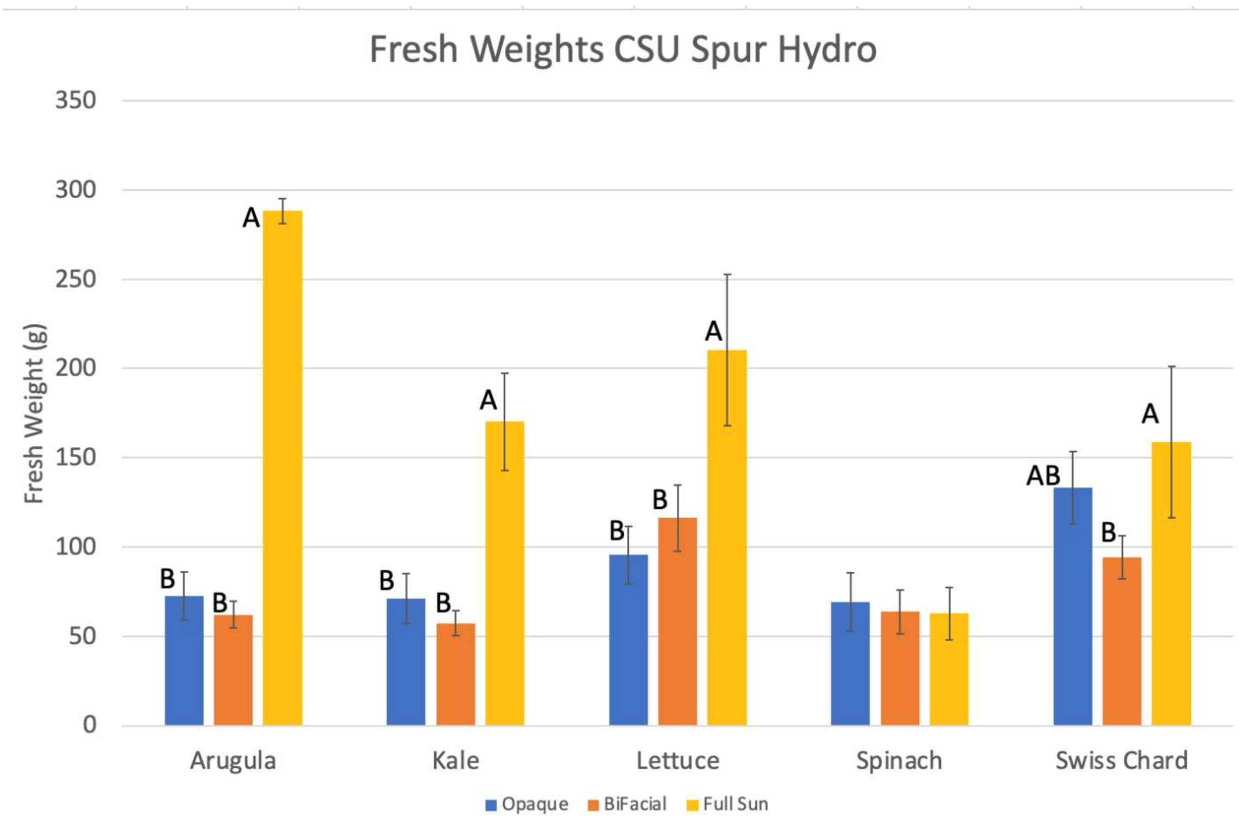

Figure 12. Fresh weights (g) of leafy of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under all three treatments at CSU Spur. The letters signify significant differences found between treatments.

3.2.2 Dry Weight

Leafy greens grown in the full sun control produced higher DW compared to the PV module treatments across most species (Figure 11). Since DW is correlated with above ground net primary production in plants (Smart et al., 2017) and deep shade can decrease productivity in plants (Rana and Rani, 2017), we expected higher DW in full sun compared to the module treatments (Figure 11).

Arugula grown under the full sun control resulted in a higher DW of 30.46 compared to the arugula grown under the PV module treatments ($p \leq 0.05$). Arugula grown under the opaque module treatment resulted in a DW of 5.81 g, and under the bifacial module treatment resulted in a DW of 5.78. Previous studies have shown that higher light availability increases DW in arugula (Stajnko et al., 2022). DW, however, only increases after 30-40 days of growth after sowing. This is due to the low number of leaves and roots at the beginning of growth. There is also a reduced amount of photoassimilates and nutrient absorption at the beginning of growth (Morais et al., 2020). With higher solar radiation in the full sun control (Figure 11), arugula replicates produced higher DW compared to the plants under the PV module treatments.

Kale grown in the full sun control resulted in a higher DW of 20.73 g compared to the PV module treatments ($p \leq 0.05$). Kale grown under both module treatments were not statically different from each other. The kale grown under the opaque treatment produced a DW of 6.82 g, and kale under the bifacial treatment produced a DW of 6.13 g. Kale DW is reduced under solar shading due to a decrease in leaf vigor and numbers (Quarshie 2023).

Lettuce grown in the full sun control plot produced a higher DW of 15.88 g compared to the PV module treatments ($p \leq 0.05$). Lettuce grown under the opaque module treatment produced a DW 6.09 g. Lettuce under the bifacial module treatment produced a DW of 6.80 g. Productivity in lettuce is increased when light levels are increased. The lettuce in the full sun control had higher light availability compared to the lettuce grown under the PV module treatments, which produced higher DW compared to the lettuce grown in under the PV module treatments. Marrou et al. (2013) reported that partial shading of lettuce in agrivoltaics systems does not affect yield. However, too much shading can reduce lettuce yield by up to 48%. The shade under the PV module treatments could have decreased productivity in lettuce, resulting in lower DW.

Spinach grown in the full sun control plot produced higher DW than the spinach grown under the opaque module treatment ($p \leq 0.05$). Spinach grown in the full sun control plot produced a DW of 7.04 g, and under the opaque module treatment, a DW of 4.73 g. Spinach grown in the full sun control did not result in significant differences compared to spinach grown under the bifacial module treatment. Spinach has been shown to have increased DW under increased light conditions in greenhouse environments (Gent, 2016). Spinach grown under continuous shade from PV modules showed decreased DW compared to spinach grown under the partial shade of PV modules (Hudelson and Lieth, 2021). Young leaves of spinach are also shown to have higher DW than older leaves (Beis et al., 2002). The spinach grown in the full sun control may have produced more leaves than in the PV module treatments, increasing the overall DW of the plant at harvest.

Swiss chard grown under the full sun control produced higher DW compared to Swiss chard grown under the PV module treatments ($p \leq 0.05$). Swiss chard grown in the full sun control plot produced a DW of 15.84 g. Swiss chard grown under the opaque PV module treatment produced a DW of 9.04 g, and under the bifacial module treatment, a DW of 7.10 g. A reduction in light by more than 80% significantly reduces growth in Swiss chard (Ria et al., 2023). As stated previously, there was an 89.78% decrease in solar radiation between the full sun control and the bifacial module treatment, and 88.37% difference between the full sun control and the opaque PV module treatment (Figure 11). The shade under the PV module treatments could have resulted in lower accumulation of sugars (Abdel et al., 2018). This would have affected the growth of the Swiss chard, reducing the DW under the PV module treatments.

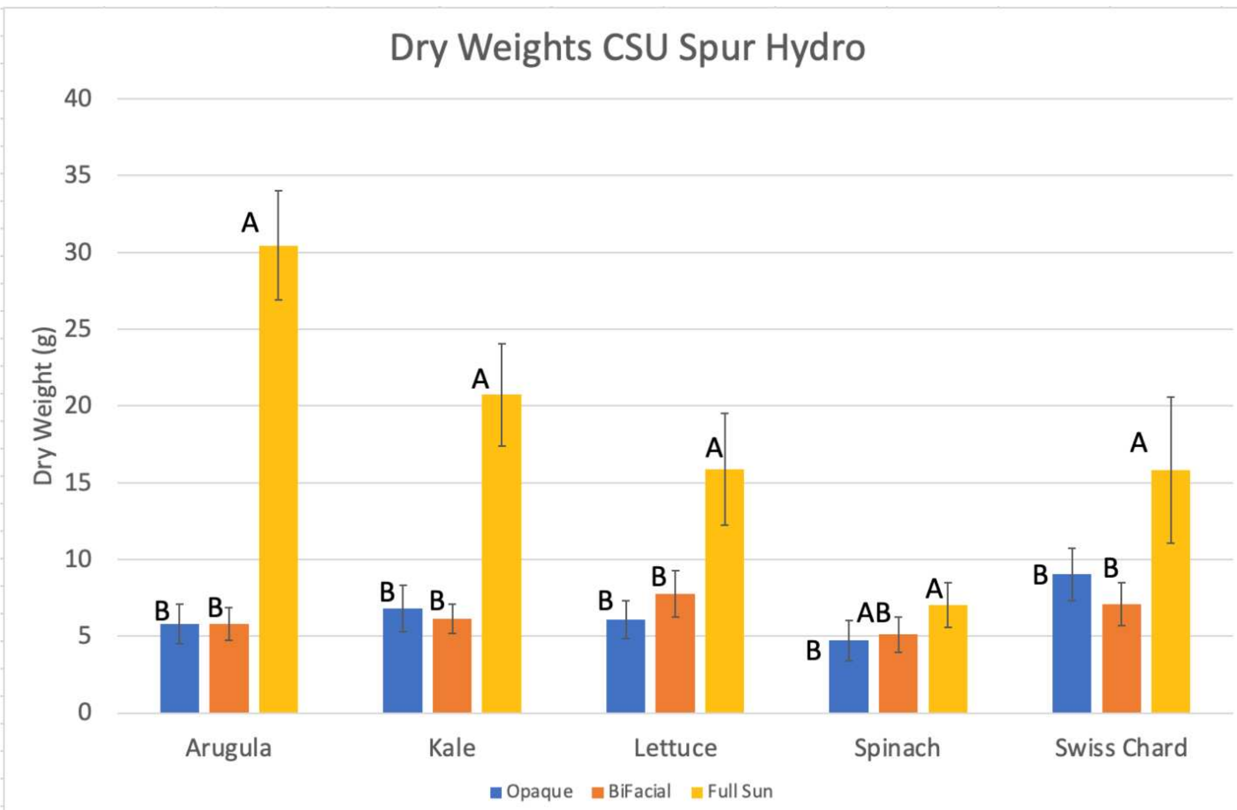

Figure 13. Dry weights (g) of leafy of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under all three treatments at CSU Spur. The letters signify significant differences found between treatments.

3.2.3 Plant Size at Harvest

PSH of lettuce and spinach grown under the PV module treatments increased compared to plants grown in the full sun control plot (Figure 14). This could be due to the lettuce and spinach leaves growing larger to reach for more sunlight in shaded areas (Abdel et al., 2018; Quarshie 2023).

Arugula grown in the full sun produced a higher PSH of 36.75 cm compared to plants grown in the bifacial module treatment ($p \leq 0.05$). Arugula grown under the bifacial module treatment produced a PSH of 30.01 cm. There was no statistical significance in PSH of arugula under the opaque module treatment compared to the other two treatments.

Lettuce grown under both PV module treatments resulted in higher PSH compared to lettuce grown in the full sun, which had a PSH of 18.65 cm ($p \leq 0.05$). Lettuce grown under the bifacial module treatment resulted in a PSH of 27.04 cm and under the opaque module treatment resulted in a PSH of 23.62 cm.

Spinach grown under the opaque PV module treatment produced a statistically higher PSH compared to the plants grown in the full sun control ($p \leq 0.05$). Spinach grown under the opaque treatment resulted in a PSH of 22.98 cm. Spinach grown in the full sun produced a PSH of 20.14 cm. Spinach grown under the bifacial module treatment resulted in a PSH of 25.43 cm. Spinach grown under the bifacial module treatment was not statistically different compared to the spinach grown under the opaque module treatment or the full sun control.

Kale or Swiss chard grown under the PV treatments did not produce any statistical differences compared to the full sun control.

In both lettuce and spinach, PSH was greater in the bifacial module treatment compared to plants grown in the opaque module treatment and the full sun control. There were slightly lower temperatures under the bifacial PV module treatment compared to the opaque PV module treatment and full sun (Figure 8). Lettuce and spinach are cool season crops. Higher temperatures can reduce plant growth due to inflorescence formation, also known as bolting, and shortening vegetative growth (Dufault et al., 2019). Bolting is the rapid lengthening of a plant stem that occurs when environmental cues, such as day length and temperature, cause changes in plant hormones (Kitashiba and Yokoi, 2017). This transitions a plant from the vegetative stage to the reproductive stage, which can affect the yield and quality of foliar crops (Rosental et al., 2021; Tränkner et al., 2017).

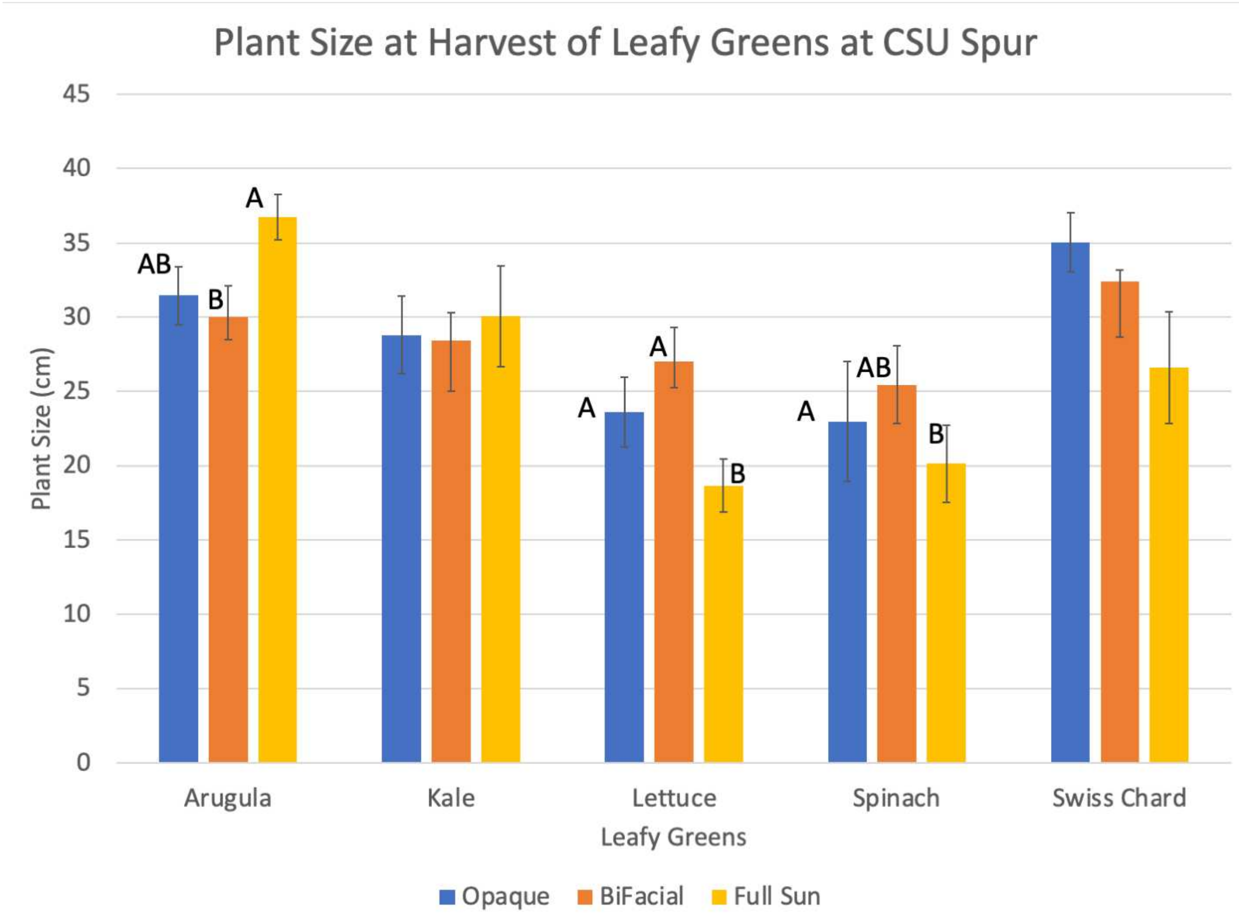

Figure 14 Plant size at harvest t(cm) of leafy of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under all three treatments at CSU Spur. The letters signify significant differences found between treatments.

3.2.4 Stomatal Conductance

Significant differences in SC of plants were found between the full sun control and the opaque PV module treatments across species (Figure 14). There were no significant differences between the bifacial module treatment and the opaque module treatment, nor the full sun control in kale. Kale under the full sun control produced a higher SC of 553 mmol/m^2/s ($p \leq 0.05$). Kale grown under the opaque module treatment resulted in an SC of 262.57 mmol/m^2/s. This could be due to the similar solar radiation conditions under the PV module treatments. Under the opaque module treatment, the solar radiation was 34.77 W/m^2. Under the bifacial module treatment, the solar radiation was 30.57 W/m^2. As PAR increases, specifically on sunlit leaves, SC increases (Zhang et al., 2011). The kale grown in the full sun control received direct sunlight on the leaves during daytime hours, thereby increasing SC compared to the kale grown under the PV module treatments.

Arugula grown in the full sun control plot resulted in a great SC of 691.30 $mm/m^2/s$ ($p \leq 0.05$). Arugula grown under the opaque module treatment resulted in a SC of 324.43 $mmol/m^2/s$, and 474.60 $mmol/m^2/s$ when grown under the bifacial module treatment. Lettuce grown in the full sun control plot resulted in a higher SC of 409.76 $mmol/m^2/s$ ($p \leq 0.05$). Lettuce grown under the opaque module treatment, produced an SC of 396.97 $mmol/m^2/s$. Lettuce grown under the bifacial module treatment resulted in an SC of 304.87 $mmol/m^2/s$. Spinach grown under the full sun control produced a higher SC of 483.22 $mmol/m^2/s$ compared to the PV module treatments ($p \leq 0.05$). Spinach grown under the opaque module treatment produced an SC of 221.81 $mmol/m^2/s$. Spinach grown under the bifacial module treatment produced an SC of 311.71 $mmol/m^2/s$. Swiss chard grown under the full sun control produced a higher SC of 477.74 $mmol/m^2/s$ compared to the PV module treatments ($p \leq 0.05$). Swiss chard grown under the opaque module treatment produced an SC of 166.02 $mmol/m^2/s$, and Swiss chard grown under the bifacial module treatment produced an SC of 297.38 $mmol/m^2/s$.

Changes in light intensity can affect metabolic processes in plants (Ouzounis et al., 2015). Since the plants under the opaque and bifacial module treatments grew in conditions with reduced light intensity during midday (Figure 11), SC was lower compared to plants grown in the full sun control (Figure 14). The direct solar radiation in the full sun control plot would then have a higher evapotranspiration rate, increasing the SC of the plants (Zhu et al., 2022), compared to the shade of the PV treatments.

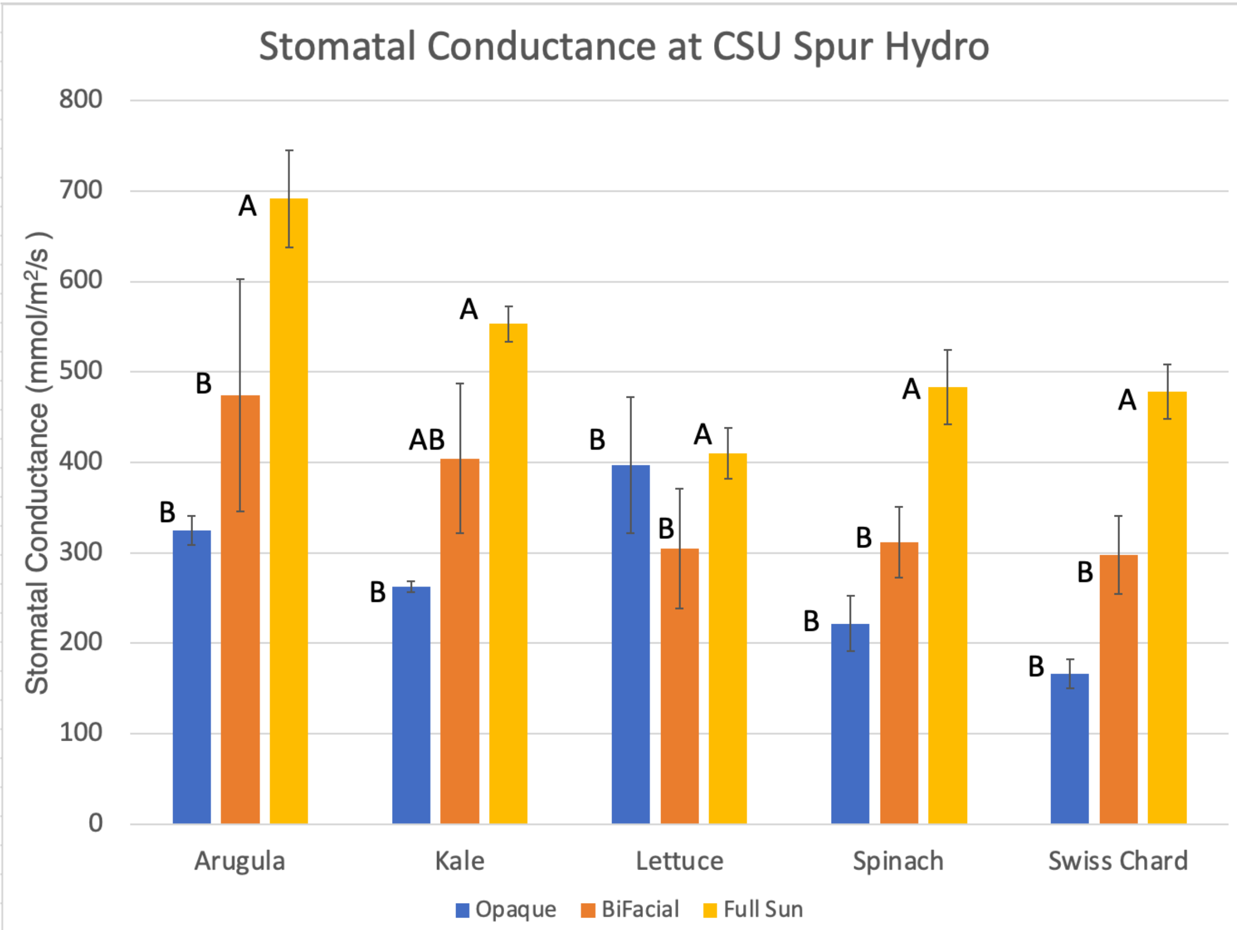

Figure 15 Stomatal conductance (mmol/m^2/s) of leafy of five leafy greens (arugula, kale, lettuce, spinach, and Swiss chard) under silicon opaque module treatment, silicon bifacial module treatment, and full sun control plot at CSU Spur.

In conclusion, the SC of leafy greens grown under the PV module treatments were reduced compared to the full sun control in traditional green roof systems. Irrigation studies in at-grade agrivoltaics indicate reduced irrigation requirements under PV treatments (AL-agele et al., 2021a; Elamri et al., 2018; Ramos-Fuentes et al., 2023). Future studies should further evaluate irrigation practices in relation to RAV. The reduced amount of evapotranspiration from plants and substrate in RAV systems can reduce total irrigation use. However, reduced evapotranspiration may reduce the cooling effect for efficient energy production from the PV modules. Future studies should monitor energy output from the modules in direct correlation with the evapotranspiration of crop production underneath.

Though leafy green FW is reduced under PV, PSH of leafy greens grown under the PV were similar to those grown in full sun. This relationship is common in shaded environments where plants stretch to reach sunlight and grow larger in leaf area yet are smaller in biomass because the plants produce fewer sugars in shade. The plants then grow thinner leaves due to the lack of sugars produced. Leafy greens grown for their leaves, like spinach or arugula, can be utilized in RAV since these crops experienced either higher PSH or no difference compared to the full sun control under the PV treatments. Further exploration of species and cultivars need to be continued to fully optimize yield and performance in RAV systems. Different combinations of PV modules need to be evaluated to fully understand which crops can be grown with each type of PV system, to better improve the mutualistic benefits found in RAV systems.

References

Abdel, C. G., Abdelreda, H. R., and Abdulrazak, M. A. (2018). Growth responses of home grown Barley (Hordeum vulgare), Lettuce (Lactuca sativa), Swiss chards (Beta vulgaris) and faba beans (Vicia faba) to sunlight and shade. *Muthanna Journal of Agriculture Science, 7*(1). https://doi.org/DOI:10.18081/MJAS/2019-7/9-16

Aghaei, Mohammadreza. (2012). A Review on Comparison between Traditional Silicon Solar Cells and Thin-Film CdTe Solar Cells.

Ahsan, S. M., and Khan, H. A. (2019). Performance comparison of CdTe thin film modules with c-Si modules under low irradiance. *IET Renewable Power Generation*, *13*(11), 1920–1926. https://doi.org/10.1049/iet-rpg.2018.5479

AL-agele, H. A., Proctor, K., Murthy, G., & Higgins, C. (2021a). A case study of tomato (solanum lycopersicon var. legend) production and water productivity in Agrivoltaic Systems. *Sustainability*, *13*(5), 2850. https://doi.org/10.3390/su13052850

Albatayneh, A., Albadaineh, R., Juaidi, A., Abdallah, R., Montoya, M. D., and Manzano-Agugliaro, F. (2022). Rooftop photovoltaic system as a shading device for uninsulated buildings. *Energy Reports*, *8*, 4223–4232. https://doi.org/10.1016/j.egyr.2022.03.082

Alonso-Marroquin, F., and Qadir, G. (2023). Synergy between photovoltaic panels and green roofs. *Energies*, *16*(13), 5184. https://doi.org/10.3390/en16135184

Armstrong, A., Ostle, N. J., and Whitaker, J. (2016). Solar Park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Ashenafi, E. L., Nyman, M. C., Holley, J. M., Mattson, N. S., and Rangarajan, A. (2022). Phenotypic plasticity and nutritional quality of three kale cultivars (brassica oleracea L. var. Acephala) under field, greenhouse, and Growth Chamber Environments. *Environmental and Experimental Botany*, *199*, 104895. https://doi.org/10.1016/j.envexpbot.2022.104895

Barron-Gafford, G., M. Pavao-Zuckerman, R. Minor, L. Sutter, I. Barnett-Moreno, D. Blackett, M. Thompson, Y. Dimond, A. Gerlak, G. Nabhan, and J. Macknick. 2019."Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands." Nature Sustainability, 2: 1-8. https://doi.org/10.1038/s41893-019-0364-5

Baudoin, W., Desjardins, Y., Dorais, M., Charrondière, U. R., Herzigova, L., El-Behairy, U., Metwaly, N., Marulanda, C., and Ba, N. (2017). Rooftop gardening for improved food and nutrition security in the urban environment. *Urban Agriculture*, 219–233. https://doi.org/10.1007/978-3-319-57720-3_13

Baumann, T., H. Nussbaumer, M. Klenk, A. Dreisiebner, F. Carigiet and F. Baumgartner. 2019. "Photovoltaic systems with vertically mounted bifacial PV modules in combination with green roofs." *Solar energy*, 190: 139-146

Beis, G. H., Siomos, A. S., & Dogras, C. C. (2002). Spinach composition as affected by leaf age and Plant Part. *Acta Horticulturae*, (579), 653–658. https://doi.org/10.17660/actahortic.2002.579.115

Bosio, A., Romeo, N., Mazzamuto, S., and Canevari, V. (2006). Polycrystalline CdTe thin films for photovoltaic applications. *Progress in Crystal Growth and Characterization of Materials*, *52*(4), 247–279. https://doi.org/10.1016/j.pcrysgrow.2006.09.001

Bousselot, J.M., T. Slabe, J.E. Klett, and R.D. Koski. 2017. "Photovoltaic array influences the growth of green roof plants." *Journal of Living Architecture*, 4(3): 9-18.

Buckley, T. N. (2019). How do stomata respond to water status? *New Phytologist*, *224*(1), 21–36. https://doi.org/10.1111/nph.15899

Calheiros, C. S., and Stefanakis, A. I. (2021). Green roofs towards circular and resilient cities. *Circular Economy and Sustainability*, *1*(1), 395–411. https://doi.org/10.1007/s43615-021-00033-0

Ciriminna, R., F. Meneguzzo, M. Pecoraino, and M. Pagliaro. 2019. "Solar Green Roofs: A Unified Outlook 20 Years On." *Energy Technology,* 7(6): 1900128.

Davis, W. V., Weber, C., Wechsler, S., Wakefield, H., & Lucier, G., Vegetables and Pulses Outlook: April 2024 (2024). USDA. Retrieved May 12, 2024, from https://www.ers.usda.gov/publications/pub-details/?pubid=109066.

Dinesh, H., and Pearce, J. M. (2016). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *54*, 299–308. https://doi.org/10.1016/j.rser.2015.10.024

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., and Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new AGRIVOLTAIC schemes. *Renewable Energy*, *36*(10), 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005

Elamri, Y., B. Cheviron, J-M. Lopez, C. Dejean, and G. Belaud. 2018. "Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces." *Agricultural Water Management*, 208: 440-453.

Ferreira, A. J., Guilherme, R. I., Ferreira, C. S., and Oliveira, M. de. (2018). Urban Agriculture, a tool towards more resilient urban communities? *Current Opinion in Environmental Science and; Health*, *5*, 93–97. https://doi.org/10.1016/j.coesh.2018.06.004

Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2016). *Rooftop Solar Photovoltaic Technical Potential in the United States. A Detailed Assessment*. https://doi.org/10.2172/1236153

Gent, M. P. N. (2016). Effect of irradiance and temperature on composition of spinach. *HortScience*, *51*(2), 133–140. https://doi.org/10.21273/hortsci.51.2.133

Getter, K., B. Rowe, and B. Cregg. 2009. "Solar radiation intensity influences extensive green roof plant communities." *Urban Forestry and Urban Greening,* 8(4): 269-281.

Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., & Andresen, J. A. (2009). Carbon sequestration potential of extensive green roofs. *Environmental Science & Technology*, *43*(19), 7564–7570. https://doi.org/10.1021/es901539x

Gottesfeld, P. (2019). Commentary health risks from climate fix: The downside of Energy Storage Batteries. *Environmental Research*, *178*, 108677. https://doi.org/10.1016/j.envres.2019.108677

Gupta, S., P. Anand, S. Kakkar, P. Sagar, and A. Dubey. 2017. "Effect of evapotranspiration on performance improvement of photovoltaic-green roof integrated system." *Journal of Renewable Energy and Smart Grid Technology*, 12(1): 63-76.

Hassanpour Adeh, E., Selker, J. S., and Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLOS ONE*, *13*(11). https://doi.org/10.1371/journal.pone.0203256

Hendarti, R. 2013. "The influence of the evapotranspiration process of green roof tops on PV modules in the tropics." Doctoral Dissertation, National University of Singapore.

Hickey, T. (2023). *Plant Growth Under Photovoltaic Arrays of Varying Transparencies – A study of Plant Response to Light and Shadow in Agrivoltaic Systems* (thesis). Colorado State University ProQuest Dissertation Publishing, Fort Collins.

HM Government. (2022, April 5). *What is net zero and why do we need to act?* GOV.UK. https://www.gov.uk/government/publications/net-zero-strategy/executive-summary

Huang, K., Li, X., Liu, X., Seto1, K. C., and https://orcid.org/0000-0001-6877-9442, K. H. (2019, September 2). *IOPscience*. Environmental Research Letters. https://iopscience.iop.org/article/10.1088/1748-9326/ab4b71

Dufault, R. J., Ward, B., & Hassell, R. L. (2009). Dynamic relationships between field temperatures and Romaine lettuce yield and head quality. *Scientia Horticulturae*, *120*(4), 452–459. https://doi.org/10.1016/j.scienta.2009.01.002

Hudelson, T., and Lieth, J. H. (2021). Crop production in partial shade of solar photovoltaic panels on trackers. *AIP Conference Proceedings*. https://doi.org/10.1063/5.0055174

Hui, S., and S. Chan. 2011. "Integration of green roof and solar photovoltaic systems." In *Paper submitted to Joint Symposium*.

Hunter, M., A. Sorensen, T. Nogeire-McRae, S. Beck, S. Shutts, R. Murphy. 2022. Farms Under Threat 2040: Choosing an Abundant Future. Washington, D.C.: American Farmland Trust.

Jahanfar, A., Drake, J., Gharabaghi, B., and Sleep, B. (2020). An experimental and Modeling Study of evapotranspiration from Integrated Green Roof Photovoltaic Systems. *Ecological Engineering*, *152*, 105767. https://doi.org/10.1016/j.ecoleng.2020.105767

Jahanfar, A., Sleep, B., and Drake, J. (2018). Energy and carbon-emission analysis of integrated green-roof photovoltaic systems: Probabilistic Approach. *Journal of Infrastructure Systems*, *24*(1). https://doi.org/10.1061/(asce)is.1943-555x.0000399

Jahanfar, A., J. Drake, B. Sleep, and L. Margolis. 2019. "Evaluating the shading effect of photovoltaic panels on green roof discharge reduction and plant growth." *Journal of hydrology* 568: 919-928.

Jin, W., Ji, Y., Larsen, D. H., Huang, Y., Heuvelink, E., and Marcelis, L. F. M. (2023). Gradually increasing light intensity during the growth period increases dry weight production compared to constant or gradually decreasing light intensity in lettuce. *Scientia Horticulturae*, *311*, 111807. https://doi.org/10.1016/j.scienta.2022.111807

Jing, R., Liu, J., Zhang, H., Zhong, F., Liu, Y., and Lin, J. (2022). Unlock the hidden potential of urban rooftop agrivoltaics energy-food-nexus. *Energy*, *256*, 124626. https://doi.org/10.1016/j.energy.2022.124626

Kirmani, S., and Kalimullah, M. (2017). Degradation analysis of a rooftop solar photovoltaic system—a case study. *Smart Grid and Renewable Energy*, *08*(06), 212–219. https://doi.org/10.4236/sgre.2017.86014

Kitashiba, H., & Yokoi, S. (2017). Genes for bolting and flowering. *Compendium of Plant Genomes*, 151–163. https://doi.org/10.1007/978-3-319-59253-4_11

Klokov, A. V., Loktionov, E. Yu., Loktionov, Y. V., Panchenko, V. A., and Sharaborova, E. S. (2023). *A Mini-Review of Current Activities and Future Trends in Agrivoltaics*. https://doi.org/10.20944/preprints202301.0391.v2

Köhler, M, Feige, R, and Wiartalla, W. 2007 *Interaction between PV-systems and extensive green roofs.* Canada

Köhler, M., M. Schmidt, M. Laar, U. Wachsmann, and S. Krauter. 2002. "Photovoltaic panels on greened roofs." *Rio,* 2: 151-158.

Lamnatou, Chr., and Chemisana, D. (2015). A critical analysis of factors affecting photovoltaic-green roof performance. *Renewable and Sustainable Energy Reviews*, *43*, 264–280. https://doi.org/10.1016/j.rser.2014.11.048

Langemeyer, J., Madrid-Lopez, C., Mendoza Beltran, A., and Villalba Mendez, G. (2021a). Urban Agriculture — a necessary pathway towards urban resilience and global sustainability? *Landscape and Urban Planning*, *210*, 104055. https://doi.org/10.1016/j.landurbplan.2021.104055

Lefsrud, M. G., Kopsell, D. A., Augé, R. M., & Both, A. J. (2006). Biomass production and pigment accumulation in kale grown under increasing photoperiods. *HortScience*, *41*(3), 603–606. https://doi.org/10.21273/hortsci.41.3.603

Ley, A., Ackermann, K., Beretta, S., Busch, S., Dieterle, J., El-Shahat, M. M., Hosni, J., Laue, F., Moustanjidi, Y., and Stützel, V. (2020). Public usable space as a catalyst for quality of life improvement: The case of cape town's social farming projects. *Handbook of Quality of Life and Sustainability*, 469–495. https://doi.org/10.1007/978-3-030-50540-0_24

Liao, Q., Ding, R., Du, T., Kang, S., Tong, L., and Li, S. (2022). Stomatal conductance drives variations of yield and water use of maize under water and nitrogen stress. *Agricultural Water Management*, *268*, 107651. https://doi.org/10.1016/j.agwat.2022.107651

Liu, W., Omer, A. A., and Li, M. (2023). Agrivoltaic: Challenge and progress. *Agronomy*, *13*(7), 1934. https://doi.org/10.3390/agronomy13071934

Loconsole, D., Cocetta, G., Santoro, P., and Ferrante, A. (2019). Optimization of LED lighting and quality evaluation of romaine lettuce grown in an innovative indoor cultivation system. *Sustainability*, *11*(3), 841. https://doi.org/10.3390/su11030841

Lubna, F. A., Lewus, D. C., Shelford, T. J., and Both, A.-J. (2022). What you may not realize about vertical farming. *Horticulturae*, *8*(4), 322. https://doi.org/10.3390/horticulturae8040322

Mahmud, M., Huda, N., Farjana, S., & Lang, C. (2018). Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment. *Energies*, *11*(9), 2346. https://doi.org/10.3390/en11092346

Mangarotti, D. P., Rezende, R., Saath, R., Hachmann, T. L., Matumoto-Pintro, P. T., & Anjo, F. A. (2020). Use of selenium to increase antioxidant activity and water use efficiency in Arugula (Eruca vesicaria SSP.. sativa) exposed to drought stress. *Research, Society and Development*, *9*(12). https://doi.org/10.33448/rsd-v9i12.10670

Manso, M., Teotónio, I., Silva, C. M., and Cruz, C. O. (2021). Green roof and green wall benefits and costs: A review of the quantitative evidence. *Renewable and Sustainable Energy Reviews*, *135*, 110111. https://doi.org/10.1016/j.rser.2020.110111

Marrou, H., L. Guilioni, L. Dufour, C. Dupraz, and J. Wéry. 2013. "Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?" *Agricultural and Forest Meteorology,* 177: 117-132.

Maseko, I., Ncube, B., Mabhaudhi, T., Tesfay, S., Chimonyo, V. G. P., Araya, H. T., Fessehazion, M., and Du Plooy, C. P. (2019). Moisture stress on physiology and yield of some indigenous leafy vegetables under field conditions. *South African Journal of Botany*, *126*, 85–91. https://doi.org/10.1016/j.sajb.2019.07.018

McCandless, B. E., & Sites, J. R. (2011). Chapter 14: Cadmium Telluride Solar Cella. In *Handbook of Photovoltaic Science and Engineering* (2nd ed., pp. 600–600). essay, John Wiley and Sons Ltd.

Morais, E. G., Freire, M. M., Santos, A. Y., Silva, G. G., Oliveira, E. M., Franco, L. B., and Souza, G. L. (2020). Growth and accumulation of macronutrients in arugula. *International Journal of Advanced Engineering Research and Science*, *7*(9), 176–183. https://doi.org/10.22161/ijaers.79.20

METI. (2022, May). *Japan's roadmap to "Beyond-zero" carbon*. METI Ministry of Economy, Trade and Industry. https://www.meti.go.jp/english/policy/energy_environment/global_warming/roadmap/

Mustafa, R. J., Gomaa, M. R., Al-Dhaifallah, M., and Rezk, H. (2020). Environmental impacts on the performance of Solar Photovoltaic Systems. *Sustainability*, *12*(2), 608. https://doi.org/10.3390/su12020608

Oleson, K. W., Bonan, G. B., & Feddema, J. (2010). Effects of white roofs on urban temperature in a global climate model. *Geophysical Research Letters*, *37*(3). https://doi.org/10.1029/2009gl042194

O'Regan, A. C., and Nyhan, M. M. (2023). Towards sustainable and net-zero cities: A review of environmental modelling and monitoring tools for optimizing emissions reduction strategies for improved air quality in urban areas. *Environmental Research*, *231*, 116242. https://doi.org/10.1016/j.envres.2023.116242

Quarshie, P. K. (2023). *Effect of Photovoltaic Panel Shading on the Growth of Ginger and Kale* [Master's thesis, Ohio University]. OhioLINK Electronic Theses and Dissertations Center. http://rave.ohiolink.edu/etdc/view?acc_num=ohiou1691061940493163

Ouzounis, T., Rosenqvist, E., and Ottosen, C.-O. (2015). Spectral effects of artificial light on plant physiology and secondary metabolism: A Review. *HortScience*, *50*(8), 1128–1135. https://doi.org/10.21273/hortsci.50.8.1128

Paithankar, D. N., & Taji, S. G. (2020). Investigating the hydrological performance of green roofs using storm water management model. *Materials Today: Proceedings*, *32*, 943–950. https://doi.org/10.1016/j.matpr.2020.05.085

Rabaia, M. K., Abdelkareem, M. A., Sayed, E. T., Elsaid, K., Chae, K.-J., Wilberforce, T., and Olabi, A. G. (2021). Environmental impacts of solar energy systems: A Review. *Science of The Total Environment*, *754*, 141989. https://doi.org/10.1016/j.scitotenv.2020.141989

Raji, B., Tenpierik, M. J., and van den Dobbelsteen, A. (2015). The impact of Greening Systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*, *45*, 610–623. https://doi.org/10.1016/j.rser.2015.02.011

Ramos-Fuentes, I. A., Elamri, Y., Cheviron, B., Dejean, C., Belaud, G., & Fumey, D. (2023). Effects of shade and deficit irrigation on maize growth and development in fixed and dynamic AgriVoltaic Systems. *Agricultural Water Management*, *280*, 108187. https://doi.org/10.1016/j.agwat.2023.108187

Rana, M., and Rani, P. (2017). Swiss Chard. In *Vegetable Crop Science* (pp. 243–243). essay, CRC Press.

Rayner, J. P., Farrell, C., Raynor, K. J., Murphy, S. M., & Williams, N. S. G. (2016). Plant establishment on a green roof under extreme hot and dry conditions: The importance of leaf succulence in plant selection. *Urban Forestry & Urban Greening*, *15*, 6–14. https://doi.org/10.1016/j.ufug.2015.11.004

Redweik, P., Catita, C., and Brito, M. (2013). Solar energy potential on roofs and facades in an urban landscape. *Solar Energy*, *97*, 332–341. https://doi.org/10.1016/j.solener.2013.08.036

Reyes, R., Bustamante, W., Gironás, J., Pastén, P. A., Rojas, V., Suárez, F., Vera, S., Victorero, F., & Bonilla, C. A. (2016). Effect of substrate depth and roof layers on green roof temperature and water requirements in a semi-arid climate. *Ecological Engineering*, *97*, 624–632. https://doi.org/10.1016/j.ecoleng.2016.10.025

Ria, R., Lakitan, B., Sulaiman, F., Yakup, Y., P Negara, Z., and Susilawati, S. (2023). Artificial shade adaptation and population density on Swiss chard (beta vulgaris subsp.. CICLA (L) W.D.J Koch) in urban AR-EA. *BIOVALENTIA: Biological Research Journal*, *9*(1), 71–83. https://doi.org/10.24233/biov.9.1.2023.384

Riaz, M. H., Imran, H., & Butt, N. Z. (2020). Optimization of PV array density for fixed tilt bifacial solar panels for efficient Agrivoltaic Systems. *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*. https://doi.org/10.1109/pvsc45281.2020.9300670

Rosental, L., Still, D. W., You, Y., Hayes, R. J., & Simko, I. (2021). *Mapping and Identification of Genetic Loci Affecting Earliness of Bolting and Flowering in Lettuce*. https://doi.org/10.21203/rs.3.rs-432642/v1

Ruszkowski, K. M., and Bousselot, J. M. (2024). Green roofs affect the floral abundance and phenology of four flowering plant species in the western United States. *Land*, *13*(1), 115. https://doi.org/10.3390/land13010115

Salerno, A. (2023). *Quantitative Analysis of Runoff in Green Roof Structures in the Colorado Front Range* (thesis). Colorado State University ProQuest Dissertations Publishing, Fort Collins.

SB23-016 bill summary. SB23-016 BILL SUMMARY | Colorado General Assembly. (2023). https://leg.colorado.gov/sb23-016-bill-summary

Schindler, B. Y., Blank, L., Levy, S., Kadas, G., Pearlmutter, D., and Blaustein, L. (2016). Integration of photovoltaic panels and green roofs: Review and predictions of effects on electricity production and Plant Communities. *Israel Journal of Ecology and Evolution*, *62*(1–2), 68–73. https://doi.org/10.1080/15659801.2015.1048617

Sehgal, A., Reddy, K. R., Walne, C. H., Barickman, T. C., Brazel, S., Chastain, D., and Gao, W. (2022). Climate stressors on growth, yield, and functional biochemistry of two brassica species, kale and mustard. *Life*, *12*(10), 1546. https://doi.org/10.3390/life12101546

Semeraro, T., Scarano, A., Curci, L. M., Leggieri, A., Lenucci, M., Basset, A., Santino, A., Piro, G., and De Caroli, M. (2024). Shading effects in AGRIVOLTAIC systems can make the difference in boosting food security in climate change. *Applied Energy*, *358*, 122565. https://doi.org/10.1016/j.apenergy.2023.122565

Seto, K. C., Churkina, G., Hsu, A., Keller, M., Newman, P. W. G., Qin, B., & Ramaswami, A. (2021). From low- to net-zero carbon cities: The next global agenda. *Annual Review of Environment and Resources*, *46*(1), 377–415. https://doi.org/10.1146/annurev-environ-050120-113117

Seyedabadi, M. R., Eicker, U., and Karimi, S. (2021). Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint. *Environmental Challenges*, *4*, 100119. https://doi.org/10.1016/j.envc.2021.100119

Shafique, M., Luo, X., and Zuo, J. (2020). Photovoltaic-green roofs: A review of benefits, limitations, and Trends. *Solar Energy*, *202*, 485–497. https://doi.org/10.1016/j.solener.2020.02.101

Smart, S. M., Glanville, H. C., Blanes, M. del, Mercado, L. M., Emmett, B. A., Jones, D. L., Cosby, B. J., Marrs, R. H., Butler, A., Marshall, M. R., Reinsch, S., Herrero-Jáuregui, C., and Hodgson, J. G. (2017). Leaf dry matter content is better at predicting above-ground net primary production than specific leaf area. *Functional Ecology*, *31*(6), 1336–1344. https://doi.org/10.1111/1365-2435.12832

Smith, J. P., Meerow, S., and Turner, B. L. (2021). Planning Urban Community Gardens strategically through Multicriteria Decision Analysis. *Urban Forestry and Urban Greening*, *58*, 126897. https://doi.org/10.1016/j.ufug.2020.126897

Stagnari, F., Galieni, A., and Pisante, M. (2015). Shading and nitrogen management affect quality, safety and yield of greenhouse-grown leaf lettuce. *Scientia Horticulturae*, *192*, 70–79. https://doi.org/10.1016/j.scienta.2015.05.003

Stajnko, D., Berk, P., Orgulan, A., Gomboc, M., Kelc, D., and Rakun, J. (2022). Growth and glucosinolate profiles of Eruca Sativa (mill.) (rocket salad) and diplotaxis tenuifolia (L.) DC. under different LED lighting regimes. *Plant, Soil and Environment*, *68*(10), 466–478. https://doi.org/10.17221/44/2022-pse

Stoven, V. (2010, August 3). The potential of green roofs to manage urban stormwater. Wiley Online Library. Retrieved November 15, 2022, from https://onlinelibrary.wiley.com/doi/full/10.1111/j.1747-6593.2009.00174.x

Sun, J., & Jasieniak, J. J. (2017). Semi-transparent solar cells. *Journal of Physics D: Applied Physics*, *50*(9), 093001. https://doi.org/10.1088/1361-6463/aa53d7

Tai, C., Sawada, Y., Masuda, J., Daimon, H., and Fukao, Y. (2020). Cultivation of spinach in hot seasons using a micro-mist-based temperature-control system. *Scientia Horticulturae*, *273*, 109603. https://doi.org/10.1016/j.scienta.2020.109603

Tang, Y., Wen, X., Lu, Q., Yang, Z., Cheng, Z., and Lu, C. (2006). Heat stress induces an aggregation of the light-harvesting complex of photosystem II in spinach plants. *Plant Physiology*, *143*(2), 629–638. https://doi.org/10.1104/pp.106.090712

Teng, J. W., Soh, C. B., Devihosur, S. C., Tay, R. H., and Jusuf, S. K. (2022). Effects of Agrivoltaic systems on the surrounding rooftop microclimate. *Sustainability*, *14*(12), 7089. https://doi.org/10.3390/su14127089

Tränkner, C., Pfeiffer, N., Kirchhoff, M., Kopisch-Obuch, F. J., van Dijk, H., Schilhabel, M., Hasler, M., & Emrani, N. (2017). Deciphering the complex nature of bolting time regulation in beta vulgaris. *Theoretical and Applied Genetics*, *130*(8), 1649–1667. https://doi.org/10.1007/s00122-017-2916-2

Uchanski, M., Hickey, T., Bousselot, J., and Barth, K. L. (2023). Characterization of agrivoltaic crop environment conditions using opaque and thin-film semi-transparent modules. *Energies*, *16*(7), 3012. https://doi.org/10.3390/en16073012

Uematsu, T., Tsutsui, K., Yazawa, Y., Warabisako, T., Araki, I., Eguchi, Y., and Joge, T. (2003). Development of bifacial PV cells for new applications of flat-plate modules. *Solar Energy Materials and Solar Cells*, *75*(3–4), 557–566. https://doi.org/10.1016/s0927-0248(02)00197-6

United Nations. (2018). 68% of the world population projected to live in urban areas by 2050, says un | UN Desa Department of Economic and Social Affairs. https://www.un.org/development/desa/en/news/population/2018-revision-of-world urbanization-prospects.html

United Nations. (2022, December 14). *Climate ambition alliance: Net zero 2050*. Climate Ambition Alliance: Net Zero 2050 - Climate Initiatives Platform. https://climateinitiativesplatform.org/index.php/Climate_Ambition_Alliance:_Net_Zero_2050

USDA ERS - Chart Detail. (n.d.). *U.S. lettuce production shifts regionally by season*. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=106516

USGS (2018, June 12). *Evapotranspiration and the water cycle completed*. Evapotranspiration and the Water Cycle | U.S. Geological Survey. https://www.usgs.gov/special-topics/water-science-school/science/evapotranspiration-and-water-cycle

Ushasree, P. M., and Bora, B. (2019). Silicon Solar Cells. *Solar Energy Capture Materials*, 1–55. https://doi.org/10.1039/9781788013512-00001

Valle, B., Simonneau, T., Sourd, F., Pechier, P., Hamard, P., Frisson, T., Ryckewaert, M., and Christophe, A. (2017). Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Applied Energy*, *206*, 1495–1507. https://doi.org/10.1016/j.apenergy.2017.09.113

van Delden, S. H., SharathKumar, M., Butturini, M., Graamans, L. J., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R. S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., van Ieperen, W., Verdonk, J. C., Vialet-Chabrand, S., Woltering, E. J., van de Zedde, R., Zhang, Y., and Marcelis, L. F. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nature Food*, *2*(12), 944–956. https://doi.org/10.1038/s43016-021-00402-w

Walston, L. J., Barley, T., Bhandari, I., Campbell, B., McCall, J., Hartmann, H. M., and Dolezal, A. G. (2022). Opportunities for agrivoltaic systems to achieve synergistic food-energy-environmental needs and address sustainability goals. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.932018

Walters, S. A., and Stoelzle Midden, K. (2018, October 25). *Sustainability of urban agriculture: Vegetable production on green roofs*. MDPI. Retrieved September 8, 2022, from https://www.mdpi.com/2077-0472/8/11/168

Wang, D., and Sun, Y. (2018). Optimizing light environment of the oblique single-axis tracking Agrivoltaic system. *IOP Conference Series: Earth and Environmental Science*, *170*, 042069. https://doi.org/10.1088/1755-1315/170/4/042069

Wang, D., Sun, Y., Lin, Y., and Gao, Y. (2017). Analysis of light environment under solar panels and crop layout. *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*. https://doi.org/10.1109/pvsc.2017.8521475

Whittinghill, L. J., Rowe, D. B., and Cregg, B. M. (2013). Evaluation of vegetable production on extensive green roofs. *Agroecology and Sustainable Food Systems*, *37*(4), 465–484. https://doi.org/10.1080/21683565.2012.756847

Widmer, J., Christ, B., Grenz, J., and Norgrove, L. (2024). Agrivoltaics, a promising new tool for electricity and food production: A systematic review. *Renewable and Sustainable Energy Reviews*, *192*, 114277. https://doi.org/10.1016/j.rser.2023.114277

Zhang, B., Liu, Y., Xu, D., Cai, J., & Li, F. (2011). Evapotranspiraton estimation based on scaling up from leaf stomatal conductance to canopy conductance. *Agricultural and Forest Meteorology*, *151*(8), 1086–1095. https://doi.org/10.1016/j.agrformet.2011.03.012

Zhang, J., Yue, Y., Sha, Z., Kirumba, G., Zhang, Y., Bei, Z., and Cao, L. (2014). Spinach-irrigating and fertilizing for optimum quality, quantity, and economy. *Acta Agriculturae Scandinavica, Section B — Soil and Plant Science*, *64*(7), 590–598. https://doi.org/10.1080/09064710.2014.936489

Zhu, Y., Cheng, Z., Feng, K., Chen, Z., Cao, C., Huang, J., Ye, H., and Gao, Y. (2022). Influencing factors for transpiration rate: A numerical simulation of an individual leaf system. *Thermal Science and Engineering Progress*, *27*, 101110. https://doi.org/10.1016/j.tsep.2021.101110