THESIS

EXPLORING THE IMPACT OF GREEN ROOFS ON CHILE PEPPER (*Capsicum annuum* L.) PRODUCTION, GROWTH, AND CONSUMER ACCEPTANCE

Submitted by

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ABSTRACT

EXPLORING THE IMPACT OF GREEN ROOFS ON CHILE PEPPER (*Capsicum annuum* L.) PRODUCTION, GROWTH, AND CONSUMER ACCEPTANCE

The progression of climate change is creating challenges for current agriculture systems with more intense and variable weather patterns as well as the degradation of land. In some places arable land has been converted for renewable energy production because of climate change challenges, but this further strains current food systems. Amidst this, the demand for food globally is also expected to increase while rapid urbanization takes place, which results in increased rates of food insecurity in urban areas. One solution may be rooftop agrivoltaics (RAV) which is a novel system that combines crop production on green roofs with photovoltaic (PV) arrays. This study explored the impact of RAV on chile pepper production and plant growth over two growing seasons to characterize this novel growing environment and better understand chile pepper suitability for such system. Season 2023 included four cultivars of chile peppers (‘Mosco’, ‘Hatch’, ‘CSU’, and ‘Primrose’) grown on the Hydro green roof located at the CSU Spur campus in Denver, Colorado. Each cultivar was grown in a full sun plot (control), in a plot under a bifacial PV array (treatment), and in a plot under an opaque PV array (treatment). Season 2024 focused on the first three cultivars with the addition of two treatment plots: 40% shade cloth treatment to simulate semi-transparent PV and an at grade plot for more direct comparison to traditional growing methods. Results demonstrated significantly decreased yield under bifacial and opaque PV arrays compared to full sun and shade cloth plots. Plant growth and biomass were significantly impacted by shade from the PV though results were not consistent across seasons. Stomatal conductance was reduced significantly in the first part of the growing season in the shade cloth, bifacial, and opaque plots suggesting reduced plant water use. Overall, the results demonstrated that the 40% shade cloth plot resulted in high yields and optimum plant growth. The use of semi-transparent panels could provide an ideal growing environment for effective chile pepper production in RAV while also producing renewable energy.

Roasted chile peppers are a culturally important part of the diet to many Coloradoans, however little research has been conducted to understand how different growing environments may impact sensory attributes. ‘Mosco’ and ‘Hatch’ chile peppers grown in full sun on a green roof and at grade were roasted for sensory evaluation by consumers in Denver, Colorado. Samples were evaluated using a just-about-right (JAR) scale for 7 attributes and a standard 9-point hedonic scale for overall liking. There was no significant difference between treatments for each cultivar in overall liking. Panelists did show a slight preference for green roof grown roasted chile peppers compared to at-grade roasted chile peppers for each cultivar, and a desire for some attributes to be more intense was noticed in JAR results. Overall, urban farmers can confidently grow ‘Mosco’ and ‘Hatch’ chile peppers on green roofs without significant impact to consumer acceptance. Chile peppers are a suitable crop for growing both on green roofs and in certain RAV systems with additional considerations.

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1.1 Introduction

Over the past century the global population has become increasingly urbanized with more than half of the population currently living in urban areas (Ritchie, 2019). By 2050 it is estimated that this will increase to two thirds of the global population (Ritchie, 2019). By that same year the demand for food and feed is expected to grow by 70% globally (FAO, 2009). Currently it is estimated that about 75% of the world's food insecure population, about 1.7 billion people, lives in urban and peri-urban areas (CWFS, 2024). This is an issue in both developing countries and post-industrial countries (Ackerman et al., 2014). Historically the emphasis for affordable food access has been on staple crops that are produced in a large-scale, typically monoculture, agriculture systems (CWFS, 2024). This has led to the marginalization of smaller, more diverse growers as well as a nutritionally unbalanced diet being available to the urban population that is food insecure (CWFS, 2024). Increasing urban crop production is vital to support growing urban populations, offer more balanced nutrition, educate urban populations about agriculture, and reduce high levels of food insecurity.

As the pressure to increase food production grows, climate change creates more challenges for an agriculture system that is already struggling to meet demand (FAO, 2009). The natural resource base, such as arable land, currently in use to produce food and feed is degrading at a concerning rate, and these resources are particularly vulnerable to further impacts from climate change in the future (FAO, 2009). Weather patterns are becoming more variable, and crop yield is expected to be significantly impacted leading to greater instances of food insecurity (Schmidhuber & Tubiello, 2007). Reimagining systems of food production is now vital to create an agricultural system that is resilient to the impacts of climate change and capable of meeting the demands of the population (Wheeler & Braun, 2013).

This will require a multi-faceted approach that both supports the increased urban population and the need to increase sustainability. One route may be rooftop agrivoltaics (RAV), which combines the use of green roofs and solar panels to produce crops and renewable energy. This novel system is an innovative version of agrivoltaics (AV), a system that has already proven successful, and it could be an important step into the future of how food production and urban landscapes are thought about (Barron-Gafford et al., 2019; Hickey et al., 2024a; Hickey et al., 2024b).

1.2 Agrivoltaics (AV)

In an effort to expand renewable energy production and to slow climate change, the use of photovoltaics (PV) has grown. In some places this leads to arable land being converted into land used for renewable energy production, often large arrays of PV, further increasing the challenges food systems face (Barron-Gafford et al., 2019). Improving energy production systems is key to facing the challenges ahead from climate change, however with conventional systems this reduces the potential for crop production as the demand for solar arrays increases (Dupraz et al., 2011). It leads to an ‘either-or’ system that supports a solution to one issue at the expense of aggravating another issue (Barron-Gafford et al., 2019; Dupraz et al., 2011). It is imperative that renewable energy production does not come at the cost of crop production (Barron-Gafford et al., 2019).

AV is one solution to this ‘either-or’ thinking by combining crop production with renewable energy production. AV is the method of growing plants below PV (Barron-Gafford et al., 2019, Dupraz et al., 2011). This system has the potential to increase land productivity by up to 70% depending on system design (Weselek et al., 2019). This approach offers the benefit of utilizing space to produce two different commodities, food and energy. Additionally, the PV provides shade from solar radiation for the plants, moderating the air temperature around the plants, reducing plant stress, and reducing plant water use (Barron-Gafford et al., 2019; Hudelson & Lieth, 2021; Uchanski et al., 2023). Increased shading from PV may support higher yields for certain crops such as peppers, cherry tomatoes, broccoli, arugula, kale, and lettuce (Barron-Gafford et al., 2019; Hickey et al., 2024b; Hudelson & Lieth, 2021; Villa-Ignacio, 2024). For other crops, such as jalapeno and Swiss chard, increased shading may produce similar yields to full sun (Barron-Gafford et al., 2019; Villa-Ignacio, 2024). Some crops, such as squash, may experience reduced yield due to the increased shading, emphasizing the importance of proper crop selection and making considerations to mitigate the impact of light reduction on plant growth (Hickey et al., 2024b; Marrou et al., 2013).

AV is likely to reduce irrigation needs due to the increased shading, which is especially important in arid climates and water-limited locations (Barron-Gafford et al., 2019; Weselek et al., 2019). This system benefits not only the plants but also the PV. Energy production is more efficient when PV are located within AV systems (Barron-Gafford et al., 2019). Plants transpire, releasing water and cooling the air around the panels, which allows them to operate more efficiently (Barron-Gafford et al., 2019). Depending on the size of the AV system and type of panels, the reduction in panel temperature can result in a 3% increase in energy production during the growing season and a 1% increase annually (Barron-Gafford et al., 2019). To add further resilience to our food systems and renewable energy production, it is important to consider how AV can be reimagined for urban areas to fit the scale of space available within cities.

1.3 Green Roofs and Rooftop Agrivoltaics (RAV)

Increasing urban populations are expected to result in an expansion of urban land areas by 78%-171% (Huang et al., 2019). This rate of urban land expansion is projected to result in average urban temperatures increasing by 0.5°C- 0.7°C, potentially by 3°C, which contributes to the already prevalent issues caused by the urban heat island (UHI) effect (Huang et al., 2019; Phelan et al., 2015). The UHI effect is the difference in temperature between the urban built environment and the surrounding natural environment, which is caused by the retention of heat from high amounts of impervious surfaces in urban areas (Phelan et al., 2015). Excess heat is associated with negative health effects, increased energy costs, poor water runoff quality, and worsening air quality (Getter & Rowe, 2006; Phelan et al., 2015). Green infrastructure is known to help reduce the UHI, so incorporating more green roofs in urban landscapes is important to address these challenges (Wong et al., 2003).

Green roofs can improve the energy efficiency of buildings they are built on and extend the lifespan of a roof membrane (Getter & Rowe, 2006; Wong et al., 2003). Additionally, they support improved stormwater management in urban areas by reducing the total stormwater runoff and delaying the peak flow time (Getter & Rowe, 2006; Shafique et al., 2018). This is especially important in cities with combined sewer systems to reduce the chances of sewage overflow (Getter & Rowe, 2006). Green roofs can filter out pollutants from stormwater as water moves through the substrate, improving stormwater runoff quality (Getter & Rowe, 2006).

Green roofs can be a challenging environment to grow plants because they have unique microclimates and components. Green roof substrate is typically made up of a lightweight and well-draining mixture of expanded shale, slate, or clay and other components like pumice or perlite (Getter & Rowe, 2006). This results in a lower water holding capacity than at-grade native soil creating an environment that is considered water limited (Uchanski et al., 2023). Plants on a green roof often experience high levels of solar radiation which can exacerbate drought conditions (Getter & Rowe, 2006). The most common type of green roof built is an extensive green roof that is planted with sedums due to structural loading capacities of buildings, lower cost, and lower maintenance (Getter & Rowe, 2006).

Because of these differences from at-grade growing, cultivation of food crops on a green roof is very different from traditional methods. There has been some exploration into crop production on extensive green roofs; tomatoes, beans, and cucumbers had yields within range of traditional agriculture methods with careful management (Whittinghill et al., 2016). Some crops produce higher yields when grown on a green roof than at-grade (Aloisio et al., 2016). Crop production in extensive green roofs requires frequent irrigation and careful nutrient input to account for the lack of nutrients in green roof substrates (Walters & Stoelzle Midden, 2018; Whittinghill et al., 2016).

The exploration of crop production on green roofs so far has been mostly limited to extensive green roof systems which are typically less than 15cm deep (Snodgrass & McIntyre, 2010). These studies have been successful for many shallow rooting crops, but the shallow substrate depth means that frequent irrigation is required (Walters & Stoelzle Midden, 2018; Whittinghill et al., 2013; Whittinghill et al., 2016). Extensive green roofs may not be suitable for deeper rooting crops or crops that require more water (Walters & Stoelzle Midden, 2018). Intensive green roofs, which are deeper than 15cm, are able to support a more diverse selection of plants and retain more moisture (Snodgrass & McIntyre, 2010; Vandegrift et al., 2019). The deeper substrate found in intensive green roofs may be able to support a wider variety of agricultural crops and help reduce the frequency or amount of irrigation needed. Currently there is a lack of research on crop production in intensive green roof systems, and further exploration is needed to understand how intensive green roofs could be key to increasing urban crop production.

RAV is a novel solution to the challenges of rapid urbanization and climate change that combines AV with green roofs. Growing food crops on a green roof under PV arrays takes advantage of underutilized spaces in urban areas that could add stability to current food systems while also producing renewable energy and supporting sustainable infrastructure. Roofs account for about 30-40% of impervious surfaces in most cities (Stovin, 2009). RAV allows AV to be scaled for urban areas and encourages the use of these underutilized rooftops for multiple benefits. RAV may minimize some of the challenges of growing crops on a green roof while providing an additional product in renewable energy. Increasing crop production within the urban landscape can reduce the carbon footprint typically associated with transporting food crops long distances to reach urban populations (Pirog et al., 2001).

RAV creates a beneficial, partially shaded environment that may reduce plant water use for crops growing in the high heat and low water environment on a green roof (Hickey et al., 2024a; Uchanski et al., 2023; Villa-Ignacio, 2024). Shading is an effective tool in climates that experience high rates of evaporation and are water limited to reduce the amount of water plants use, and shading can improve the quality and marketable yield of crops (Lorenzo et al., 2006). Higher soil moisture is found under PV arrays than in full sun treatments, suggesting RAV could reduce drought stress challenges commonly experienced on green roofs (Bousselot et al., 2017; Hickey et al., 2024a; Villa-Ignacio, 2024). Plants grown under PV modules on a green roof experience cooler temperatures and smaller temperature variations than plants in full sun on a green roof (Bousselot et al., 2017; Hickey et al., 2024a). Shade provided by PV modules on a green roof resulted in greater plant coverage compared to plants that did not receive shade from the PV modules (Bousselot et al., 2017). The reciprocal relationship between plants and PV seen in at-grade AV is also evident in rooftop applications (Alshayeb & Chang 2018). PV arrays operate more efficiently and produce more energy when installed over a green roof compared to a black rooftop as a result of the green roof plants transpiring and moderating temperatures around the panels (Alshayeb & Chang, 2018).

Because this is a novel system, there is a need to further investigate how RAV can provide support and resilience to the agricultural industry. This project aims to better understand which food crops are suitable to grow in an RAV system and how RAV may reduce water use of plants, increase marketable yield, and provide greater access to crop production in urban areas.

1.4 Chile Peppers

Chile peppers (*Capsicum annuum* L.) are a high value crop grown in Colorado with cultural significance rooted in the Arkansas Valley Region (Haverluck, 2002; Lawrence, 2022). They became a staple crop in the 1990s, and they are well adapted to the semiarid climate in Colorado (Haverluck, 2002). This makes them a suitable selection to be grown in a hot and water limited environment such as a green roof.

Studies have explored the impact of various levels of shade on plant growth and yield of pepper plants. Growing piquin peppers (*Capsicum annuum* L. var. *glabriusculum*) under 35% shade cloths can increase yield and reduce flower and fruit abscission (Valiente-Banuet & Gutiérrez-Ochoa, 2016). Similar yield results were produced when sweet peppers were grown under 40% shade cloths (López-Marín et al., 2012). Marketable yield was increased significantly for bell peppers grown under 30% shade nets (Kabir et al., 2020), and in another study marketable yield was highest under 25% shade for chile peppers compared to 0%, 50%, and 75%

shade (Ahmed et al., 2023). When grown under 50% shade cloth, chile peppers produced similar total yields to chile peppers grown in full sun but had lower marketable yield (Masabni et al., 2016). Under 70% shade cloth, total yield from chile peppers was significantly reduced (Masabni et al., 2016). This suggests that shade levels less than 50% are more optimal for pepper production (Masabni et al., 2016). Because chile peppers produce well in partial shade, they are a good candidate for further investigation in RAV systems.

Shade can impact other plant metrics like growth habit, water use and chlorophyll content. Growing piquin peppers under 35% shade cloth resulted in increased vegetative growth suggesting a greater capacity for photosynthesis and fruit production (Valiente-Banuet & Gutiérrez-Ochoa, 2016). Hot peppers had smaller stem diameters as shade increased from 0% to 80%, and plants grown in full sun were shortest with the largest stem diameter (Ahmed et al., 2023). These results suggest that peppers grown under higher levels of shade have stems that are less lignified and weaker (Ahmed et al., 2023).

Stomatal conductance results seem to vary in previous studies, and this could be a result of varying climactic environments. One study that was conducted at Hawassa University in humid Ethiopia showed that stomatal conductance for hot peppers increased as shade increased up to 50% and then decreased as shade increased above 50% (Ahmed et al., 2023). Another study done in humid Georgia, USA, showed similar results of stomatal conductance of bell peppers increasing as shade increased to 47% and then decreased as shade increased higher than 47% (Kabir et al., 2020). In contrast to those two studies, a study conducted in semiarid southeast Spain found that stomatal conductance was highest in full sun for sweet peppers, and the stomatal conductance decreased as shade increased (López-Marín et al., 2012). Stomatal conductance typically increases as air temperature increases so the environmental conditions of these previous studies likely influenced stomatal conductance results (Urban et al., 2017). The relative humidity and time of day data measures were collected could impact stomatal conductance due to varying air temperatures as well.

Studies show that shade can positively impact chlorophyll content in pepper plants. One study shows that hot peppers grown under shade levels between 25% and 50% had higher chlorophyll a, chlorophyll b, and total chlorophyll than full sun and 75% shade (Ahmed et al., 2023). Another study found that growing chile peppers under white net shade cloth resulted in higher chlorophyll content than chile peppers grown in full sun, under red shade cloths, and green shade cloths (Agyemang Duah et al., 2021).

Other vegetable crops have been studied in RAV systems. Leafy greens (arugula, spinach, kale, and Swiss chard) were grown in a RAV and simulated RAV environment in northern Colorado (Villa-Ignacio, 2024). Arugula, kale, and lettuce produced higher yields under 40% semi-transparent PV compared to full sun and had lower stomatal conductance (Villa-Ignacio, 2024). These crops as well as spinach and Swiss chard produced fresh weight yields similar to full sun treatments when grown under opaque PV (Villa-Ignacio, 2024). This demonstrates crop production can be successful under a variety of RAV systems (Villa-Ignacio, 2024). There is a need for exploration into other crop types, like fruiting crops, because shading can delay and reduce flowering resulting in decreased yields (Miller et al., 2015). Additional investigation is needed for ideal crop selection and system design for RAV.

1.5 Shade Response

While shade can provide many benefits in RAV such as reducing plant water use, reducing heat stress, and increasing marketable yield, too much shade can lead to negative impacts on plant growth and production (Ahmed et al., 2023; Barron-Gafford et al., 2019;

Hickey et al., 2024b; López-Marín et al., 2012; Valiente-Banuet & Gutiérrez-Ochoa, 2016). The light compensation point may not be reached if plants are grown under shade levels that are higher than what they are adapted for. This can induce a shade response, which, for chile peppers, results in tall plants with thin stem diameters (Ahmed et al., 2023). This is typically not desired in fruiting food crops because increased plant height and decreased biomass potentially increases plant susceptibility to wind damage (Ahmed et al., 2023; Díaz-Pérez, 2013; Gross et al., 2024; Kabir et al., 2020; Valiente-Banuet & Gutiérrez-Ochoa, 2016). The individual leaf area of pepper plants increases as shade levels increase, but the weight of the leaves decreases (Kabir et al., 2020). As shade level increases, pepper plants have larger growth indexes suggesting they occupy a larger space (Gross et al., 2024; Masabni et al., 2016). These morphological changes are likely a result of the plant adapting to lower solar radiation in an attempt to maximize light capture and photosynthesis (Kabir et al., 2020).

If shade levels are too high for a plant, yield can be negatively impacted. Growing peppers under too much shade lowers rates of transpiration and photosynthesis below ideal levels, impacting plant productivity (Díaz-Pérez, 2014). Total yield for peppers grown in 80% shade is lower than other shade levels and full-sun grown peppers (Kabir et al., 2020; Valiente-Banuet & Gutiérrez-Ochoa, 2016). Too much shade can not only decrease total yield but also reduce the amount of marketable yield (Ahmed et al., 2023; Kabir et al., 2020; Masabni et al., 2016).

High levels of shade become detrimental to several components of crop production. Decreased crop production, such as reduced yield and reduced biomass, under high levels of shade is likely a result of plants not accessing enough sunlight and more energy being allocated to vegetative growth in order to maximize sunlight capture (Valiente-Banuet & Gutiérrez-Ochoa, 2016). The shade levels of an RAV system need to be carefully considered in crop selection to ensure crop production and plant growth is not negatively impacted as a result.

1.6 Conclusion

Exploring chile pepper production in a Colorado RAV system is key to characterizing this unique growing environment. Early research with RAV systems has shown that leafy greens can produce well under PV arrays (Villa-Ignacio, 2024). The impact of this system on fruiting crops is important to understand because of their high market value potential. Understanding which crops are most suitable for RAV and how to best design the RAV system for crops with high market value are key to long term viability of RAV systems. Our current agricultural systems are undergoing major changes to address the challenges of climate change, and new systems that support urban agriculture development while supporting efforts to increase renewable energy production are vital.

CHAPTER 2: EVALUATING CHILE PEPPER (*Capsicum annuum* L.) PRODUCTION AND GROWTH IN A ROOFTOP AGRIVOLTAIC SYSTEM

2.1 Introduction

One of the biggest issues facing communities across the world is climate change. These long-term shifts in temperatures and weather patterns driven by fossil fuels use and other human activities often lead to more volatile weather patterns. Increased utility costs and degradation of arable land are just a couple of the many pressures the world faces in a changing climate (FAO, 2009; Schmidhuber & Tubiello, 2007). While climate change continues to create challenges, urbanization is rapidly increasing, and it is estimated that this trend will continue with two thirds of the global population living in cities by 2050 (Ritchie, 2019). By that same year it is expected that the need for food and feed will increase by 70% (FAO, 2009).

Food insecurity is a problem already facing an estimated 1.7 billion people living in urban and peri-urban areas (CWFS, 2024). Challenges created by climate change in conjunction with rapid urbanization are issues that need to be addressed in order to sustain the current agriculture system and create more stability in future food systems. Solutions to these challenges will require a multi-faceted approach to address climate concerns and support the needs of urban populations.

One approach to slowing climate change is the push for renewable energy by using photovoltaics (PV). While PV arrays are an important aspect of creating renewable energy, the installation of large arrays sometimes takes place on arable land (Barron-Gafford et al., 2019). Renewable energy production often comes at the cost of a reduction of crop production that is necessary to feed the growing global population. However renewable energy does not have to come at the expense of crop production (Barron-Gafford et al., 2019; Dupraz et al., 2011).

Agrivoltaics (AV) is a system that combines agriculture and PV arrays in a way that can benefit both crop production and energy production (Barron-Gafford et al., 2019). PV arrays provide shade for crops reducing plant water use, heat stress, and unmarketable yield (Barron-Gafford et al., 2019; Hudelson & Lieth, 2021; Uchanski et al., 2023). Some crops produce higher yields when grown in an AV system, like peppers, cherry tomatoes, and lettuce (Barron-Gafford et al., 2019; Hickey et al., 2024b). The PV arrays also benefit from this system because as the crops transpire, they release water into the surrounding environment, decreasing the air temperature around the PV panels and subsequently reducing the panel temperature (Barron-Gafford et al., 2019). A small decrease in panel temperature during the growing season can increase energy production efficiency (Barron-Gafford et al., 2019).

AV installations are often large-scale systems located outside of urban areas and can be configured in many different ways. In an ecovoltaics system, pollinator gardens and native plants are grown under large PV arrays. Some AV systems integrate PV arrays and grazing livestock like cattle or sheep. One of the more complex AV systems is growing food crops under the PV arrays because of the shading and amount of labor involved in food crop production. All of these AV systems play an important role in the multi-faceted approach to addressing climate change and food insecurity. However, it is imperative to consider how it can be reimagined for urban areas to provide stability to urban food systems and produce additional renewable energy.

Many cities have turned to green infrastructure as one approach to reducing the impacts of climate change and the urban heat island (UHI) effect (Phelan, et al., 2015). The UHI effect is the difference in temperatures between urban areas and surrounding natural environments (Phelan et al., 2015). Because of high amounts of impervious surfaces, urban areas retain excessive amounts of heat, which is damaging to human health, leads to increased energy costs, and worsens air quality (Getter & Rowe, 2006; Phelan et al., 2015). Green roofs are one component of green infrastructure that can help increase vegetated areas and reduce the UHI effect (Wong et al., 2003).

Green roofs can reduce the energy consumption of the buildings they are built on due to the insulation they provide (Wong et al., 2003). They also can extend the life of the roof membrane and improve stormwater management by delaying peak runoff and reducing total stormwater runoff volume (Getter & Rowe, 2006; Shafique et al., 2018). Green roofs can improve stormwater quality as water filters through the substrate (Getter & Rowe, 2006). In addition to the positive environmental impacts of green roofs, they can provide valuable space to produce crops in urban areas. Growing food on a green roof comes with some additional challenges not found in traditional agriculture due to the high amount of solar radiation and green roof substrate that has limited water holding capacities (Getter & Rowe, 2006; Uchanski et al., 2023). This creates hot, dry conditions that make it difficult to grow crops that are not especially drought hardy.

Despite these challenges, many food crops are able to be grown successfully on a green roof compared to traditional at grade growing environments. Crops, such as tomatoes, beans, and cucumbers can produce yields that are similar to traditional agriculture with careful management (Whittinghill et al., 2016). Most exploration into crop production has used extensive green roofs which are less than 15cm deep and require very frequent irrigation to maintain plant health (Snodgrass & McIntyre, 2010; Walters & Stoelzle Midden, 2018; Whittinghill et al., 2016). Intensive green roofs with substrate depths greater than 15cm may provide a more suitable growing environment for deep rooting crops as well as reduce irrigation needs.

Green roofs offer a space where AV could be scaled for urban areas with a novel system called rooftop agrivoltaics (RAV). Adding PV arrays above crops on green roofs allows for dual use of space that is often underutilized. RAV could reduce irrigation requirements for plants because it provides shade for crops in a hot growing environment, reduces plant water use, and increases soil moisture compared to full sun plots on a green roof (Bousselot et al., 2017; Hickey et al., 2024a; Villa-Ignacio, 2024). In RAV systems, PV arrays see similar increased efficiency as they do in at grade AV systems due to plants cooling the air around them (Alshayeb & Chang, 2018).

Limited research has explored the impacts of RAV on crop production so far. Growing arugula, kale, and lettuce in a simulated RAV system under semi-transparent panels resulted in significantly higher fresh weights compared to full sun treatments (Villa-Ignacio, 2024). However, fruiting crops tend to bring higher market values, require more sunlight, and have longer crop cycles than leafy greens, so it is vital to expand research to investigate additional crop types.

One crop that may be well suited for RAV systems is the chile pepper. Chile peppers are a key cultural crop to Colorado and the Arkansas Valley farming region (Haverluck, 2002; Lawrence, 2022). They are well adapted to growing in arid climates which are similar to a green roof environment (Haverluck, 2002). Peppers have also demonstrated a preference for growing under shade levels between 30% and 40% (Ahmed et al., 2023; Kabir et al., 2020; López-Marín et al., 2012; Valiente-Banuet & Gutiérrez-Ochoa, 2016). These qualities make chile peppers a great candidate for the RAV growing environment. Additional exploration into which crops are best suited for this growing environment as well as better understanding the impacts of RAV on crops is needed for RAV to be an effective urban agricultural growing system.

The objective of this study was to examine the impact of RAV on chile pepper production, plant water use, and plant growth. We investigated the suitability of chile peppers in a novel RAV system and the impact of different PV treatments on fruiting crops. This project took place over two growing seasons. Results from Season 2023 and Season 2024 will be presented separately as multiple changes were made during the second growing season. Therefore in 2023 we hypothesized that the RAV system would affect chile pepper production measured by total yield weight, plant water use measured by stomatal conductance, and plant size measured by both plant growth index (PGI) and biomass accumulation when compared to chile peppers grown on a green roof without PV. We predicted that the plants grown under PV would have slightly lower yield, lower plant water use, and higher biomass accumulation than the plants grown in full sun on the green roof. Due to challenges with weather events and plant response to shading effects, we modified our hypothesis and predictions for the 2024 season. In 2024 we hypothesized that the 40% shade cloth, bifacial PV, and opaque PV would affect chile pepper production, plant water use, and plant size compared to chile peppers grown in full sun on the green roof and at grade. We predicted that the plants grown under the 40% shade cloth would have greater yield weight, lower plant water use, and higher biomass accumulation than the plants grown in the full sun, bifacial PV, opaque PV, and at grade treatment plots.

2.2 Materials and Methods

2.2.1 Site Description

The experiment was conducted on the rooftop of the Hydro building located on the Colorado State University Spur Campus (CSU Spur) at 4777 National Western Dr., Denver CO 80216, which is 1609 meters above sea level (39° 47.0092’ N, 104° 58.4378’ W). The green roof is an Intensive Garden Roof® 45.72 cm deep and comprised of LITETOP® intensive agriculture blend by American Hydrotech Inc. (American Hydrotech Inc., Chicago, IL, USA). The first year of this experiment was the first year of planting this green roof.

2.2.2 Season 2023 Experimental Design

Three treatment plots were planted on the Hydro rooftop (Figure 1). The first plot was planted under an array of opaque silicon-based PV (LR4-72HPH, Longi, Sydny, Australia). It was expected that the opaque PV array would provide the highest level of shade. The second plot was planted under an array of bifacial silicon-based PV. The bifacial PV array has solar cells on both sides of the panels, which creates gaps that allow sunlight to pass through. It was expected that this plot would provide less shade than the opaque PV plot. Both AV arrays were mounted using a standard ground-mounted racking on a rooftop and have an angle of about 44 degrees due east. The third plot was planted in full sun with no PV. Each plot was planted in rows by cultivar in a randomized block design. For each cultivar, 15 individuals were planted in each treatment. This design is blocked based on shade treatment as the PV location and orientation are fixed.

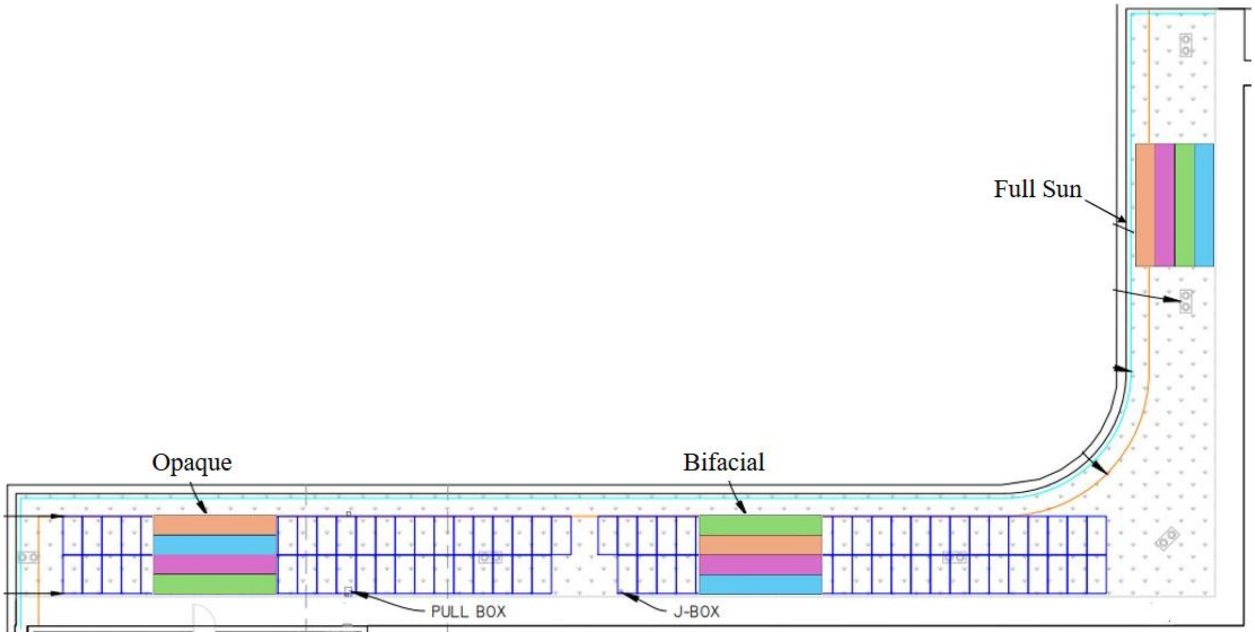


Figure 1. Rooftop layout of plots in 2023. Blueprint of the Hydro rooftop with the three treatment plots overlayed. Colors coordinate to cultivar. Blue represents ‘Mosco’, green represents ‘Hatch’, orange represents ‘CSU’, and purple represents ‘Primrose’.

2.2.3 Season 2023 Plant Material

Four cultivars of chile peppers (*Capsicum annuum* L.) were selected (Table 1). The ‘Mosco’ chile pepper is known for its thick, fleshy fruits and for being well adapted to the semiarid climate of Colorado. These characteristics have made it especially popular for roasting. The ‘Hatch’ chile pepper is one of the most notable green chile cultivars in North America and is popular in the diet of Coloradoans and south westerners in general. The unnamed CSU-474-21 chile pepper is a new unnamed cultivar developed by CSU that originated from a land race of the Mira Sol chile pepper. It has been selectively bred to have thick fruit walls that make it a good choice for roasting, and for its large fruit. This pepper will be referred to as ‘CSU’. Finally, the ‘Primrose’ chile pepper is an ornamental pepper that growers are interested in for its potential to be an agricultural crop.

Table 1. *Capsicum annuum* L. cultivar descriptions.

Cultivar	**Average Height**	**Fruit Length**	**Location Typically Grown**	**Scoville Units**
Capsicum annuum L. 'Mosco'	76.2cm	12-16cm	Pueblo, CO	5,000-6,000
Capsicum annuum L. 'Hatch'	76.2cm	15.24cm	New Mexico	1,000
Capsicum annuum L. 'CSU-474-21' ('CSU Experimental')	70-80cm	22-25cm	Pueblo, CO	~2,500
Capsicum annuum L. 'Primrose'	30-40cm	3-4cm	Pueblo, CO	*

*Not listed as this pepper is marketed as ornamental and not yet widely cultivated as an edible crop

Six weeks before the transplant date, seeds were sown (April 12, 2023) using Lambert LM-GPS germination mix (Lambert: Rivère-Ouelle, Quèbec, CA) in 50 cell deep plug flats (Johnny's Selected Seeds: Winslow, ME, USA). During the transplanting of seedlings into each research plot (May 31, 2023), 250mL of EcoGro compost (A1 Organics: Commerce City, CO, USA) was mixed into the substrate in each planting hole to provide nutrients and organic matter. Individuals were planted 30.5cm apart from each other in rows separated by cultivar. The rows were planted ≥30.5cm from adjacent rows. An MP Rotator sprinkler system (Hunter Industries: San Marcos, CA, USA) was used to water all plots every morning for 7 minutes. This is equal to approximately 1.17cm of water a week based on the flow rate of each sprinkler head. Each plant was fertilized one time (June 29, 2023) with 30ml of Dynamite 18-6-8 slow-release fertilizer (Sun Bulb Co Inc.: Arcadia, FL, USA).

2.2.4 Microclimate Data Collection

Multiple microclimate conditions were monitored to better characterize what the growing environment is like in an RAV system. HOBO 12-Bit Temperature Smart sensors connected to the HOBO H21-USB micro station data logger (Onset Computer Corporation: Bourne, MA, USA) were used to measure air temperature below and above the PV panels. The below panel temperature sensor was mounted about 45cm above the substrate surface. Above panel sensors were placed 15 cm above the solar panels in the bifacial and opaque plots. EC5 Soil Moisture Smart Sensors (Onset Computer Corporation: Bourne, MA, USA) measured substrate moisture in each plot. Solar radiation was monitored using HOBO Solar Radiation (Silicon Pyranometer) Smart Sensors (Onset Computer Corporation: Bourne, MA, USA) mounted about 45cm above the substrate surface near the center of the plot. Data on each environmental condition was recorded every 15 minutes for the duration of the growing season.

2.2.5 Yield

Chile pepper fruits were harvested once every week when they were of harvestable size based on the cultivar from August 4, 2023 to October 10, 2023. Fruit was counted, weighed in grams, and recorded per individual plant.

2.2.6 Plant Growth and Physiological Measurements

Multiple measures were taken at three time points: 1) flower initiation, 2) peak harvest, and 3) final harvest. These occurred on July 13, August 23, and October 10, 2023, respectively. These measures included PGI, stomatal conductance, and chlorophyll content. PGI was calculated by averaging the height, widest width, and width perpendicular to the widest width. This measurement represents the amount of space a plant occupies and helps characterize the growth habit. The stomatal conductance was measured using an SC-1 Leaf Porometer System (Meter Group: Pullman, WA, USA) to characterize how light may impact plant water use. The chlorophyll content was measured using an atLEAF CHL BLUE (atLEAF: Wilmington, DE, USA) to characterize the health of the plant and its response to environmental stressors. Fully expanded leaves located close to the growing point of the central leader were used for measuring stomatal conductance and chlorophyll content. All plant growth and physiological measurements were taken on 5 plants of each cultivar in each treatment plot.

2.2.7 Biomass Accumulation

Before the first autumn freeze (October 13, 2023), all plants were destructively harvested. Each plant was cut using pruners at the substrate level and placed into a labeled paper bag to be oven dried for 72 hours at a minimum of 80°C. Plants were then weighed to characterize the accumulation of biomass over the course of the growing season.

2.2.8 Season 2024

Based on the results of the 2023 season, some changes were made to narrow the focus of the second year of the experiment and expand the treatments. The focus shifted to the three cultivars established for culinary use (‘Mosco’, ‘Hatch’, and ‘CSU’), so the ‘Primrose’ cultivar was not planted. Two additional treatment plots were also added (Figure 2). The first treatment added was an at grade plot, which was incorporated to better compare results of green roof and RAV chile pepper production to more traditional agricultural practices. The second treatment added was a 40% shade cloth plot using a Be Cool Solutions™ 40% White Pearl Shade Cloth (Greenhouse Megastore: Danville, IL, USA) on the Hydro green roof to test shade levels closer to the ideal for chile peppers and simulate what could be possible with semi-transparent PV. Semi-transparent PV panels offer the ability to select for specific levels of transparency, however they are not yet UL listed. There was a notable wind event that caused lodging in July during the 2023 growing season, so Davis® Wind Speed and Direction Smart Sensors (Onset Computer Corporation: Bourne, MA, USA) were added to each treatment plot in 2024 to better characterize how wind plays a role in the growing environment. In addition to wind sensors, plants were planted deeper in the second year and staked individually to prevent potential damage from wind gusts. Marketable and unmarketable yield data were collected in addition to total yield during the second growing season to investigate how RAV could improve marketable yield.

In 2024, 12 individuals of each cultivar were planted in each treatment plot. They were seeded on April 10, 2024, and transplanted on May 14, 2024, using the same materials and methods as in 2023. Plants were fertilized on June 27, 2024. Yield data was collected from July 26, 2024 to October 11, 2024. Data for the repeated measures were collected on July 15, August 27, and October 10, 2024. Plants were destructively harvested on October 14, 2024, and oven dried for 72 hours at 80° C.

Soil and substrate samples were analyzed for each plot prior to Season 2024 (Table 2). The pH of each plot on the green roof was fairly consistent, while the at grade plot had a more alkaline pH of 8.0. Across treatments the nitrogen levels varied from very low (<5ppm) to very high (>50ppm). Phosphorus levels were very high (>20ppm) in all plots. Potassium levels ranged from low (60-120ppm) in the full sun plot to very high (>280) in the at grade plot. At grade soil had a sandy loam texture.

Table 2. Substrate and soil analysis for each treatment prior to planting Season 2024. Amounts of nitrogen, phosphorus, and potassium are listed in parts per million.

	pH	**N**	**P**	**K**
Full Sun	7.4	9	107	110
Shade Cloth	7.4	3	28	179
Bifacial	7.2	85	200	228
Opaque	7.3	35	32	142
At Grade	8.0	3	162	921

Pest pressures were present during both growing seasons. In Season 2023, aphids were observed on plants under both the bifacial and opaque PV arrays. Plants were treated with Safer® Brand Insect Killing Soap (Safer® Brand, Lancaster, PA, USA) weekly once detected. The plants in the bifacial plot had lower pest pressure and pest treatments were more effective in that plot. The plants in the opaque plot were more severely impacted by the aphids. In Season 2024, aphids were observed under both the bifacial and opaque PV arrays starting in July, and they were treated weekly for the duration of the growing season. Similar to Season 2023, the plants in the opaque treatment had higher pest pressure. Aphid activity was not noticed on plants in the full sun, shade cloth, or at-grade plots.

In Season 2024, grasshopper herbivory primarily impacted the plants in the full sun and at grade plots at the beginning of the growing season. We observed herbivory in young transplants in both of these plots. We created molasses traps by mixing 1 part molasses to 5 parts water. This pest control method did not appear to be effective at reducing grasshopper populations. We netted grasshoppers with butterfly nets to reduce populations, and this was somewhat effective. Grasshopper herbivory was not observed on plants in the shade cloth, bifacial, or opaque plots.

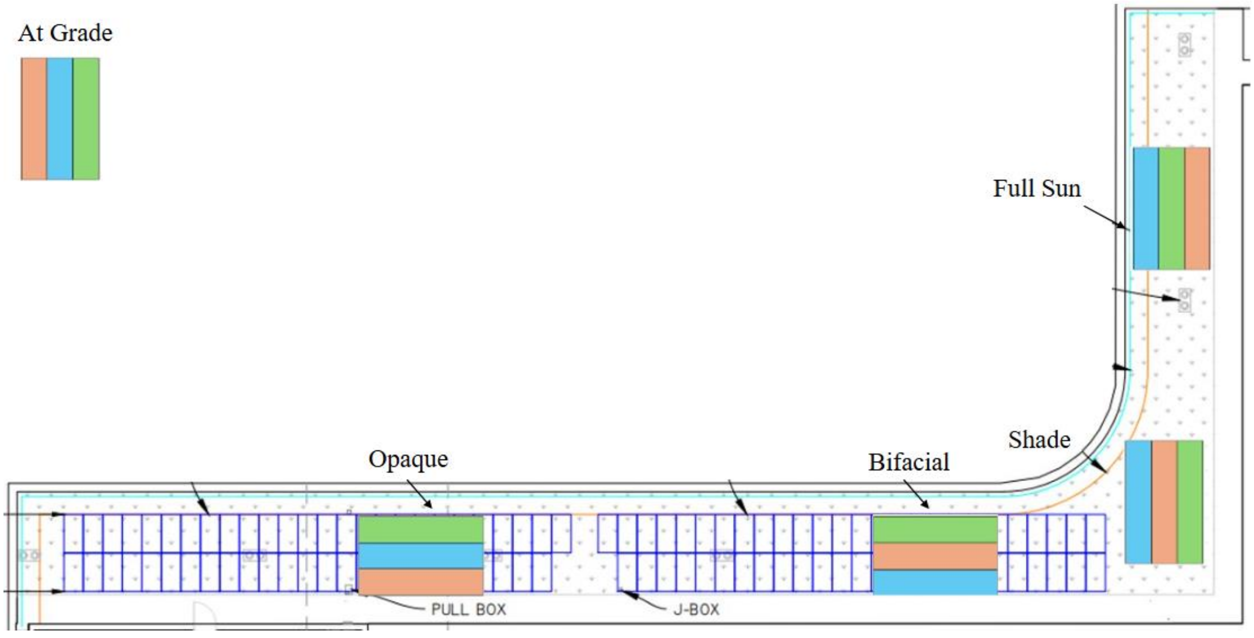


Figure 2. Rooftop layout of plots in 2024. Blueprint of the Hydro rooftop with the five treatment plots overlayed. Colors coordinate to cultivar. Blue represents ‘Mosco’, green represents ‘Hatch’, and orange represents ‘CSU’.

2.2.9 Statistical Analysis

Analysis using R-Studio (Boston, MA, USA) was performed within cultivar across treatments using a one-way ANOVA with pairwise comparisons for single time point measures. This includes yield and biomass accumulation. Total yield is considered a single time point measure cumulative at the end of the season because the total yield is what is most valuable to farmers. For the repeated measures a linear mixed effects model was used (Equation 1).

Equation 1: $y = \mu + \text{Treatment} + \text{Time (3 levels)} + \text{Treatment*Time} + (1|\text{PlantID})$

This model accounts for a fixed effect from treatment, a fixed effect from time, a fixed effect from the interaction of the treatment and time, and then a random effect of plant ID. Because the data being analyzed with these models is continuous, a normal distribution can be assumed, and Tukeys HSD was utilized for means separation, and significant differences are noted when $p \leq 0.05$. Log transformations were performed on both 'Hatch' and 'CSU' stomatal conductance data from Season 2024 to satisfy assumption of equal variance. In text values are original data and log transformed data is visualized.

2.3 Results and Discussion

2.3.1 Microclimate Data

Results from the 2023 growing season have been previously summarized in Gross et al. (2024) (Table 3). The hottest temperature recorded for the full sun plot (45.75°C) and bifacial plot (39.69°C) occurred in July while the hottest temperature recorded for the opaque plot (40.49°C) was in September. The lowest temperatures recorded nearly reached freezing in October for all three plots. In all months except for August, the low temperatures recorded in both PV plots were slightly higher than the low temperatures recorded in the full sun plot. Mean temperatures were slightly lower in both PV plots than in full sun for all months. This potentially suggests that temperatures may be slightly moderated for plants grown under PV arrays. This aligns with previous findings from Uchanski et al. where they observed lower day time temperatures under PV arrays (2023).

Table 3. The minimum, maximum, and mean air temperatures (°C) in each treatment plot during the 2023 season.

		Full Sun	**Bifacial**	**Opaque**
June	Max	35.64	36.20	36.12
	Min	8.67	10.10	9.51
	Mean	20.42	20.35	20.33
July	Max	45.75	39.69	39.40
	Min	11.30	12.29	12.60
	Mean	25.41	24.66	24.87
August	Max	38.70	39.04	39.23
	Min	12.90	11.35	12.65
	Mean	24.32	24.02	24.19
September	Max	37.76	39.49	40.49
	Min	5.67	7.07	6.69
	Mean	20.68	20.39	20.45
October	Max	29.97	29.67	29.89
	Min	0.69	2.40	1.86
	Mean	14.94	14.93	14.37

There does not seem to be a consistent pattern comparing the maximum, minimum, and mean air temperatures across treatments in Season 2024 (Table 4). The full sun plot had the highest mean air temperature in June (26.26°C), July (25.53°C), and August (24.62°C) suggesting that shaded green roof plots did have slightly moderated temperatures during the hottest months of the season. The opaque plot (22.81°C) had the highest mean air temperature in September, and the at-grade plot (17.93°C) had the highest mean air temperature in October. The full sun plot (40.14°C) had the highest air temperature in June, and the opaque plot had the highest air temperature in July (42.15°C), August (42.06°C), and September (37.92°C). This may be a result of the orientation of the PV. Each day after the sun passes solar noon toward the west, it shines directly under the PV. Since the opaque PV panels have a white backing on the underside, light and heat reflected down on the plant canopy thus increasing the air temperature in that plot. The at grade plot had the highest temperature across treatments in October. The at grade plot had the lowest air temperature in June, July, and August, while the shade cloth plot had the lowest air temperature in September and October. The opaque plot did not have data to compare in October because the logger stopped collecting data.

Table 4. The minimum, maximum, and mean air temperatures (°C) in each treatment plot during the 2024 season. *Data loggers stopped logging data in the opaque plot during October.

		Full Sun	**Shade**	**Bifacial**	**Opaque**	**At Grade**
June	Max	40.14	36.01	33.44	33.68	34.81
	Min	15.49	13.93	12.85	14.82	11.83
	Mean	26.26	24.31	23.85	23.77	24.15
July	Max	40.09	40.78	40.31	42.15	40.92
	Min	11.95	12.34	10.66	12.53	10.32
	Mean	25.53	25.31	24.99	25.08	25.19
August	Max	40.17	39.74	41.39	42.06	40.72
	Min	13.21	12.75	13.02	13.31	13.02
	Mean	24.62	24.33	24.23	24.27	24.34
September	Max	35.34	34.94	35.66	37.92	36.50
	Min	8.05	7.59	9.21	12.07	8.44
	Mean	21.78	21.08	21.58	22.81	21.49
October	Max	32.74	31.61	33.76	*	34.26
	Min	5.44	4.56	6.08	*	6.38
	Mean	17.74	17.08	17.81	*	17.93

Comparing the air temperature data from 2023 (Table 3) and 2024 (Table 4) shows a difference in highs, lows and means towards the end of the growing season. In September 2023 high temperatures were 37.76°C, 39.49°C, and 40.49°C, while in September 2024 high temperatures were 35.34°C, 34.94°C, 35.66°C, 37.92°C, and 36.50°C. As a result of the higher temperatures in 2023 wilting was noticed in the full sun plot beginning in late August and continued for the duration of the growing season. Additional irrigation had to be applied in order to keep the full sun plants alive. The first frost in 2023 arrived earlier in the year than in 2024 and this is seen in both Table 3 and Table 4. The low temperatures in October 2023 reached 0.69°C, 2.40°C, and 1.86°C while the low temperatures in October 2024 only reached 5.44°C, 4.56°C, 6.08°C, and 6.38°C. The means for October 2023 were colder than 2024. Wilting in the full sun plot at the very end of Season 2023 may have been a result of frost damage as evidenced by the low temperatures recorded in October during Season 2023.

Single day microclimate data was visualized to characterize the differences in microclimates over the course of a day. The day used in both years was around peak harvest time in late August to characterize growing conditions in each plot. Air temperatures are illustrated over the course of a single day in 2023 (Figure 3). The drop in temperature around 7:00am is attributed to the irrigation system turning on (Villa-Ignacio, 2024). The full sun plot experiences higher temperatures earlier in the day and also cools off more quickly than the PV treatment plots (Villa-Ignacio, 2024).

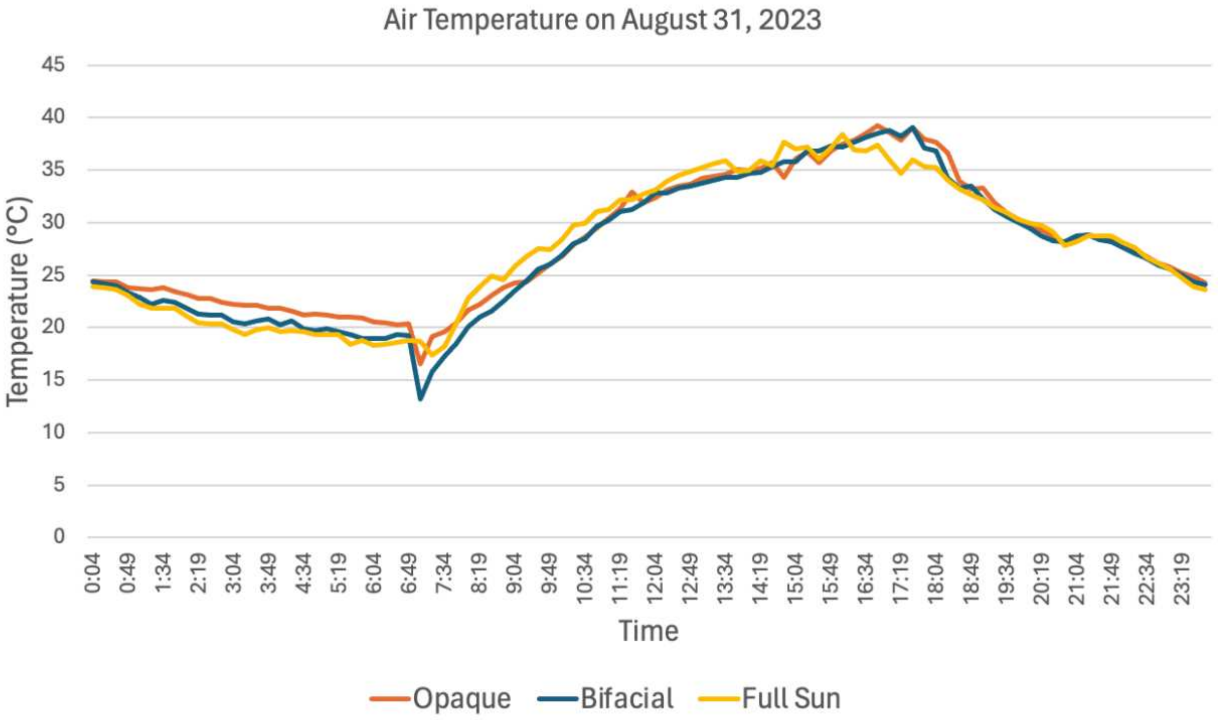


Figure 3. Air temperature (°C) graphed over the course of August 31, 2023, for full sun, bifacial, and opaque plots (Villa-Ignacio, 2024).

In 2024 the pattern of air temperatures over the course of a single day are fairly similar to the pattern in 2023 (Figure 4). There is a slight peak of air temperature seen in both the bifacial and opaque plots (32.56°C and 33.91°C respectfully) that happens later than the other plots around 6:00pm. This delay in peak air temperature is likely due to heat retention in the solar panels. As the day cools temperatures decrease, the solar panels begin to release heat and slow wind gusts, warming the air underneath the panels. The full sun plot experienced warmer temperatures earlier in the day than all other plots, peaking at 31.3°C, likely due to the higher amount of solar radiation that the full sun plot experienced earlier in the day.

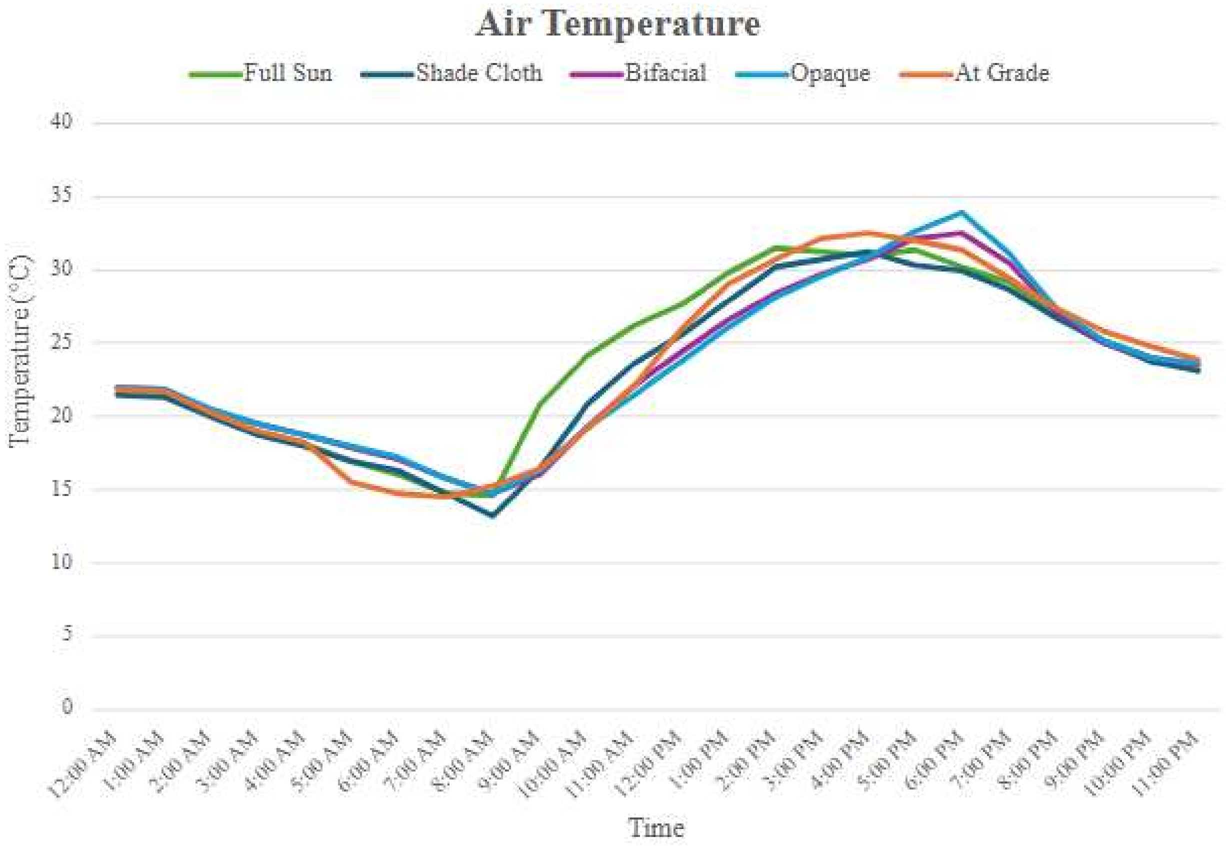


Figure 4. Air temperature (°C) graphed over the course of August 27, 2024 for full sun, shade cloth, bifacial, opaque, and at grade plots.

The 2023 single day solar radiation visualization shows that there was lower solar radiation under both PV treatments compared to full sun (Figure 5) (Villa-Ignacio, 2024). There are peaks in solar radiation for both PV treatment plots that occur when the sun passes far enough to the west that the PV panels no longer block direct sunlight from the plots (Villa-Ignacio, 2024). This data in Season 2023 indicated that the bifacial PV did not offer significantly less shade than the opaque PV as was previously expected. Based on our data, both PV types provided higher levels of shade than chile pepper plants prefer in order to flower and fruit. The 40% shade cloth was added in Season 2024 to simulate more ideal levels of shade that could be achieved with the use of semi-transparent PV.

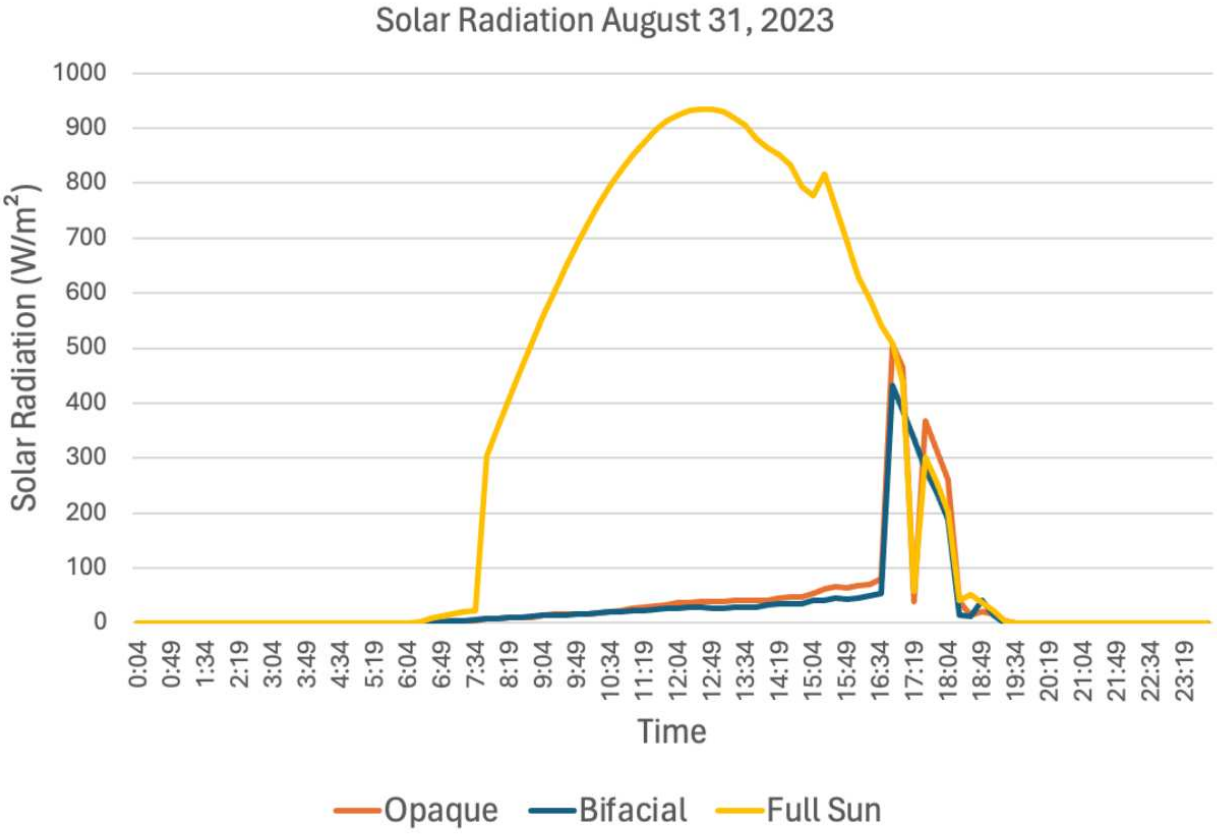


Figure 5. Solar radiation (W/m^2) over the course of August 31, 2023, for full sun, bifacial, and opaque plots (Villa-Ignacio, 2024).

We also illustrated the solar radiation over the course of one day for the 2024 growing season (Figure 6). The full sun plot line is a consistent bell-shaped curve suggesting this was a sunny day without clouds, and it peaked at 871.9W/m^2. There is a reduction in solar radiation in the shade cloth plot compared to the full sun plot as expected. It is not a smooth curve likely because of the nature of a woven shade cloth. There are time points when sun may have hit the pyranometer directly when passing through the gaps of the shade cloth. Over the course of this day, the shade cloth reduced solar radiation by about 31.1% compared to the full sun treatment. The solar radiation in the shade cloth plot peaked at 800.6W/m^2. Bifacial and opaque plots showed a reduction in solar radiation of about 87.0% and 85.6% respectively. The higher level of shade observed in the bifacial plot may be a result of the location of the plot under the bifacial PV. It was located towards the north end of the larger bifacial PV array, so more building and PV racking infrastructure likely blocked sun than in the opaque plot which was closer to the south end of the building.

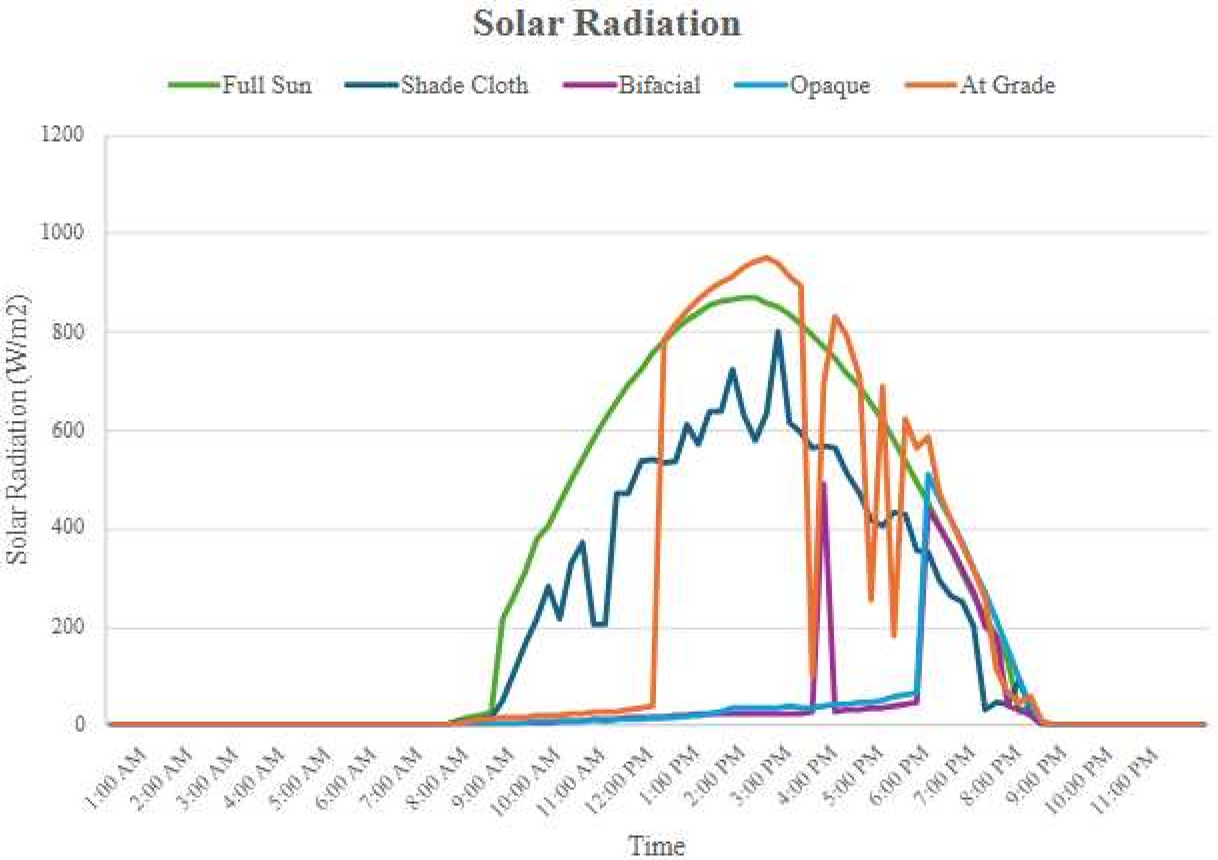


Figure 6. Solar radiation (W/m^2) over the course of August 27, 2024, collected in full sun, shade cloth, bifacial, opaque, and at grade plots.

The bifacial and opaque plots experienced low amounts of solar radiation for much of the day until the sun moved far enough west and shined directly under the panels (Figure 4). This happened around 4:00pm, then 7:00pm for the bifacial plot and 7:00pm for the opaque plot. The at grade plot had a drop in solar radiation at a few points in the day likely due to the proximity of it to the Hydro building which cast shade on the plot resulting in about a 25.8% reduction in solar radiation over the course of the entire day.

Substrate temperatures under the PV treatments in 2023 show lower temperatures for much of the day compared to full sun likely due to the shade provided by the PV arrays (Figure 7) (Villa-Ignacio, 2024). Substrate temperatures under the PV treatments spiked around noon and then increased again later in the day while the full sun substrate temperatures showed a more gradual increase (Villa-Ignacio, 2024).

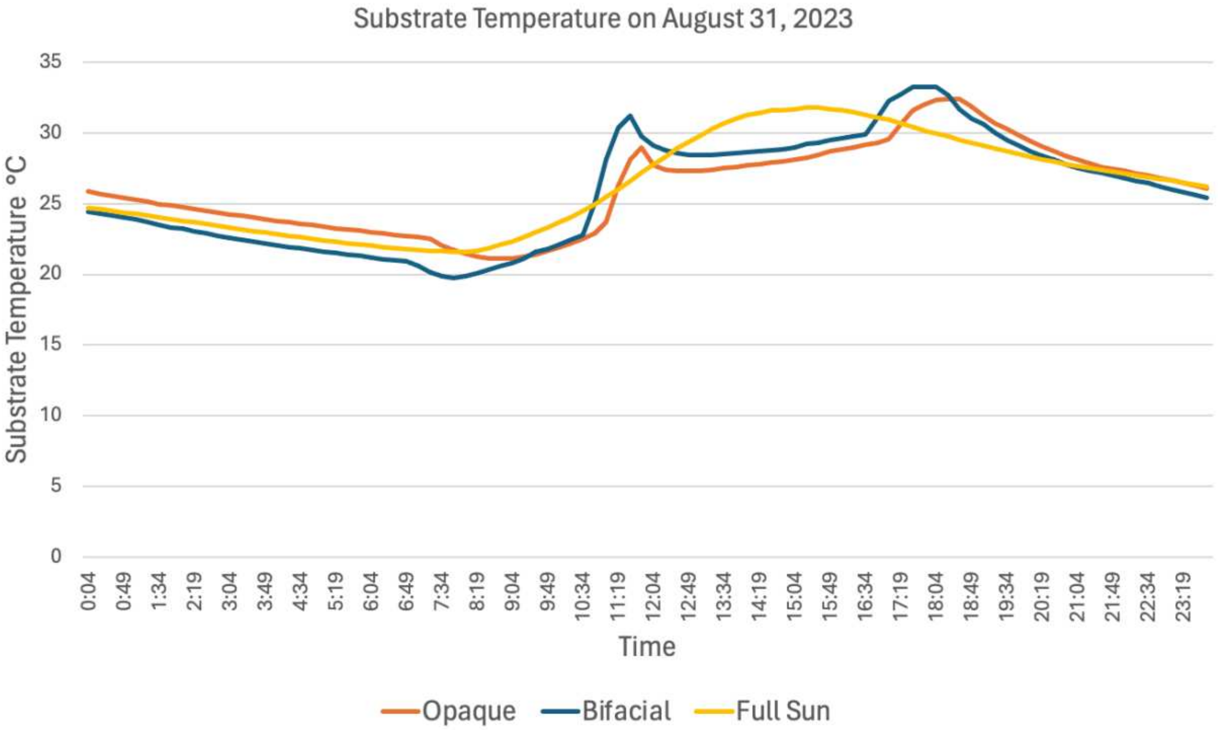


Figure 7. Substrate temperature (°C) graphed over the course of August 31, 2023 for full sun, bifacial, and opaque plots (Villa-Ignacio, 2024).

Substrate temperatures show more differences between treatment plots over the course of a day than air temperature, which is consistent with Uchanski et al. (2023) (Figure 8). The full sun plot experienced the warmest substrate temperatures peaking at 31.84°C while the shade cloth plot peaked at 28.48°C. The full sun and shade cloth plots had consistently higher substrate temperatures than the other three treatments. The at grade plot experienced the lowest substrate temperature dropping to 18.41°C.

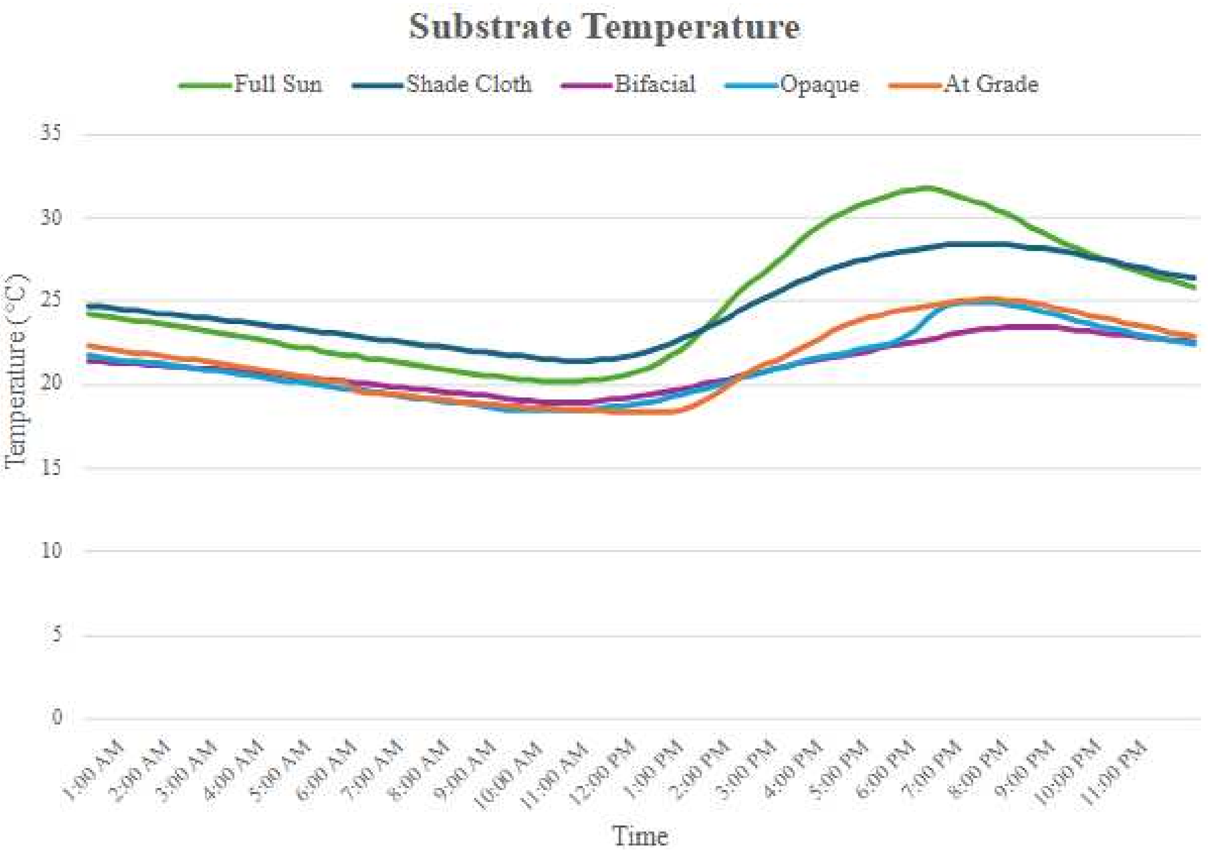


Figure 8. Substrate temperature (°C) graphed over the course of August 27, 2024 for full sun, shade cloth, bifacial, opaque, and at grade plots.

Substrate moisture in 2023 shows that the opaque plot had higher substrate moisture than the full sun and bifacial plots for the duration of the day (Figure 9) (Villa-Ignacio, 2024). The full sun plot had slightly higher substrate moisture than the bifacial plot for most of the day as well until about 5:00pm (Villa-Ignacio, 2024).

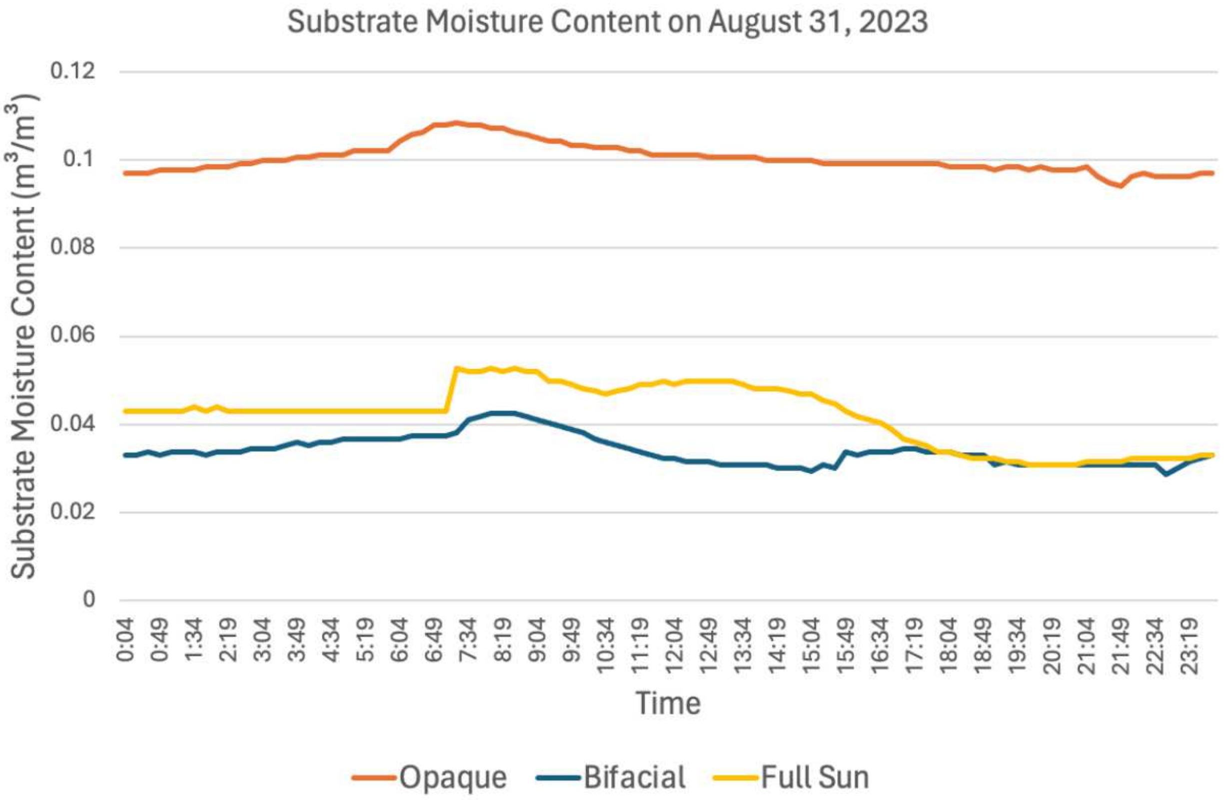


Figure 9. Substrate moisture (m^3/m^3) graphed over the course of August 31, 2023, for full sun, bifacial, and opaque plots (Villa-Ignacio, 2024).

In season 2024 the at-grade plot had consistently the highest substrate moisture reaching 0.33m^3/m^3 (Figure 10). This was the only plot that was in native soil rather than green roof substrate which is designed to be fast draining. The sandy loam soil in the at grade plot contained smaller particles than the larger aggregate blend of the green roof substate, allowing for increased water retention. The elevated substrate moisture in the at grade plot does not necessarily indicate that there was more plant available water though as soil texture plays a role in how easy it is for plants to access the water.

The next highest substrate moisture was found in the opaque plot (0.15m^3/m^3) followed by the full sun plot (0.10m^3/m^3). The shade cloth plot had the lowest substrate moisture (0.07m^3/m^3) for the majority of the day though it was similar to the substrate moisture in the bifacial plot (0.08m^3/m^3). The shade cloth plot was located in the corner of the green roof due to space constraints when this plot was added in 2024. Spatial variability due to the location of the sprinklers and the plots may have impacted the substrate moisture readings. Visually it was confirmed that irrigation reached the entirety of the plot, but because it was located further from some rotor sprinklers, it may not have received as much water.

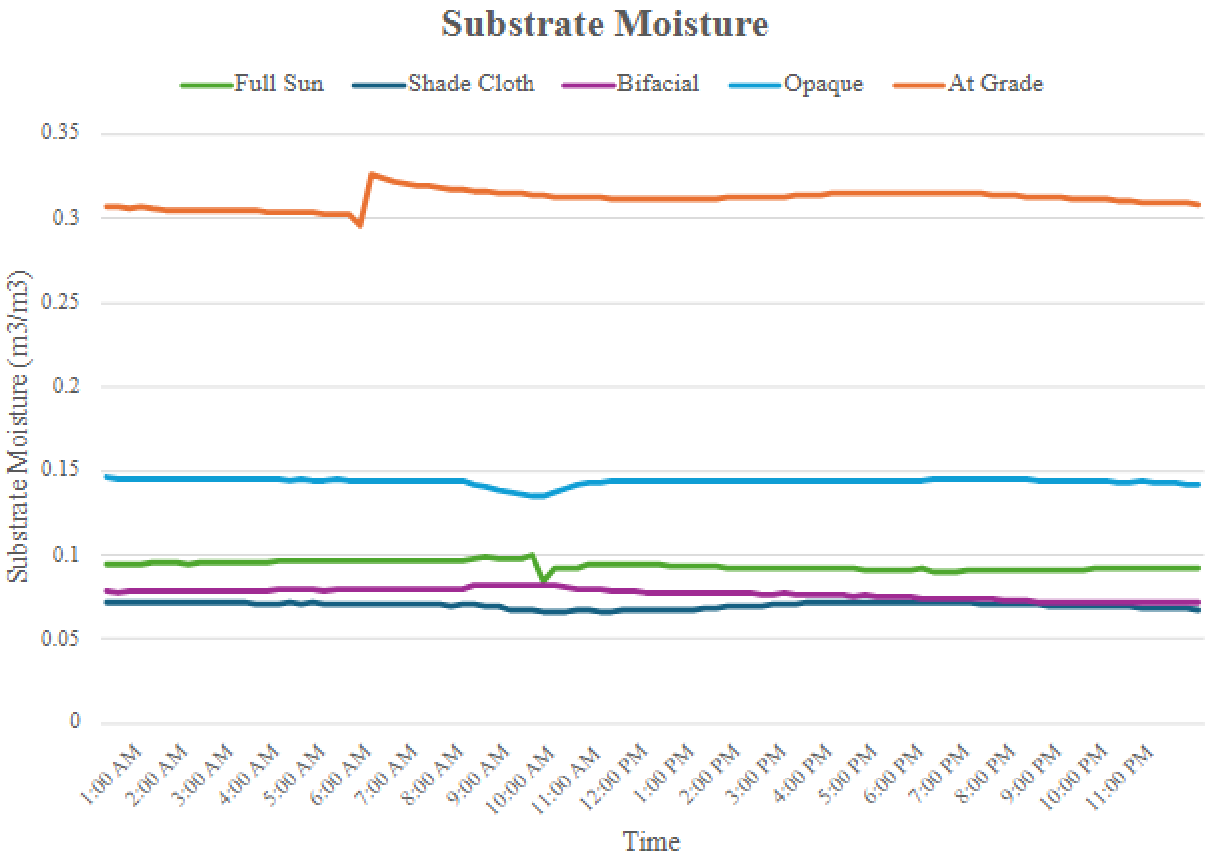


Figure 10. Substrate moisture (m^3/m^3) graphed over the course of August 27, 2024 for full sun, shade cloth, bifacial, opaque, and at grade plots.

2.3.2 Yield

In 2023 each cultivar produced a significantly higher ($p \leq 0.05$) yield in the full sun plot compared to the other treatments (Figure 11). For the ‘Hatch’ peppers the bifacial plants had significantly higher yield (281g) than the opaque plants (42.6g). In the other three cultivars, there was no significant difference in total yield between the bifacial and opaque treatment plots. During the 2023 growing season there was a wind event in July that caused lodging in all treatments though the plants under both PV treatments seemed most impacted. This resulted in a high rate of flower loss and thus delayed fruiting on the plants in both PV treatments. The full sun plants did not seem to be impacted as much, which may have been because they were already fruiting at this point in time, had not etiolated, and were not light limited. The high level of shade may have prevented the bifacial and opaque plants from recovering as quickly. It is also possible that the PV arrays created a wind tunnel that led to more intense wind in the PV plots. This is what led to the addition of wind sensors in the second growing season.

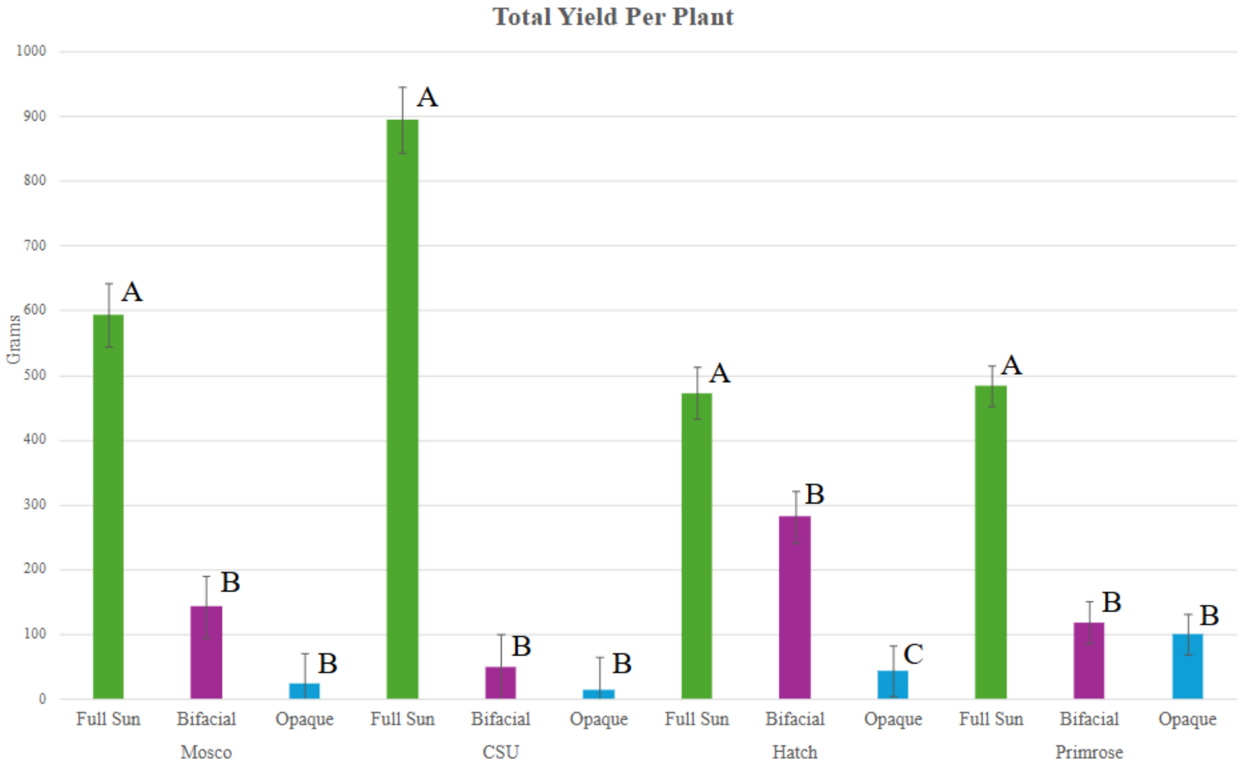


Figure 11. Comparison of the mean weight of yield within each cultivar by treatment (2023). Statistical significance (p≤0.05) from ANOVA results denoted by a difference of letters next to the error bars.

The precautions taken to prevent potential wind damage in 2024 were successful, so wind data is not reported. In 2024 there was no significant difference between the total yield of the full sun and shade cloth treatment peppers for all three cultivars. Both the full sun and shade cloth plants produced significantly higher ($p \leq 0.05$) mean total yields than the bifacial, opaque, and at grade plants treatments in all cultivars. The ‘Mosco’ plants in the shade cloth treatment (2,471.00g) produced slightly higher total yields than the full sun treatment (2,456.00g). The ‘CSU’ full sun plants (3,026.23g) produced higher total yield than the shade cloth grown plants (2,160.81g), though it was not statistically significant. The ‘CSU’ at grade plants (979.09g) produced significantly higher ($p \leq 0.05$) total yield than bifacial (4.12g) and opaque (0g) plants. ‘Hatch’ shade cloth plants (1,903.35g) produced slightly higher total yield than the full sun plants (1,436.67g) though it was not significant.

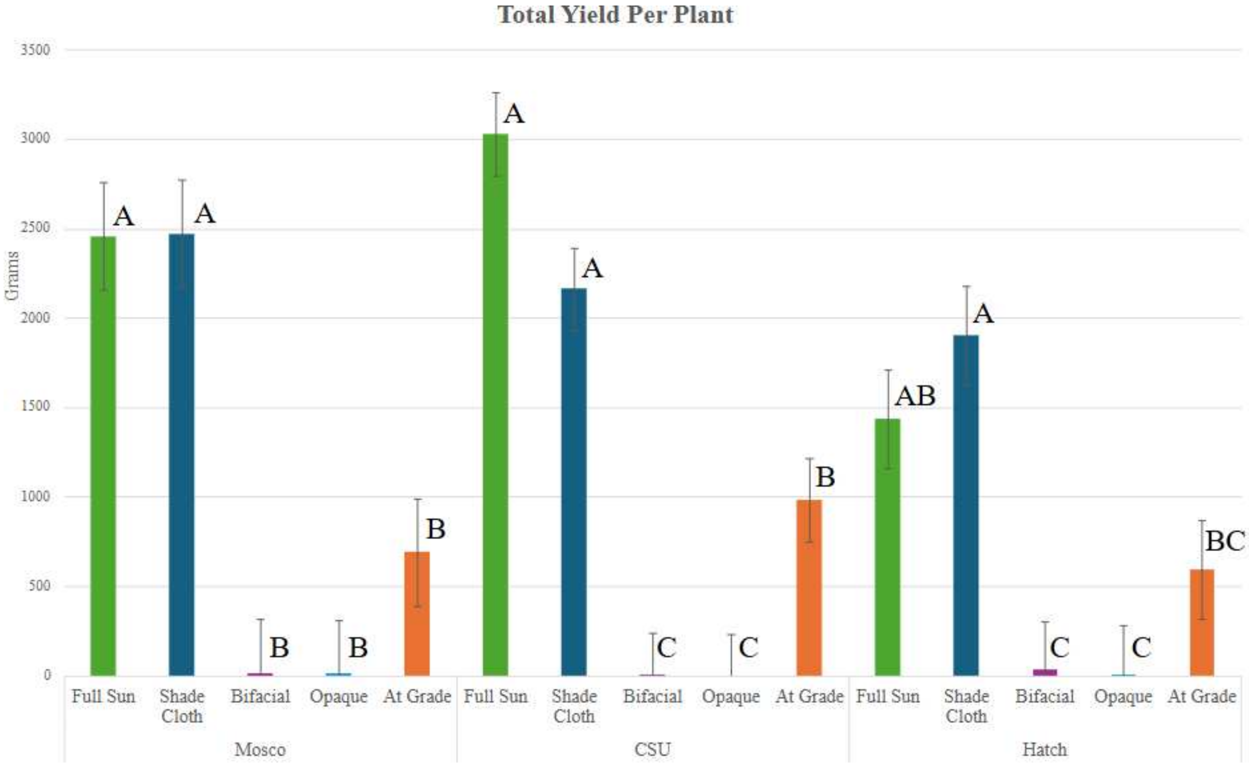


Figure 12. Comparison of the mean weight of yield within each cultivar by treatment (2024). Statistical significance ($p \leq 0.05$) from ANOVA results denoted by a difference of letters next to the error bars.

Despite drought stress causing wilting in the full sun plot in the last month and a half of the 2023 growing season, the ‘CSU’ plants continued to perform well. They continued producing quality fruit and did not seem to be as impacted by the lack of water as the ‘Mosco’ and ‘Hatch’ full sun plants though the subcategory of ‘marketable’ yield data was not collected during the 2023 growing season. ‘CSU’ plants in the full sun treatment (3,026.23g) were the only cultivar to produce higher yields than plants in the shade cloth treatment (2,160.81g) in 2024 though the difference was not statistically significant. Season 2023 had higher air temperatures in September when both the ‘Mosco’ and ‘Hatch’ full sun plants were observed wilting, but the ‘CSU’ plants were not. This information coupled with the higher yields in full sun compared to the shade cloth treatment suggests that the ‘CSU’ cultivar may be more heat and sun tolerant than the other two cultivars. Specific crop selection for RAV and green roof cultivation is key in maximizing yield.

Yield results for all three cultivars demonstrate that both in full sun and under ideal shade conditions, chile peppers can produce higher yields when grown on a green roof than at grade. For all three cultivars, the bifacial and opaque plants produced the lowest yields in both seasons, suggesting that the shade provided by the bifacial and opaque PV arrays was higher than the ideal levels for chile pepper production. The data from both years indicates that plants grown on a green roof in full sun produce more peppers than those grown in high levels of shade (>80%) on a green roof. This trend is in line with previous research demonstrating that peppers prefer more moderate levels of shade between 30%-40% and production tends to decline with higher shade levels (Ahmed et al., 2023; Díaz-Pérez, 2014; López-Marín et al., 2012; Valiente-Banuet & Gutiérrez-Ochoa, 2016). The yield results from the shade cloth plot also demonstrate the potential success that chile peppers grown in RAV could have with the use of semi-transparent PV panels.

Marketable yield data shows that for both ‘Mosco’ and ‘CSU’ cultivars the shade cloth grown chile peppers had a higher percent marketable yield weight of their total yield weight (Figure 13). ‘Hatch’ at grade peppers had a slightly higher percent marketable yield than shade cloth peppers. In all three cultivars the shade cloth grown peppers had higher percent marketable yield than their full sun counter parts. These results are generally in line with previous research showing that moderate levels of shade can increase marketable yield for peppers (Kabir et al., 2020). For all three cultivars, the bifacial and opaque plants had the lowest percent marketable yield compared to other treatments within cultivar. The ‘CSU’ peppers grown under both PV treatments did not produce any marketable yield. High levels of shade seem to reduce the marketable yield of chile peppers.

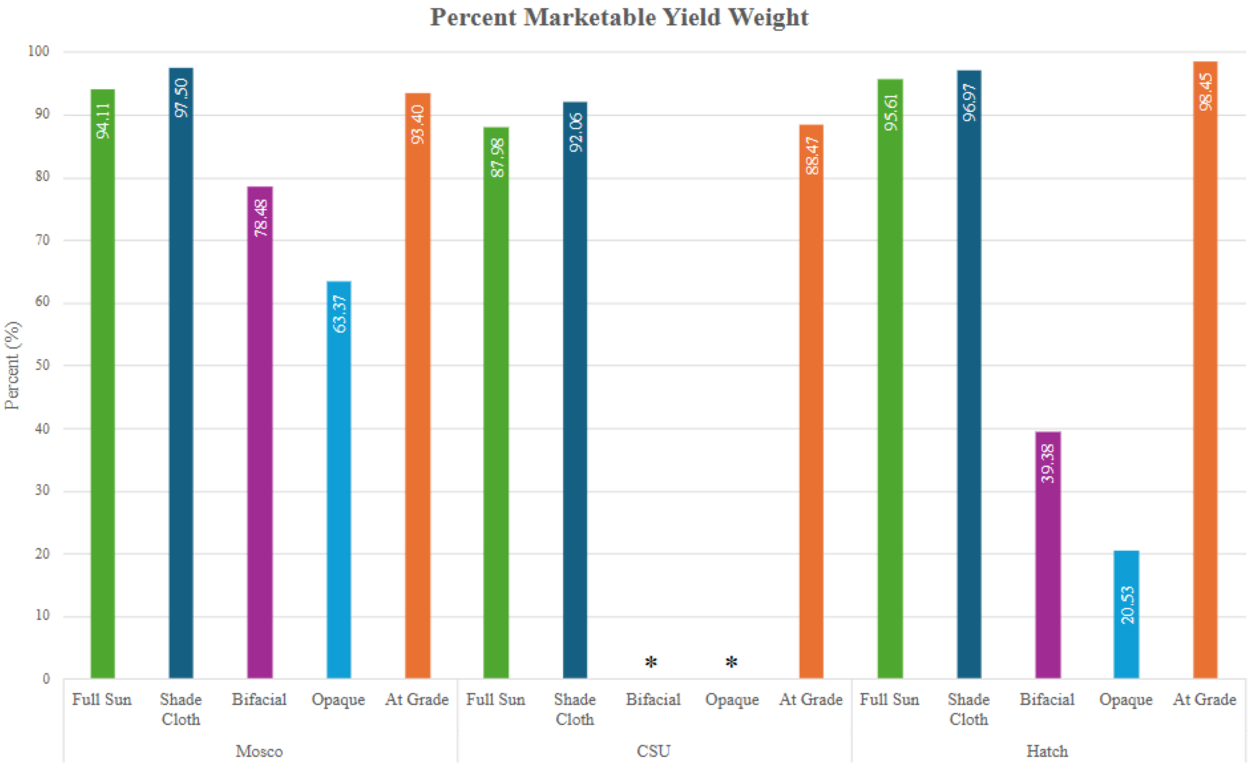


Figure 13. Percent marketable yield weight of the total yield weight for each treatment within cultivar in 2024. * Denotes zero marketable yield.

2.3.3 Plant Growth Index

PGI analysis from Season 2023 (Gross et al., 2024) does not show clear patterns of differences across cultivars and treatments (Figure 14). ‘Mosco’ bifacial peppers PGI at peak (49.6cm) and final harvest (59.9cm) was significantly higher ($p \leq 0.05$) than the full sun ‘Mosco’ peppers at both time points (41.1cm, 39.8cm respectively). ‘Mosco’ opaque peppers (25.6cm, 46.6cm, 57.9cm) had significantly higher ($p \leq 0.05$) PGI than the ‘Mosco’ full sun plants (20.4cm, 41.1cm, 39.8cm) at all three time points. The peppers may be exhibiting a shade response due to the decreased light conditions. Previous research has made similar observations that plant height increases and stem diameter decreases as the level of shade increases resulting in taller plants that are not as wind resistant (Ahmed et al., 2023). There was no significant difference in PGI between ‘Mosco’ bifacial and ‘Mosco’ opaque plants at any time point suggesting that for the ‘Mosco’ chile pepper plants the PV type did not significantly impact the PGI.

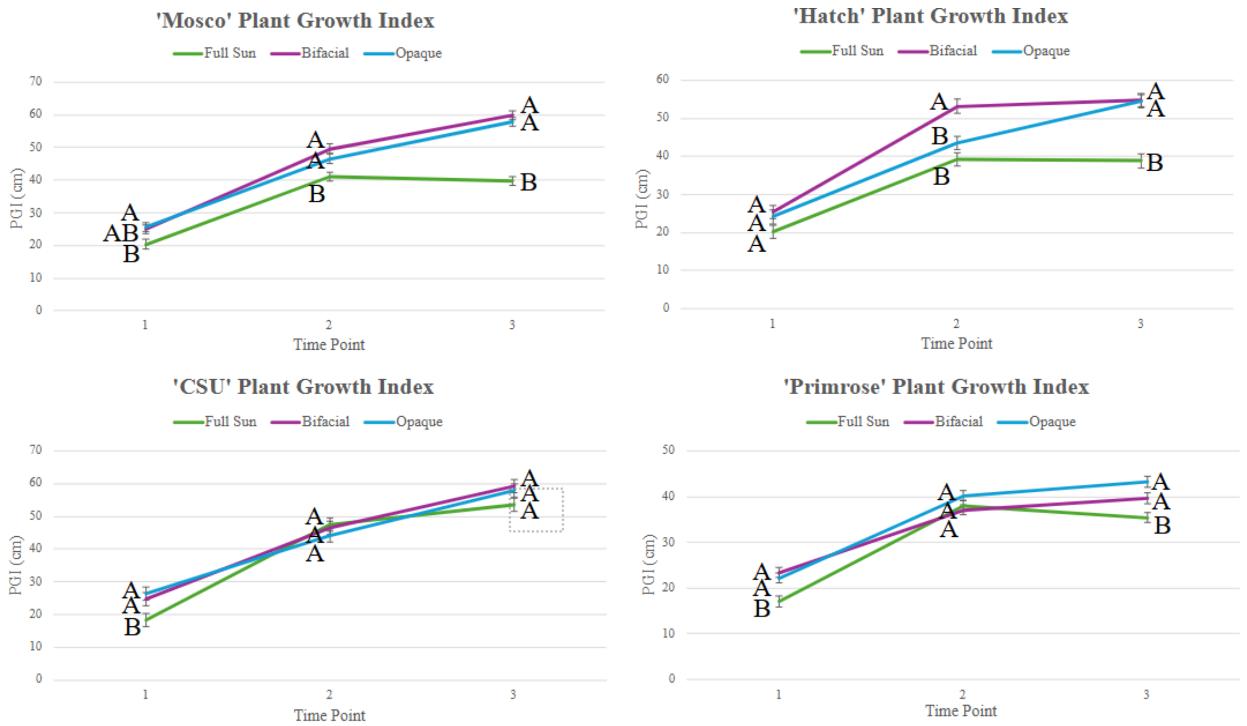


Figure 14. Comparison of means of PGI (2023) charted over three time points: 1) flower initiation (July 13, 2023), 2) peak harvest (August 24, 2023), and 3) final harvest (October 10, 2023). Statistical significance (p≤0.05) denoted by a difference of letters next to data points. The y-axis varies by cultivar to show accurate comparisons between treatments.

'Hatch' bifacial peppers PGI (53.2cm) was significantly higher (p≤0.05) than 'Hatch' peppers grown in the opaque (43.6cm) and full sun (39.1cm) treatments at peak harvest. The PGI of 'Hatch' bifacial (54.9cm) and opaque (54.4cm) peppers at final harvest was significantly higher (p≤0.05) than peppers grown in full sun (38.8cm).

The PGI of 'CSU' peppers was significantly higher (p≤0.05) in both the bifacial (24.6cm) and opaque (26.3cm) treatments than peppers grown in full sun (18.3cm) at flower initiation. However, after the wind event, there were no significant differences in PGI at the other time points across treatments. 'CSU' plants on average grow taller than the other cultivars (see Table 2), which may have made them more prone to severe lodging from the wind event. The lodging created bends near the base of the stems that formed callus tissue as plants continued growing more upright afterwards. This mechanical damage likely resulted in lower heights but did not greatly impact the width measurements as plants reached upwards for sunlight over the progression of the growing season.

The PGI of ‘Primrose’ peppers grown in both bifacial (23.4cm, 39.6cm) and opaque (22.2cm, 43.2cm) treatments was significantly higher ($p \leq 0.05$) than peppers grown in full sun (17.1cm, 35.4cm) at flower initiation and final harvest, but there was no significant difference in PGI at peak harvest across treatments.

PGI analysis from Season 2024 revealed that the shade cloth treatment resulted in the highest PGI for all 3 cultivars at all time points except for ‘CSU’ at final harvest (Figure 15). At flower initiation there was no significant difference for ‘Mosco’ peppers across all treatments. ‘Mosco’ shade cloth plants (68.2cm) had a significantly higher ($p \leq 0.05$) PGI than bifacial (49.5cm), opaque (51.6cm), and at grade plants (25.6cm) at peak harvest. ‘Mosco’ shade cloth (82.7cm) plants had significantly higher ($p \leq 0.05$) PGI than full sun (62.2cm), bifacial (64.8cm), opaque (53.0cm), and at grade plants (57.7cm) at final harvest.

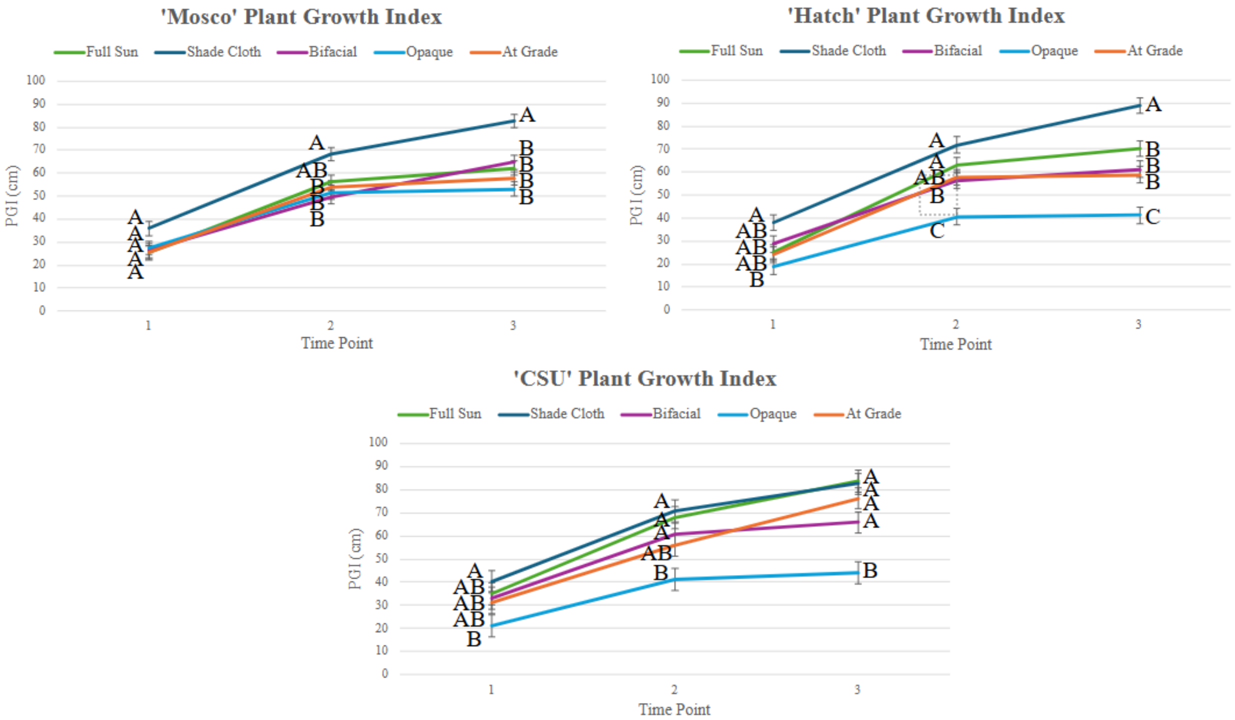


Figure 15. Comparison of means of PGI (2024) charted over three time points: 1) flower initiation (July 15, 2024), 2) peak harvest (August 27, 2024), and 3) final harvest (October 10, 2024). Statistical significance ($p \leq 0.05$) denoted by a difference of letters next to data points. The y-axis varies by cultivar to show accurate comparisons between treatments.

'Hatch' shade cloth plants (38.0cm) had significantly higher ($p \leq 0.05$) PGI than opaque plants (18.8cm) at flower initiation. At peak harvest 'Hatch' shade cloth plants (71.8cm) had significantly higher ($p \leq 0.05$) PGI than both bifacial (56.5cm) and opaque plants (40.7cm). 'Hatch' shade cloth plants (88.8cm) had significantly higher ($p \leq 0.05$) PGI than all other treatments at final harvest, and opaque plants had significantly lower ($p \leq 0.05$) PGI than all other treatments. One 'Hatch opaque plant senesced prior to the final harvest data collection for the repeated measures. Data from that individual was used in the first two time points but omitted in the third time point.

'CSU' shade cloth plants (40.4cm, 70.7cm, and 82.6cm) had significantly higher ($p \leq 0.05$) PGI than opaque plants (21.2cm, 41.1cm, and 44cm) at all three time points. There was no significant difference in PGI of ‘CSU’ plants in full sun, shade cloth, bifacial, and at grade treatments at all three time points.

While results varied in 2023, in general the full sun plants had lower PGIs suggesting that the full sun plants were more compact than their counterparts planted in the bifacial and opaque plots. This pattern did not show up in 2024. Instead, the opaque PGI was the lowest in most cases, while the full sun PGI was consistently higher than most treatments aside from the shade cloth treatment. This may be a result of differences in climate patterns as drought stress was a concern in 2023 in the full sun plot due to a hotter end of the growing season followed by much colder temps than plants experienced in 2024. Additional irrigation had to be applied to the full sun plot from peak harvest until the end of the season in order to keep the full sun plants alive.

Shading altered the growth habit of the plants in the bifacial and opaque treatments though not clearly demonstrated in the PGI alone. High levels of shade from the bifacial and opaque panels led plants to favor vegetative growth over fruit production. This led to increased height and width of the plants in Season 2023 likely to capture more sunlight (Valiente-Banuet and Gutiérrez-Ochoa, 2016). This was not as evident in Season 2024 data, which may be a result of slowed growth overall in the bifacial and opaque plots. The plants under the PV arrays had smaller PGIs in Season 2024 than in Season 2023, and they generally seemed to grow slowly especially in the first portion of the growing season.

Moderate levels of shade provided by the shade cloth in Season 2024 resulted in higher PGIs which could suggest a positive partial shade response, or it may be a result of the plants being more protected and less heat or drought stressed. Vegetative growth and fruit yield similarly increased under intermediate levels of shade in Valiente-Banuet and Gutiérrez-Ochoa (2016).

2.3.4 Biomass Accumulation

In 2023, there was no significant difference for 'Mosco' plants across treatments though the full sun plants did produce greater biomass (Figure 16). 'CSU' full sun plants (130.7g) had significantly higher ($p \leq 0.05$) biomass than plants in the bifacial (55.5g) and opaque (65.0g) treatments. 'Hatch' full sun plants (82.3g) had significantly higher ($p \leq 0.05$) biomass than plants in the opaque (50.2g) treatment but not compared to the plants grown in the bifacial (69.4g) treatment. 'Primrose' full sun plants (63.4g) had significantly higher ($p \leq 0.05$) biomass than plants in the bifacial (18.3g) and opaque (28.8g) treatments.

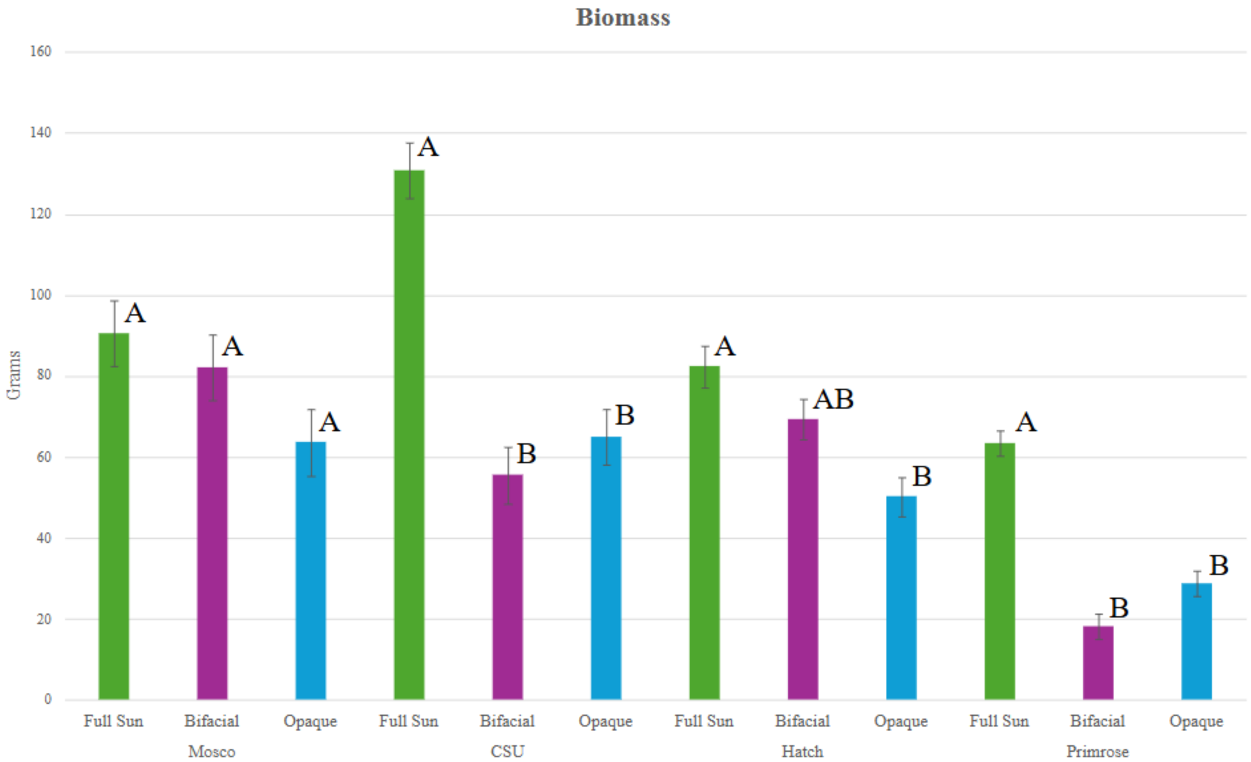


Figure 16. Comparison of means of biomass accumulation at the end of the 2023 growing season. Statistical significance ($p \leq 0.05$) is denoted by a difference of letters next to the error bars.

In 2024 the 'Mosco' shade cloth plants (364.0g) had significantly higher ($p \leq 0.05$) biomass than full sun (218.0g), bifacial (71.2g), opaque (46.8g), and at grade plants (106.3g)

(Figure 17). The 'Mosco' full sun plants had significantly higher ($p \leq 0.05$) biomass than the bifacial and opaque plants. 'CSU' full sun (345.5g) and shade cloth plants (313.5g) had similar biomasses that were both significantly higher ($p \leq 0.05$) than the bifacial (79.0g), opaque (22.1g), and at grade (145.6g) plants. 'Hatch' shade cloth plants (275.8g) had higher biomass than full sun (207.0g), though it was not statistically significant. Both 'Hatch' full sun and shade cloth plants had significantly higher ($p \leq 0.05$) biomass than bifacial (73.0g), opaque (22.7g), and at grade plants (106.3g).

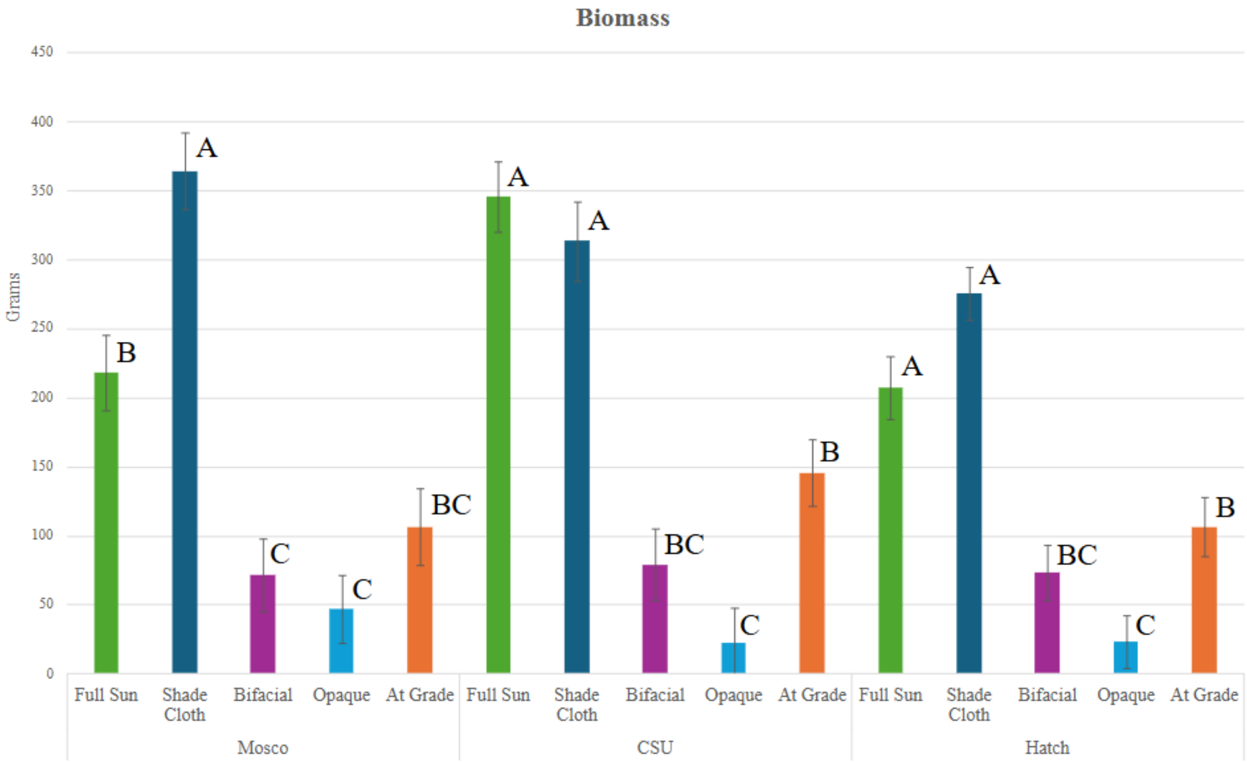


Figure 17. Comparison of means of biomass accumulation at the end of the 2024 growing season. Statistical significance ($p \leq 0.05$) is denoted by a difference of letters next to the error bars.

Across both growing seasons, it is evident that limiting light too much reduces biomass accumulation which is in line with expectations as a certain level of light is a necessary component for proper pepper plant growth (Ahmed et al., 2023; Barron-Gafford et al., 2019; Hickey et al., 2024b; López-Marín et al., 2012; Valiente-Banuet & Gutiérrez-Ochoa, 2016). PGI measurements characterize the amount of space a plant occupies, but they do not provide information on how much plant material is in that space. Biomass accumulation is important to consider when examining PGI to better understand allocation of plant energy and carbon towards vegetative growth.

Full sun plants in 2023 showed higher biomass accumulation and lower PGI generally, suggesting that they had bushier, shorter growth habits with some combination of thicker stems, more branches, and more leaves. Plants grown under the PV panels in 2023 generally had higher PGI but lower biomass accumulations. This suggests that the plants grew taller as a result of the limited light, but within the space the plant occupied, there was less plant matter. Previous research shows similar results that as shade levels increased, plant height increased but stem diameter, leaf number, and branch number decreased which would result in less biomass (Ahmed et al., 2023).

In 2024, plants grown in the bifacial and opaque plots generally had lower PGI and significantly lower biomass than full sun and shade cloth plants. This suggests that in the second year the plants were not as tall or wide compared to other treatments, and they had less plant matter within that space. It is common for plants to have thinner stem diameters and even thinner leaves as a response to too much shade, which would contribute to an overall lower biomass (Ahmed et al., 2023; Díaz-Pérez, 2013; Gross et al., 2024; Kabir et al., 2020; Valiente-Banuet & Gutiérrez-Ochoa, 2016).

Shade cloth plants across cultivars had high PGIs and high biomass suggesting that while the 40% shade may have resulted in taller plants, the stems may have been thicker, and the vegetative growth within that space was robust. Rather than a shade avoidance response, these plants may have been able to increase vegetative growth while maintaining yield production as a result of being more protected under the shade cloth.

Pest pressure from aphids in both seasons may have negatively impacted plant growth and yield in the later part of the growing season for the plants under the bifacial and opaque PV arrays. The grasshopper presence may have also impacted plants in the first portion of the growing season. Herbivory was noticed to be especially impactful in the at-grade plot and may have affected plant growth. Under the shade cloth and PV treatments, seedlings did not seem to experience herbivory. Similar observations have been documented when examining the impact of shading from PV on beet leafhopper presence (Joukhadar et al., 2024). A 55% reduction in beet leafhopper presence was found in plots shaded by a PV panel compared to full sun treatments (Joukhadar et al., 2024). This could indicate that consistent, moderate levels of shade may reduce certain pest challenges, and too much shade could exacerbate others. Future research could explore the potential impact of RAV on reducing pest challenges and pesticide use in crop production.

2.3.5 Stomatal Conductance

In 2023, full sun plants across all four cultivars had significantly higher ($p \leq 0.05$) stomatal conductance at flower initiation compared to the bifacial and opaque plants (Figure 18). This suggests that there was higher plant water use in the first part of the growing season in plants grown in full sun. Mean air temperatures in the full sun plot were slightly higher than mean air temperatures in the bifacial and opaque plots for the duration of the growing season, which may have impacted plant water use (Urban et al., 2017). Across all cultivars, there was also no significant difference in stomatal conductance at final harvest between treatments. This indicates that plant processes were likely slowing down as the growing season came to an end. This may have been a result of the temperature dropping below 2.5°C and signaling the end of the growing season, as stomatal conductance decreases as air temperature decreases (Urban et al., 2017).

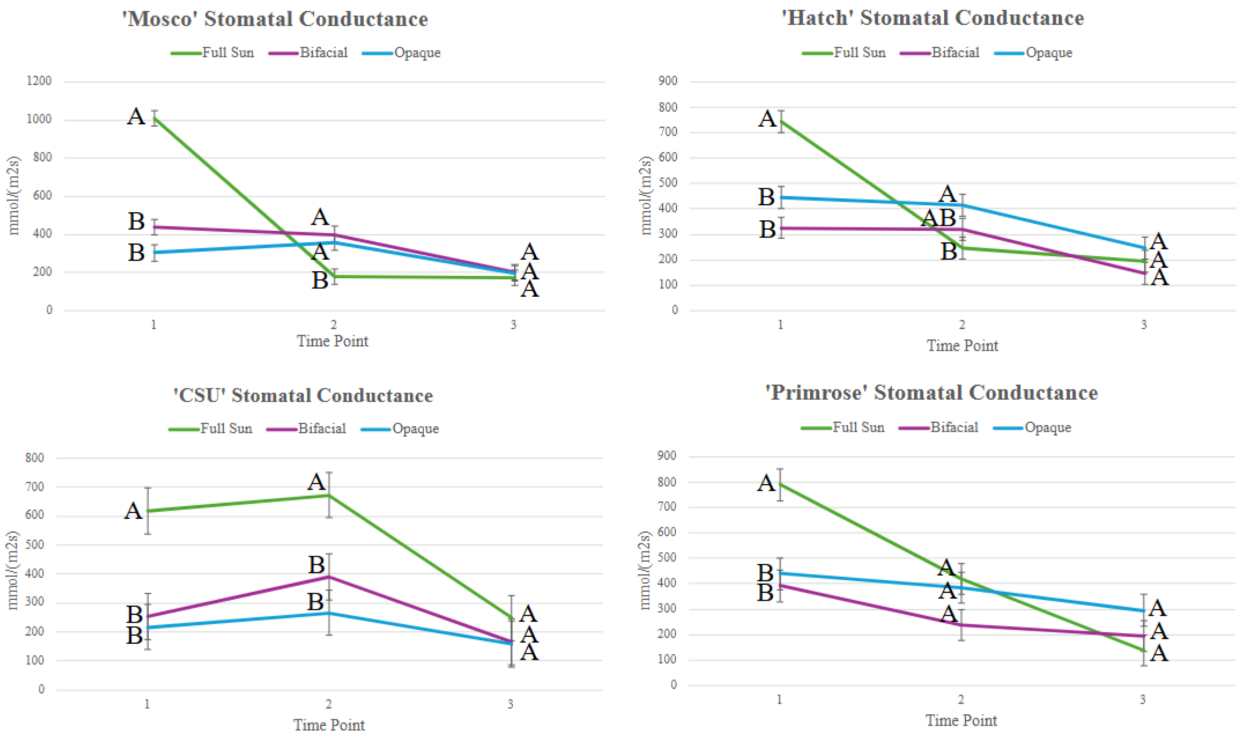
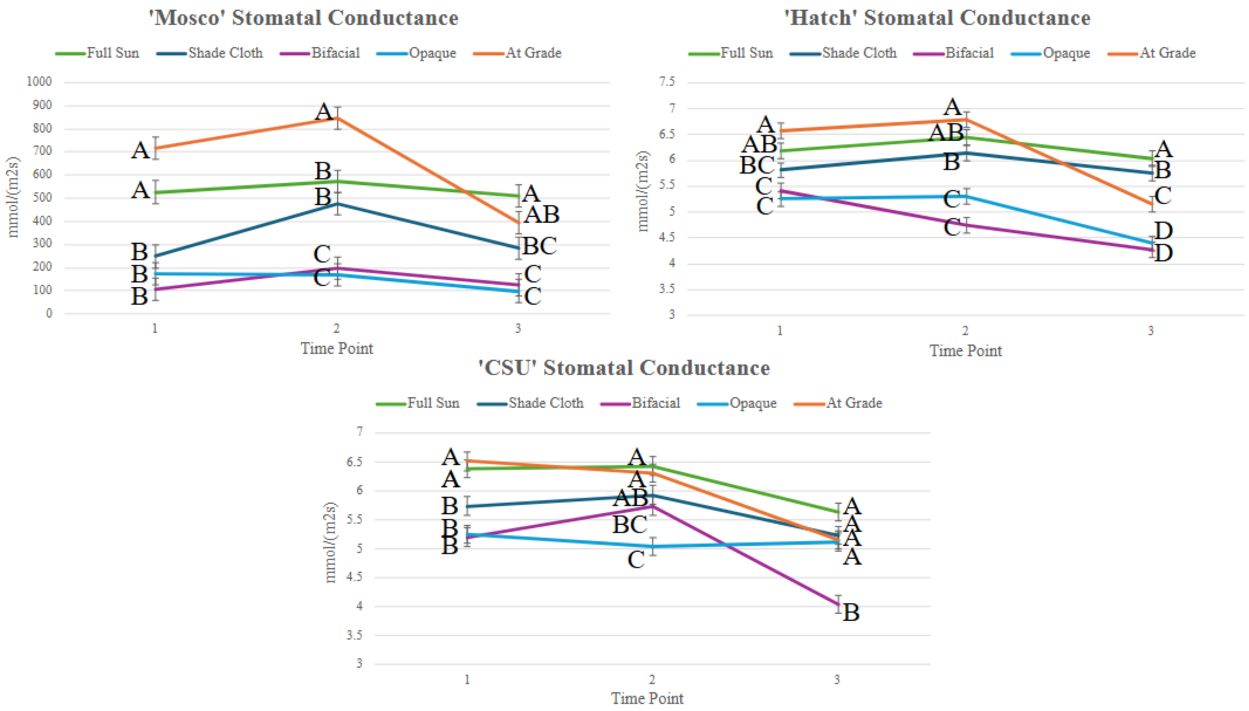


Figure 18. Comparison of means of stomatal conductance (2023) charted over three time points: 1) flower initiation (July 13, 2023), 2) peak harvest (August 24, 2023), and 3) final harvest (October 10, 2023). Statistical significance ($p \leq 0.05$) denoted by a difference of letters next to data points. The y-axis varies by cultivar to show accurate comparisons between treatments.

At peak harvest the results varied across cultivars. 'Mosco' bifacial (400mmol/(m^2s)) and opaque (356mmol/(m^2s)) plants had significantly higher ($p \leq 0.05$) stomatal conductance at the second time point than full sun plants (179mmol/(m^2s)). 'Hatch' opaque plants (415mmol/(m^2s)) had significantly higher ($p \leq 0.05$) stomatal conductance than full sun plants (245mmol/(m^2s)) but not bifacial plants (321mmol/(m^2s)). 'CSU' full sun plants (672mmol/(m^2s)) had significantly higher ($p \leq 0.05$) stomatal conductance than both bifacial (391mmol/(m^2s)) and opaque plants

(266mmol/(m^{2}s)) at peak harvest. The final cultivar, ‘Primrose’, had no significant differences in stomatal conductance at peak harvest.

The results from 2024 show that the full sun and at grade plants across all cultivars had higher stomatal conductance at flower initiation and peak harvest than the other three treatments though it was not significantly different in all cases (Figure 19). ‘Mosco’ at grade (716.4mmol/(m^{2}s)) and full sun plants (526.6mmol/(m^{2}s)) had significantly higher ($p \leq 0.05$) stomatal conductance than shade cloth (248.7mmol/(m^{2}s)), bifacial (108.7mmol/(m^{2}s)), and opaque plants (175.1mmol/(m^{2}s)) at flower initiation. ‘Mosco’ at grade plants (844.9mmol/(m^{2}s) had significantly higher ($p \leq 0.05$) stomatal conductance than all other treatments at peak harvest. At final harvest, ‘Mosco’ full sun plants (510.4mmol/(m^{2}s)) had significantly higher ($p \leq 0.05$) stomatal conductance than shade cloth (286.4mmol/(m^{2}s)), bifacial (127.1mmol/(m^{2}s)), and opaque plants (99.6mmol/(m^{2}s)). ‘Mosco’ shade cloth plants had similar stomatal conductance to the bifacial and opaque plants at the flower initiation and final harvest.


'Mosco' Stomatal Conductance

'Hatch' Stomatal Conductance

'CSU' Stomatal Conductance

Figure 19. Comparison of means of stomatal conductance (2024) charted over three time points: 1) flower initiation (July 15, 2024), 2) peak harvest (August 27, 2024), and 3) final harvest (October 10, 2024). Statistical significance ($p \leq 0.05$) denoted by a difference of letters next to data points. Log transformations were performed on both 'Hatch' and 'CSU' data to satisfy assumption of equal variance. The y-axis varies by cultivar to show accurate comparisons between treatments.

'Hatch' at grade plants (751.6mmol/(m^{2}s), 949.3mmol/(m^{2}s)) had significantly higher ($p \leq 0.05$) stomatal conductance at flower initiation and peak harvest than shade cloth (360.4mmol/(m^{2}s), 493.0mmol/(m^{2}s)), bifacial (245.0mmol/(m^{2}s), 118.3mmol/(m^{2}s)), and opaque plants (181.4mmol/(m^{2}s), 209.3mmol/(m^{2}s)). The 'Hatch' full sun plants (430.1mmol/(m^{2}s)) had significantly higher ($p \leq 0.05$) stomatal conductance at final harvest than all other treatments. 'Hatch' shade cloth plants had similar stomatal conductance as the full sun plants (496.3mmol/(m^{2}s), 645.2mmol/(m^{2}s)) at the flower initiation and peak harvest. 'Hatch' bifacial and opaque had significantly lower ($p \leq 0.05$) stomatal conductance at all three time points compared to all other treatments aside from 'Hatch' shade cloth plants at flower initiation.

‘CSU’ full sun (634.4mmol/(m^2s)) and at grade plants (676.6mmol/(m^2s)) had significantly higher ($p\leq0.05$) stomatal conductance at flower initiation compared to all other treatments. ‘CSU’ full sun (647.3mmol/(m^2s)) and at grade plants (579.4mmol/(m^2s)) had significantly higher ($p\leq0.05$) stomatal conductance at peak harvest compared to bifacial (250.7mmol/(m^2s)) and opaque plants (164.8mmol/(m^2s)). At peak harvest, ‘CSU’ opaque plants also had significantly lower ($p\leq0.05$) stomatal conductance than shade cloth plants (420.0mmol/(m^2s)). ‘CSU’ bifacial plants (56.9mmol/(m^2s)) had significantly lower ($p\leq0.05$) stomatal conductance at final harvest compared to full sun (297.3mmol/(m^2s)), shade cloth (195.8mmol/(m^2s)), opaque (174.5mmol/(m^2s)), and at grade plants (178.5mmol/(m^2s)).

The ‘CSU’ full sun plants did not seem as affected by the drought stress that the full sun plants faced in 2023. This is evident in the higher stomatal conductance suggesting that the ‘CSU’ plants were not as water limited. ‘CSU’ plants were larger with more carbon accumulation than the other cultivars (Figure 16 & 17). Plants that are more adapted for dry conditions often have larger root systems, which allow them greater access to substrate moisture (Lynch et al., 2012). ‘CSU’ plants may have had longer roots and were able to access deeper reserves of water. This could explain their suitability for intensive green roof systems. Additional research on root depth and water efficiency will be essential for green roof, AV, and RAV crop production research in the future.

The full sun plants of the other 3 cultivars see a drop in stomatal conductance at peak harvest, which was taken in the month with the hottest high temperatures (Table 3). This could indicate a lack of access to adequate quantities of substrate water as seen by decreased substrate moisture in our sensor data, so plants slowed down normal processes. We hand watered the full sun plants in the afternoon in order to keep them alive, but substrate moisture data still showed decreased moisture after spikes from the hand watering suggesting this was still not an adequate amount of water. This may be a result of the ‘CSU’ plants having greater proximity to irrigation heads or the ability of this specific cultivar to access water in the substrate in dry conditions. The data from 2023 as a whole suggests that in the first portion of the growing season, RAV can help reduce plant water use across all cultivars. This could have an important impact on agricultural systems because drought like conditions are expected to become more common as a result of climate change (Schmidhuber & Tubiello, 2007). As the season progresses, plant water use varies based on cultivar and treatment.

At the end of the 2023 season there is consistent (low) stomatal conductance levels across treatments within cultivar, while in 2024 stomatal conductance varied more across treatments and cultivars. In 2023 low temps dropped below 2.5°C while they did not drop below 4.5°C in 2024 (Table 3 & 4). Temperature impacts stomatal conductance, and the results indicate that in 2023 the plant processes had likely already slowed down as a result of that temperature drop (Urban et al., 2017).

Though the patterns of significance vary across cultivar, the results from 2024 demonstrate that plants grown in RAV have significantly lower stomatal conductance for at least a portion of the growing season compared to those grown in full sun and at grade. For most of the growing season, plants grown in RAV had lower stomatal conductance than full sun and at grade plants suggesting that growing chile peppers in RAV may reduce plant water use. This is likely related to the size and productivity of the plants as well. In Season 2024 plants grown under PV were significantly smaller in size, weight, and yield. For some plant species, size can be correlated to water use with smaller plants using less water (de Ollas et al., 2022). Future research should explore this further to examine more closely the impact of RAV on stomatal conductance throughout the season.

2.3.6 Chlorophyll Content

Analysis of the chlorophyll content data from Season 2023 shows mixed results across the different cultivars (Figure 21). Aside from the ‘CSU’ cultivar, the full sun plants of each cultivar generally had higher chlorophyll content compared to the other treatments. ‘Mosco’ full sun plants (67.6 SPAD, 67.6 SPAD) had significantly higher ($p \leq 0.05$) chlorophyll content than bifacial (52.9 SPAD, 54.3 SPAD) and opaque plants (50.4 SPAD, 54.6 SPAD) at flower initiation and peak harvest. There was no significant difference between treatments of ‘Mosco’ plants at final harvest.

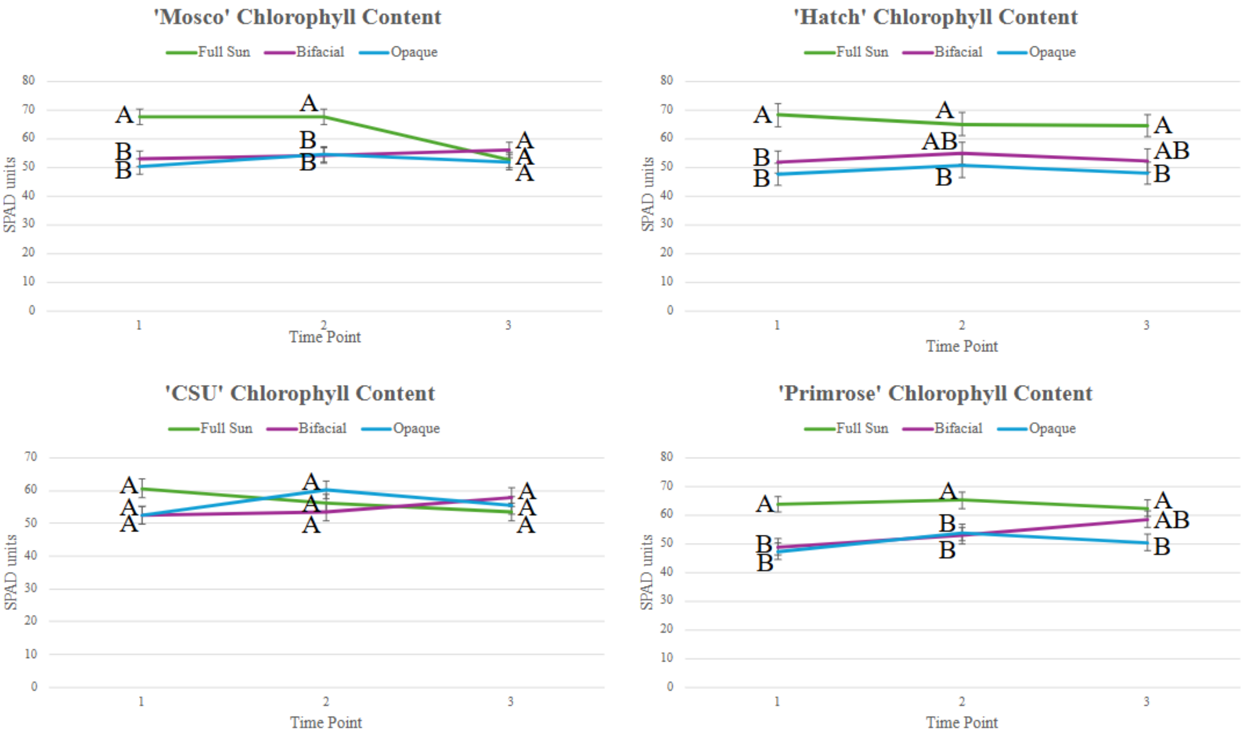


Figure 21. Comparison of means of chlorophyll content (2023) charted over three time points: 1) flower initiation (July 13, 2023), 2) peak harvest (August 24, 2023), and 3) final harvest (October 10, 2023). Statistical significance ($p \leq 0.05$) denoted by a difference of letters next to data points. The y-axis varies by cultivar to show accurate comparisons between treatments.

‘Hatch’ full sun plants (68.3 SPAD) had significantly higher ($p \leq 0.05$) chlorophyll content than bifacial plants (51.8 SPAD) at flower initiation. ‘Hatch’ full sun plants (68.3 SPAD, 65.1 SPAD, and 64.6 SPAD respectively) had significantly higher ($p \leq 0.05$) chlorophyll content than opaque plants (47.7 SPAD, 50.6 SPAD, and 48.1 SPAD respectively) at all three time points. There was no significant difference between ‘Hatch’ full sun and bifacial plants (55.0 SPAD, 52.4 SPAD) at peak and final harvest.

‘CSU’ plants had no significant difference in chlorophyll content between treatments at any of the three time points. ‘Primrose’ full sun plants (63.8 SPAD, 65.3 SPAD) had significantly higher ($p \leq 0.05$) chlorophyll content than bifacial (48.9 SPAD, 52.9 SPAD) and opaque plants (47.3 SPAD, 53.9 SPAD) at the flower initiation and peak harvest. At final harvest, ‘Primrose’ full sun plants (62.4 SPAD) had significantly higher ($p \leq 0.05$) chlorophyll content than opaque plants (50.4 SPAD) but not bifacial plants (58.6 SPAD).

As mentioned previously one ‘Hatch’ opaque plant senesced prior to the final harvest data collection in Season 2024, so data from this plant was only included for flower initiation and peak harvest. In 2024 the at grade plants from all three cultivars demonstrated lower chlorophyll content at final harvest (Figure 22). Aside from this, patterns of significance varied by cultivar. ‘Mosco’ full sun plants (56.8 SPAD, 59.3 SPAD) had significantly higher ($p \leq 0.05$) chlorophyll content than bifacial plants (48.7 SPAD, 48.7 SPAD) at flower initiation and peak harvest. ‘Mosco’ full sun plants also had significantly higher ($p \leq 0.05$) chlorophyll content than opaque (49.9 SPAD) and at grade plants (49.9 SPAD) at peak harvest. The chlorophyll content of the ‘Mosco’ plants at grade (42.4 SPAD) was significantly lower ($p \leq 0.05$) than full sun (64.4 SPAD) and shade cloth plants (58.9 SPAD) at final harvest.

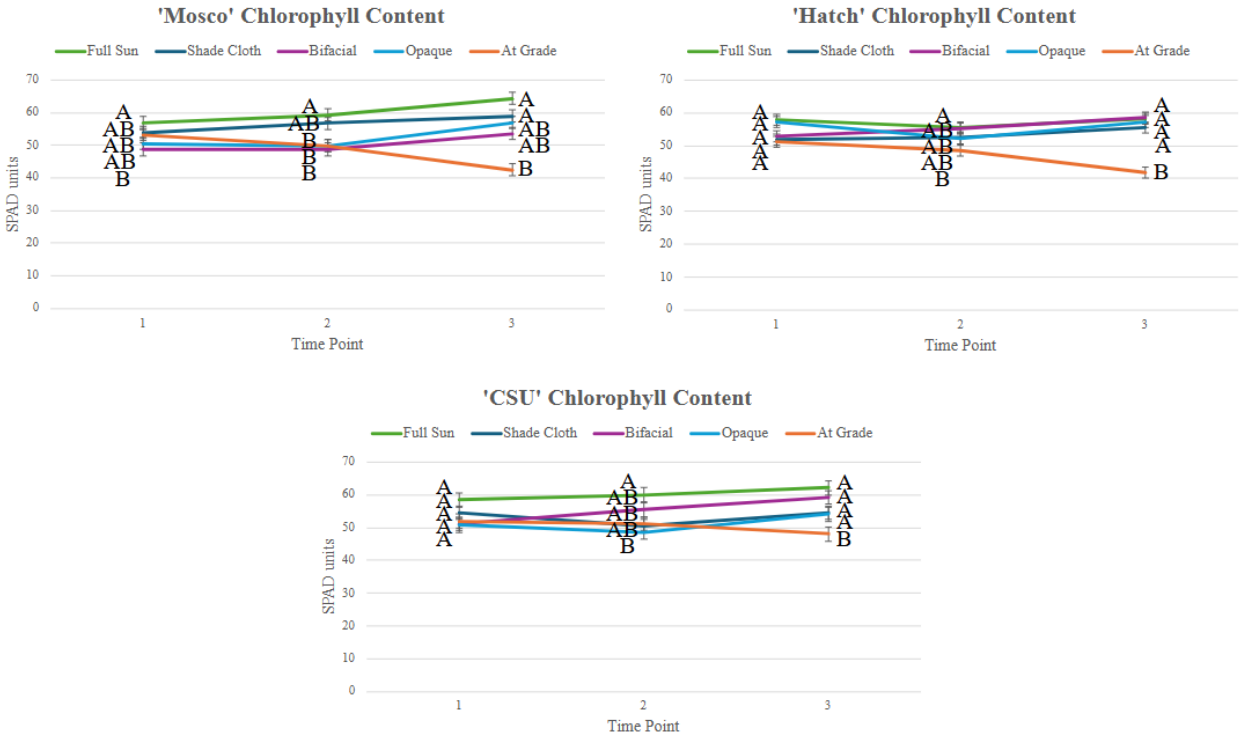


Figure 22. Comparison of means of chlorophyll content (2024) charted over three time points: 1) flower initiation (July 15, 2024), 2) peak harvest (August 27, 2024), and 3) final harvest (October 10, 2024). Statistical significance (p≤0.05) denoted by a difference of letters next to data points.

There was no significant difference in chlorophyll content for ‘Hatch’ plants across treatments at flower initiation. ‘Hatch’ full sun plants (55.6 SPAD) had significantly higher (p≤0.05) chlorophyll content than at grade plants (48.6 SPAD) at peak harvest. ‘Hatch’ at grade plants (41.9 SPAD) had significantly lower (p≤0.05) chlorophyll content at final harvest than all other treatments. There was no significant difference in chlorophyll content for 'CSU’ plants across treatments at flower initiation. ‘CSU’ full sun plants (60.0 SPAD) had significantly higher (p≤0.05) chlorophyll content than opaque plants (48.5 SPAD) at peak harvest. ‘CSU’ at grade plants (48.0 SPAD) had significantly lower (p≤0.05) chlorophyll content at final harvest than all other treatments.

Chlorophyll content is considered to be a good indicator of photosynthetic capacity and overall plant health, which can be linked to fruit production. In 2023, the chlorophyll content results indicate that the full sun plants had greater photosynthetic capacity and were healthier. The full sun yield results from 2023 support this as well. The results from 2024 do not show the same correlation between these plant metrics. While the at grade plants produced more fruit than the bifacial and opaque plants (significantly higher for 'CSU' cultivar) chlorophyll content of at grade plants was lower than the chlorophyll content in the bifacial and opaque plants. Some research shows that chlorophyll content can increase as shade levels increase though these studies were conducted in more humid environments than this study (Ahmed et al. 2023, Hassanien et al., 2022). Plants in both PV plots produced very little fruit for all three cultivars, so in this case the chlorophyll content does not seem to be correlated to fruit production.

At multiple time points the full sun plants had higher chlorophyll content than plants grown in the shade cloth, bifacial, opaque plots, which is aligned with one study that shows moderate shading of 30-40% can reduce chlorophyll content in pepper plants though not significantly (Agyemang Duah et al., 2021). There does not appear to be previous research examining the impact of a green roof growing environment on chlorophyll content of peppers so other novel environmental factors may be influencing the chlorophyll content and may be impacting the comparison to at grade plants. The results from the two years vary considerably suggesting that additional research should examine this data type more closely to better understand the impact of RAV on chlorophyll content and overall plant health.

2.3.7 Limitations

The size and orientation of the Hydro green roof was fixed, which prevented us from replicating plots of each treatment. We were not able to use semi-transparent PV in this project because they are not UL listed. We simulated semi-transparent PV by using a 40% shade cloth. The orientation of the PV arrays was predetermined for light capture and wind loading capacity rather than plant growth optimization. The shade cloth plot was added in the second year of this study so only one year of data was taken using that treatment. Another limitation of this project was that we were not able to measure the impact of this growing system on the PV panels and their efficiency.

2.4 Conclusion

Over the course of two growing seasons, results show that silicon based bifacial and opaque PV arrays provide too much shade for adequate chile pepper production and plant growth. Utilizing a 40% shade cloth as a way to mimic semi-transparent PV arrays resulted in chile peppers that produced high yields and had increased marketable yield. RAV may help reduce plant water use during portions of the growing season. Chile peppers are likely a good candidate to be grown in RAV systems that use semi-transparent panels. With this system, urban farmers may be able to produce high fruit yield and produce renewable energy in the same space that could previously only be used for production of one commodity. Future research should explore the energy capture of PV in RAV systems as well as exploring the performance of other high value crops grown in RAV.

CHAPTER 3: INVESTIGATING THE IMPACT OF GROWING ENVIRONMENT ON CONSUMER ACCEPTANCE OF ROASTED CHILE PEPPERS (*Capsicum annuum* L.)

3.1 Introduction

The progression of climate change presents new challenges for cities to face. These challenges include degradation of arable land, increased demand for food and feed, and rising rates of urbanization (Ritchie, 2019; FAO, 2009). The agricultural system is struggling to meet the current demand for food crops and will need to increase production by as much as 70% by the year 2050 (FAO, 2009). As cities look for solutions to these challenges, many are turning to green infrastructure, which can be integrated into urban areas to help reduce energy consumption, improve stormwater quality, reduce the urban heat island effect, create space for crop production, and more (Getter & Rowe, 2006; Phelan et al., 2015). Initiatives have been passed in many cities, such as the Green Buildings Ordinance in Denver, Colorado and the Sustainable Development Policy in Chicago, Illinois, that require or incentivize building green roofs on new structures (Green Buildings Ordinance Rules and Regulations, 2023; *Sustainable Development Policy*, n.d.). Green roofs are an effective way to reduce the energy consumption of the building as they act like insulation, and they can also provide thermal benefits to the environment around the building (Wong et al., 2003). Green roofs improve the quality of water runoff and air quality in the area around the building (Shafique et al., 2018).

In addition to the positive environmental impacts, green roofs create space that can be used for food crop production in urban areas where growing space on the ground is very limited. An analysis of community gardens in New York City in 2010 showed that utilizing urban areas to grow food increases food security in neighborhoods that do not have easy access to fresh produce (Ackerman et al., 2014). The Brooklyn Grange is one example of a green roof farm that produces over 45,359 kilograms of produce a year on two green roofs in New York City demonstrating the success that green roof farming can have (Brooklyn Grange, n.d.). In addition to the localized food production, green roof farming provides unique opportunities for jobs, educational programs, and community connection (Ackerman et al., 2014). Using green roofs for crop production can build resiliency into the current agriculture system by reducing the increasing pressure from climate change and supporting increased urban food security.

Though it is possible to have high levels of crop production, growing crops on green roofs can be challenging due to the unique substrate and microclimates. Green roof substrate is typically composed of lightweight aggregates with a low water holding capacity, requiring frequent irrigation for food crop cultivation (Getter & Rowe, 2006; Uchanski et al., 2023; Whittinghill et al., 2016). Most green roofs are typically extensive green roofs (<15cm deep) because of their affordability and accessibility, which further exacerbates water retention and crop selection challenges (Snodgrass & McIntyre, 2010).

Some research has explored crop suitability for green roofs. Tomatoes, beans, and cucumbers grown on an extensive green roof were able to produce yields similar to the same plants grown at grade (Whittinghill et al., 2013). Another study demonstrated that one variety of amaranthus grown on a green roof produced yields higher than nine other varieties grown at grade (Aloisio et al., 2016). Portulaca also produced high yields when grown on a green roof and is a very nutrient dense crop (Aloisio et al., 2016). With adequate nutrient input kale, lettuce, and radish can be effectively grown on a green roof as well (Walters & Stoelzle Midden, 2018). Green roofs are a viable growing environment for urban agriculture with proper management and crop selection (Whittinghill et al., 2013), however no research to date has explored the sensory acceptability of crops grown in green roof environments compared to those grown in traditional at-grade environments.

A crop that may be well suited for green roof production is the chile pepper (*Capsicum annuum* L.). Chile peppers are a high value and culturally important crop grown across the Southwest United States (Haverluck 2002; Lawrence, 2022). They are well-adapted to arid climates demonstrating heat and drought tolerance (Haverluck, 2002). Green roofs are considered water-limited environments, so chile peppers are well-suited for these environments, however it is important to understand how a green roof environment could impact crop quality.

Some research has explored the impact of different growing environments on capsaicinoid levels in chile peppers (Jeeatid et al., 2018; Jiménez-Viveros et al., 2023). Lower levels of light and higher relative humidity resulted in increased capsaicinoid production in hot peppers (*Capsicum chinense* Jacq.; Jeeatid et al., 2018). The relationship between shade levels and the phytochemical composition of peppers is complex and impacted by multiple environmental factors such as temperature, water availability and nutrient availability (Jiménez-Viveros et al., 2023). Additionally, drought stress has been shown to increase capsaicinoid levels in some chile peppers (Phimchan et al., 2012). A linear correlation has been found in other research between pungency and concentration of isolated natural capsaicinoids in sensory evaluation, (Krajewska & Powers, 1988), but more recent research demonstrates that perception of spiciness is impacted by frequency of chile consumption (Nolden & Hayes, 2017), making sensory evaluation involving capsaicinoids complex. Because green roofs are water limited and generally a higher temperature environment, this growing environment may impact the phytochemical composition and related sensory quality of roasted chile peppers. Exploring sensory attributes of roasted chile peppers in particular is a novel area of chile pepper research that could help growers and urban food industry stakeholders understand the impact of different growing conditions on consumer perception of chile peppers.

‘Hatch’ and ‘Mosco’ chile peppers are the most common chile peppers used for roasting in the southwest region of the US, and they are almost exclusively consumed after roasting though they can be consumed fresh (Brasch, 2024; Haverluck, 2002). Roasting adds smokey flavor and makes peppers easier to preserve in order to eat them year-round (Brasch, 2024; Haverluck, 2002). However, sensory research on attributes of ‘Hatch’ and ‘Mosco’ cultivars is lacking. Sensory testing has been conducted on a variety of other chile peppers, primarily fresh or preserved peppers rather than roasted (Guzmán & Bosland, 2017; Uppili et al., 2023). One study explored heat profiles (sensation patterns caused by different combinations of capsaicinoids) of 14 different chile peppers, and one of the chile peppers tested was referred to as the ‘New Mexican’ chile pepper (Guzmán & Bosland, 2017). This may be a ‘Hatch’ or similar type pepper, however, ‘New Mexican’ chile pepper can also be used to refer to a variety of other peppers that fall under that umbrella name such as ‘Sandia’ or ‘NuMex Big Jim’ (Bosland, 2015).

Sensory research related to distinct chile pepper cultivars has primarily focused on descriptive profiling rather than consumer acceptance (Guzmán & Bosland, 2017; Patel et al., 2016; Uppili et al., 2023; Yang et al., 2020). The sensory quality of roasted chile peppers is minimally understood for cultivars like ‘Hatch’ and 'Mosco' (known regionally as the ‘Pueblo chile’). Having a more nuanced understanding of consumer acceptance for specific sensory attributes of roasted ‘Hatch’ and 'Mosco' chile peppers will benefit chile pepper breeders by allowing them to develop pepper cultivars with preferred flavor profiles and encourage more urban farmers to consider growing chile peppers using green roof technology and approaches. If the growing environment provided by green roofs impacts consumer acceptance in favor of chile peppers grown at grade in native soil, it could dissuade farmers from growing chile peppers on a green roof. If green roof grown chile peppers are shown to be more flavorful and texturally appealing, it could encourage farmers to produce chile peppers on a green roof. More research is required to understand how a novel growing environment like a green roof potentially impacts consumer acceptance for commodities like chile peppers, in the form in which they are typically consumed.

We hypothesized that growing ‘Hatch’ and ‘Mosco’ chile peppers on a green roof would impact consumer acceptance for sensory attributes and overall liking in a sensory test compared to the same peppers grown at grade. The objective of this study was to assess sensory and consumer acceptability of specific sensory attributes of roasted chile peppers grown at grade and on a green roof to characterize the sensory quality of ‘Hatch’ and ‘Mosco’ chile pepper cultivars. A secondary objective of this was to assess how at-grade and green roof growing practices effect the sensory quality of chile peppers.

3.2 Materials and Methods

3.2.1 Plant and Site Description

‘Hatch’ and 'Mosco' chile peppers were grown in two treatment plots concurrent with another research project also using these chile peppers: one at-grade and the other located on a green roof at the Colorado State University Spur campus (CSU Spur) at 4777 National Western Dr., Denver CO 80216 (Gross, 2024). The site is 1609 meters above sea level (39° 47.0092’ N, 104° 58.4378’ W). Soil analysis of the at-grade plot demonstrates that the native soil has a slightly alkaline pH (7.3-7.6) and is high in organic matter (3.1-5.0). It is low in nitrogen (<5ppm) and very high in both phosphorus (>20ppm) and potassium (>280ppm). The green roof is an Intensive Garden Roof® 45.72cm deep and comprised of LITETOP® intensive agriculture blend (American Hydrotech Inc.: Chicago, IL, USA). Fruit from both cultivars in both plots were harvested weekly beginning on August 25th, 2023. ‘Hatch’ chile peppers were harvested when they were about 15.24cm long, and the 'Mosco' peppers were harvested when they were 12-16cm long.

3.2.2 Sample Preparation

Harvest data collection days were set because this study took place in conjunction with chile pepper research on rooftop agrivoltaics (Chapter 2). ‘Hatch’ peppers were harvested when they were at least 15.24cm in length, and the ‘Mosco’ peppers were harvested when they were 12-16cm in length. Only peppers free of blemishes and damage were selected for this study. Immediately after each harvest, peppers were washed and placed into paper bags and labeled by cultivar and treatment, then stored in a refrigerator (3.3°C) for three days to maintain freshness until they were roasted.

Three days following harvest, the peppers were roasted. The Lincoln CTI 2500 oven (Lincoln: Fort Wayne, IN, USA), which utilizes a conveyor belt, was set to 315.6°C and the belt speed was set to 6 minutes. This oven allowed for consistent temperature and roasting of all sides of each pepper, which is important to ensure even blistering and easier peeling (Flores & Davies, 2022). Peppers from one cultivar and one treatment were roasted at a time (Figure 23). Peppers were placed on the conveyor belt 2.54cm – 5.08cm apart.

When peppers finished roasting, they were removed from the belt using tongs and placed into a metal ‘hotel’ pan. Once all peppers from a single treatment were roasted, a lid was placed on the pan for 15 minutes to steam the peppers. After 15 minutes they were peeled manually. The tops of the peppers were removed, and a lengthwise incision was made through one wall of the pepper to remove the seeds. This process of sample roasting and preservation was done to closely follow practices used in both restaurants and homes (Brasch, 2024; Flores & Davies, 2022). Traditional roasting methods can vary from using a gas stove, an oven, or drum like chile roaster before steaming, peeling, deseeding, and preserving (Brasch, 2024, Flores & Davies, 2022; Haverluck, 2002).

Figure 23. 'Mosco' chile peppers finishing roasting on the conveyor belt.

Once all peppers for a cultivar and single treatment were peeled and deseeded, they were placed into vacuum sealed bags and labeled (Figure 24). No more than 10 peppers were placed in a vacuum seal bag. The bags were vacuum sealed and placed into the IRNOX Blast Chiller (IRNOX Professionals: Conegliano, Treviso, Italy) set at -40°C for 45-50 minutes until frozen solid. The bags were then transferred to a commercial storage freezer set to –17.8°C for storage. Traditional chile pepper processing happens in the fall across Colorado, New Mexico, and the rest of the southwest region of the United States. Roasted chiles are a key part of food culture in these regions so most are frozen or canned after roasting in order to have them for year-round cooking (Brasch, 2024).

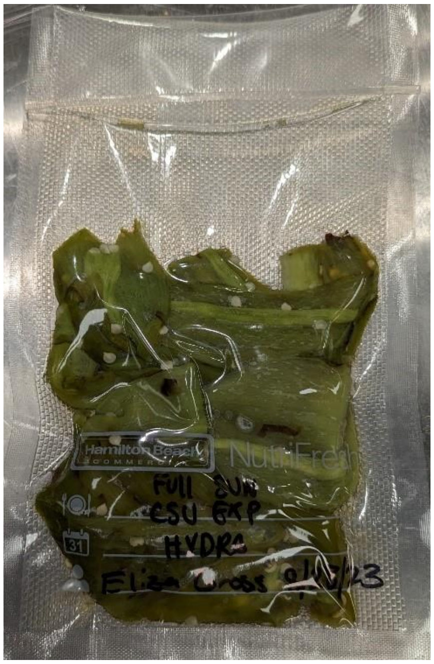


Figure 24. Roasted, peeled chile peppers in vacuum sealed bag.

All frozen roasted chile peppers were removed from the freezer 24 hours before the sensory test to thaw at room temperature. On the morning of the sensory test all the roasted chile peppers were removed from the vacuum sealed bags and chopped into 2.54cm by 2.54cm samples.

3.2.3 Sensory Test Subjects

Consumers (*n* = 62) were recruited from a database (n ~ 1800) based in the Great Denver Metropolitan (Colorado) community. In order to participate, panelists must have been 21 years of age or older, have previously consumed roasted chile peppers, and must have been comfortable smelling and tasting roasted chile peppers. Panelists were incentivized with an assortment of snacks and refreshments following participation. Informed consent was given by all consumers prior to their participation in the sensory test. All study procedures were approved by CSU’s Institutional Review Board (IRB #4887).

3.2.4 Sensory Test Evaluation

This study followed standard good practices of sensory evaluation described in Lawless and Heymann (2010). In each sensory test session, panelists were served four samples of roasted chile peppers (one from each cultivar and growing treatment, Table 1) monadically following a randomized complete block design. Sensory tests involving capsaicin from chile peppers need to account for the potential burning sensation that could cause carryover effects impacting the evaluation of the next sample (Lawless & Heymann, 2010; Stevens & Lawless, 1987). Sensitization can occur if not enough time is provided between samples, and desensitization can occur if too much time is provided (Lawless & Heymann, 2010). The ‘Hatch’ and ‘Mosco’ chile peppers are estimated to have 6,000 Scoville Heat Units (SHU) or less (Bartolo, 2014; *Hatch green mild - NM 6-4 chile seeds*, n.d.) and are considered to be mild. Based on this a 60-second time delay was enforced between evaluation of each sample for all panelists to minimize carryover effects (Ball, 1997). All samples were served in a black wineglass covered with plastic watch glasses and labeled with randomly generated 3-digit codes (Figure 25). Along with the samples, panelists were provided with a cup of water and unsalted saltine crackers to consume as needed for palette cleansing between samples (ASTM 1997, Lawless & Heymann, 2010).

Figure 25. Samples prepared for serving in black wineglasses.

Panelists were asked to evaluate the samples for attribute intensity using a Just-About-Right (JAR) scale and for overall liking using a traditional 9-point hedonic scale (Lawless & Heymann, 2010). JAR scales are commonly used in agricultural, commodity-specific research (Menezes Ayres et al., 2019; Threlfall et al., 2016; Simons et al., 2018) and are an efficient way to assess consumer acceptability and sensory attribute intensities simultaneously. In this test a five-point JAR scale was used (1 = too weak; 3 = JAR; 5 = too strong). Panelists were instructed to smell and taste each sample and evaluate the intensity of four aroma attributes (spicy, smokey, earthy, and bell pepper), sweet taste, spiciness, and the meatiness using the JAR scale. After evaluating all JAR attributes, panelists rated their overall liking of the sample on a standard 9-point hedonic scale (1 = dislike extremely; 9 = like extremely). Data was collected using Compusense software (Compusense Inc.: Guelph, Ontario, Canada).

3.2.5 Data Analysis

A one-way analysis of variance (ANOVA) and post-hoc testing (Tukey's HSD) was conducted on overall liking scores across all four samples and across growing treatments (Green Roof versus At Grade). Differences in liking across cultivars was not performed as the focus of this sensory evaluation is on the potential impact of growing environment on consumer acceptance and liking for two well established cultivars.

To analyze attribute intensities and areas for improving chile pepper quality to match consumer preferences, penalty analysis was performed using the JAR data correlated with overall liking scores. Penalty analysis indicates how attribute ratings affect sample acceptance (Lawless & Heyman, 2010).

3.3 Results and Discussion

3.3.1 Overall Liking

Analysis of the overall liking ratings show there is no significant difference in overall liking between 'Hatch' green roof (5.87) and 'Hatch' at-grade (5.71) samples (Figure 26). ANOVA results also show there is no significant difference in overall liking between 'Mosco' green roof (6.39) and 'Mosco' at-grade (5.89) samples. Additionally, ANOVA results showed no significant effect of serving order on overall liking scores, indicating that the randomized block design and 60-second enforced time delay between samples was sufficient to minimize carryover effects between samples (Lawless & Heymann, 2010).

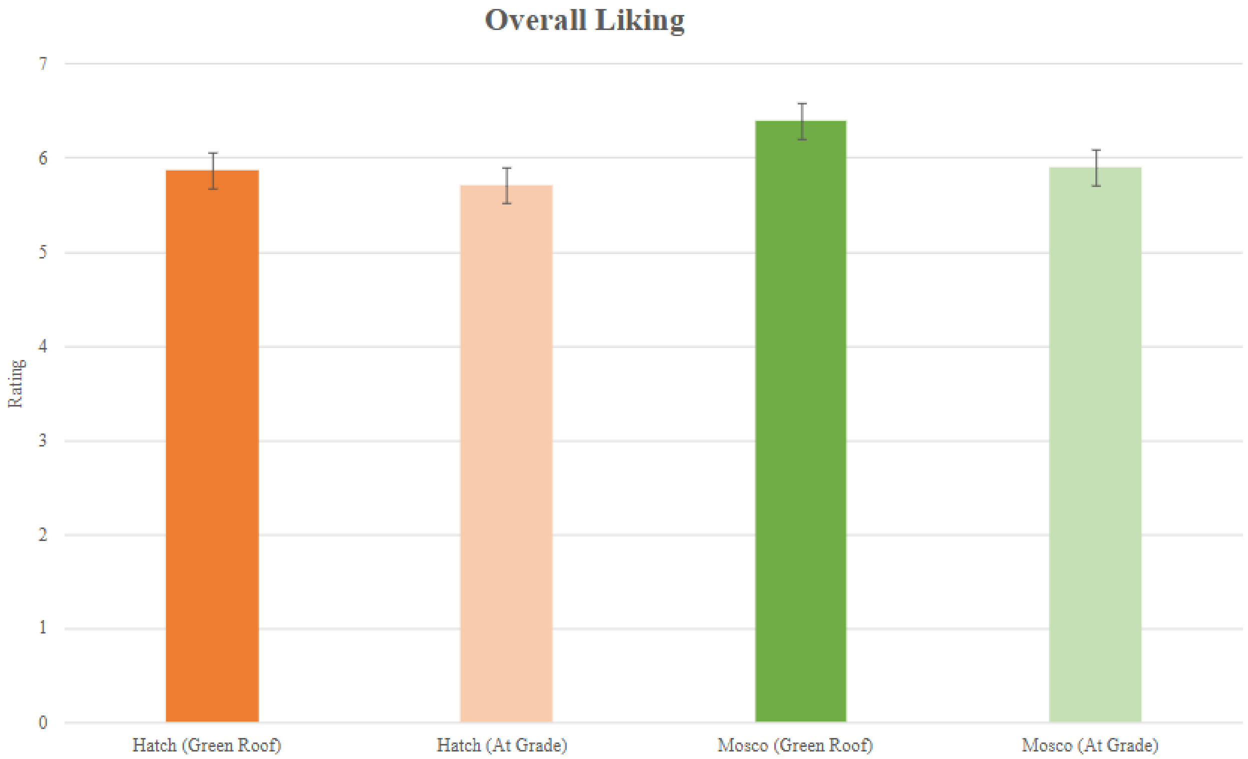


Figure 26. Comparison of the mean overall liking score from 9-point hedonic scale. ANOVA results indicated no statistical difference in overall liking between ‘Hatch’ green roof and ‘Hatch’ at-grade peppers. ANOVA results indicated no statistical difference in overall liking between ‘Mosco’ green roof and ‘Mosco’ at-grade peppers.

3.3.2 Attribute Evaluation

The results of how the seven attributes were rated by panelists are visualized (Figure 27) by percentage of ratings below-JAR (a 1 or 2 rating), at-JAR (a 3 rating), or above-JAR (a 4 or 5 rating). It is ideal to have at least 75% of panelists rate any given attribute at-JAR in consumer acceptance testing (Threlfall et al., 2016). None of seven attributes evaluated in this study meet this threshold of 75% at-JAR ratings, so all seven attributes should be examined more closely to understand how to improve consumer acceptance.

The percentage of consumer ratings for below-JAR, at-JAR, and above-JAR show that more than half of the panelists rated ‘Hatch’ and ‘Mosco’ peppers from both treatments as having a smokey aroma that was below-JAR (Figure 27A). These results reflect that panelists may desire a stronger smokey aroma in the roasted ‘Hatch’ and ‘Mosco’ peppers across both treatments. It is possible that because smokiness is commonly associated with other kinds of roasted peppers, panelists may have expected a more intense smokey aroma than what was experienced (Uppili et al., 2023). Different preparation techniques may increase smokiness to a more desired level. For both cultivars, the green roof samples had more at-JAR ratings for smokey aromas compared to the at-grade samples. Based on these results, the growing environment may have a slight effect on consumer acceptance of smokey aroma. Future research could explore how the phytochemical composition of the samples may vary and thus impact this sensory attribute.

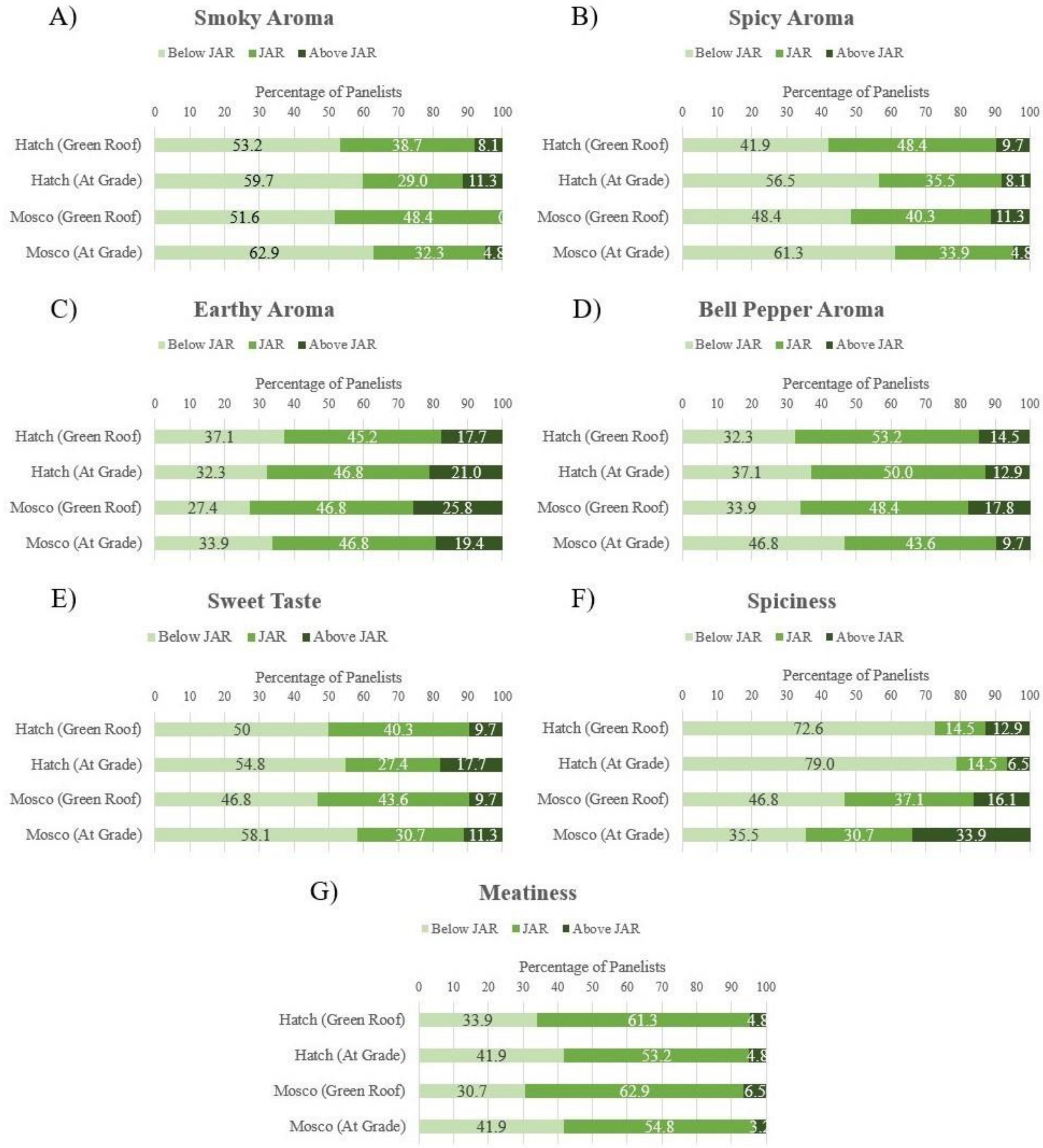


Figure 27. A-G show the percentage of panelists that rated each attribute below, at, and above-JAR.

The spicy aroma for ‘Hatch’ green roof peppers was rated at-JAR by 48.4% of panelists while 35.5% of panelists rated the spicy aroma for ‘Hatch’ at-grade peppers JAR (Figure 27B).

The spicy aroma for ‘Mosco’ green roof peppers was rated at-JAR by 40.3% of panelists, while the ‘Mosco’ at-grade peppers were rated at-JAR by 33.9% of panelists. For both cultivars, the green roof samples had higher percentages of at-JAR ratings than at-grade samples indicating that the growing environment may have impacted the experience of the spicy aroma. Future research can explore this further and seek to explore the impact of a green roof environment on capsaicinoids that contribute to spicy aromas.

The earthy aroma was rated at-JAR by a similar percentage of panelists for both ‘Hatch’ green roof peppers (45.2%) and at-grade peppers (46.8%) (Figure 27C). The earthy aroma results for both ‘Mosco’ green roof peppers and ‘Mosco’ at-grade peppers were very similar with 46.8% of panelists rating it at-JAR. Of all attributes rated, earthy aroma seems to have the most consistent results across cultivar and treatment suggesting that growing peppers on a green roof does not impact panelist acceptance of earthy aroma. Earthiness has been found in the lexicon across multiple types of peppers suggesting it is a stable, consistent attribute of peppers (Uppili et al., 2023, Yang et al., 2020). Future research may seek to explore the origin of earthiness in chile peppers and how peppers can be cultivated to increase the intensity of desirable earthy aromas.

The at-JAR ratings for bell pepper aroma by panelists were very similar across treatment for the ‘Hatch’ peppers (Figure 27D). The bell pepper aroma for ‘Hatch’ green roof peppers was rated at-JAR by 53.2% of panelists while the ‘Hatch’ at-grade peppers was rated at-JAR by 50.0% of panelists. The bell pepper aroma for ‘Mosco’ green roof peppers was rated at-JAR by 43.6.4% of panelists and for ‘Mosco’ at-grade peppers it was rated at-JAR by 48.4% of panelists. The bell pepper aroma had the highest percentage of at-JAR ratings across all aroma attributes aside from the ‘Mosco’ at-grade peppers, however, less than 75% of panelists indicated that bell pepper aroma was just right suggesting that consumers may still desire a more intense bell pepper aroma.

The sweet taste for ‘Hatch’ green roof peppers was rated at-JAR by 40.3% of panelists, and for ‘Hatch’ at-grade peppers it was rated at-JAR by 27.4% of panelists (Figure 27E). More than 50% of panelists rated the sweet taste of ‘Hatch’ green roof and at-grade peppers as having below-JAR sweet taste indicating that the ‘Hatch’ roasted chiles were not sweet enough to meet consumer preferences and expectations. The sweet taste for ‘Mosco’ green roof peppers was rated at-JAR by 30.7% of panelists, and for ‘Mosco’ at-grade peppers it was rated at-JAR by 43.6% of panelists indicating that the ‘Mosco’ peppers did not have intense enough of sweet taste.

Panelist ratings suggest a desire for a sweeter roasted chile pepper overall regardless of cultivar and treatment, and sweet taste is a common attribute associated with many different pepper cultivars (Patel et al., 2016; Uppili et al., 2023). Americans are more likely to be introduced to manufactured sweets at a young age which can impact preferences for sweetness over time (Mennella et al., 2016). Additionally, increased sweetness has been shown to increase consumer preference in sweet corn and peaches, and a similar correlation may be present with these chile peppers (Cirilli et al., 2016; Revilla et al., 2021). Exploring methods that increase the sugar content of these chile peppers may be important for chile pepper breeders to reach a more desired level of sweetness.

Spiciness for ‘Hatch’ green roof peppers and ‘Hatch’ at-grade peppers was rated as below-JAR by more than 70% of panelists who participated, and for each of the treatments only 14.5% of panelists rated them at-JAR (Figure 27F). ‘Hatch’ peppers have a SHU rating of 1,000 which is very mild (*Hatch green mild - NM 6-4 chile seeds*, n.d.). The percent of at-JAR spicy aroma ratings were higher by at least 20% compared to at-JAR spiciness ratings for these samples suggesting that the spicy aroma was more intense than then spiciness perceived on that palette once the sample was tasted. The combination of capsaicinoids present in roasted ‘Hatch’ chiles may trigger different levels of chemical responses in the nasal and oral cavities (Green, 2016; Hayes, 2016; Lawless & Heymann, 2010).

Spiciness for ‘Mosco’ green roof peppers and ‘Mosco’ at-grade peppers was rated at-JAR by 37.1% and 30.7% of panelists respectively. More panelists rated the ‘Mosco’ samples at-JAR than the ‘Hatch’ samples suggesting that the ‘Mosco’ samples have a higher and more preferred intensity of spiciness. The ‘Mosco’ peppers still did not meet the ideal 75% at-JAR ratings. ‘Mosco’ peppers have a SHU rating of 5,000-6,000 (Bartolo, 2014). The term ‘chile pepper’ refers to a wide range of peppers including peppers that are much spicier with SHU that can be up to 70,000 like the ‘Tabasco’ (*Capsicum frutescens*) cultivar (Dewitt & Bosland, 2009). Because of this, panelists may have expected a more intense spicy sensation than they experienced in both the ‘Hatch’ and ‘Mosco’ samples, resulting in more below-JAR ratings due to the mild spiciness of these cultivars.

Spiciness a sensation of irritation that can be experienced in multiple parts of the body (Cometto-Muñiz & Simons, 2015; Green, 2016; Hayes, 2016; Lawless & Heymann, 2010). Spicy sensation is a type of chemesthesis that occurs when capsaicin binds to receptors called the transient receptor potential vanilloid 1 (TRPV1) resulting in calcium entering the cell and leading to the experience of a burning sensation (Hayes, 2016; Yang & Zheng, 2017). The type of burning sensation caused by peppers can be described with many different phrases such as ‘numbing’, ‘tongue burn’, and ‘throat burn’ (Guzmán & Bosland, 2017; Uppili et al. 2023). The intensity and type of sensation that is experienced is a result of not only the capsaicinoid levels but the mixture of the different capsaicinoids (Green, 2016; Guzmán & Bosland, 2017). In addition to this the sensitivity levels of consumers to chemesthetic sensations caused by the same capsaicin levels can vary, which can impact perception of spiciness (Roukka et al., 2021). A more in-depth investigation is required to better understand the spicy sensation that is unique to roasted 'Hatch' and 'Mosco' chile peppers.

While 'Hatch' green roof peppers had more above-JAR ratings (12.9%) for spiciness than 'Hatch' at-grade peppers (6.5%), this was not the case for the 'Mosco' green roof (16.1%) and at-grade (33.9%) peppers suggesting that there is not a clear impact of the green roof environment on spiciness. Additional research should explore the phytochemical composition of the 'Hatch' and 'Mosco' peppers to better understand the impact of green roofs on specific capsaicinoid levels and the correlation to consumer acceptance of the spiciness levels.

The meatiness texture of 'Hatch' green roof samples was rated at-JAR by 61.3% of panelists, while the meatiness of the 'Hatch' at-grade samples was rated at-JAR by 53.2% suggesting that the green roof sample had a slightly more desired level of meatiness. The water limited environment and more intense heat of the green roof may have impacted the thickness of the fruit wall or the structure of the fruit (Zsófi et al., 2014). Just-about-right ratings for the meatiness texture of the 'Mosco' samples contrasted patterns across growing treatments, as seen in the 'Hatch' cultivar. 'Mosco' green roof samples were rated at-JAR for meatiness texture by 54.8% of panelists while the 'Mosco' at-grade samples were rated at-JAR for meatiness texture by 62.9% of panelists. These results suggest that environmental growing conditions do not have a consistent impact on the meatiness texture in 'Hatch' and 'Mosco' chile peppers.

3.3.3 Penalty Analysis

Penalty analysis provides information about how attribute ratings below- and at-JAR can impact the overall acceptance of a product (Lawless & Heymann, 2010). Penalties are calculated by considering the difference in liking between JAR attributes and below- or above-JAR (mean drop) and the percentage of panelists reporting scores in each category. Penalty analysis provides insight into which attributes could be improved to increase overall liking of the roasted chile peppers. Attributes in the upper right quadrant (>50% Reporting and >1 unit Mean Drop) should be focused on because those attributes have both a high mean drop and large percentage of panelists reporting in that group, which means there is a larger impact on overall liking.

The penalty analysis for the 'Hatch' samples shows that more ratings for the green roof samples have a high impact on overall liking than the at-grade 'Hatch' samples (Figure 28). The upper right quadrant of the 'Hatch' penalty analysis demonstrates there was a high impact from the ratings "too weak smokey aroma" (53.2%, 1.2 units), "too little sweetness" (50.0%, 1.9 units), and "too little spiciness" (72.6%, 1.2 units) for green roof samples. Increasing the intensity of the smokey aroma, sweetness, and spiciness may increase overall liking for 'Hatch' peppers grown on a green roof. For at-grade samples the rating "too little sweetness" (54.8%, 1.6 units) had a high impact. Panelists seem to prefer a higher intensity of sweetness across both treatments, which may be a result of Americans being introduced to sweet foods at an early age and preferring sweeter foods (Mennella et al., 2016). More exploration is needed to understand how the growing environment may have impacted consumer acceptance of these traits and how it impacts overall liking for roasted 'Hatch' chile peppers. Future research could also examine how different growing conditions could impact sugar and capsaicinoid content of 'Hatch' chile peppers.

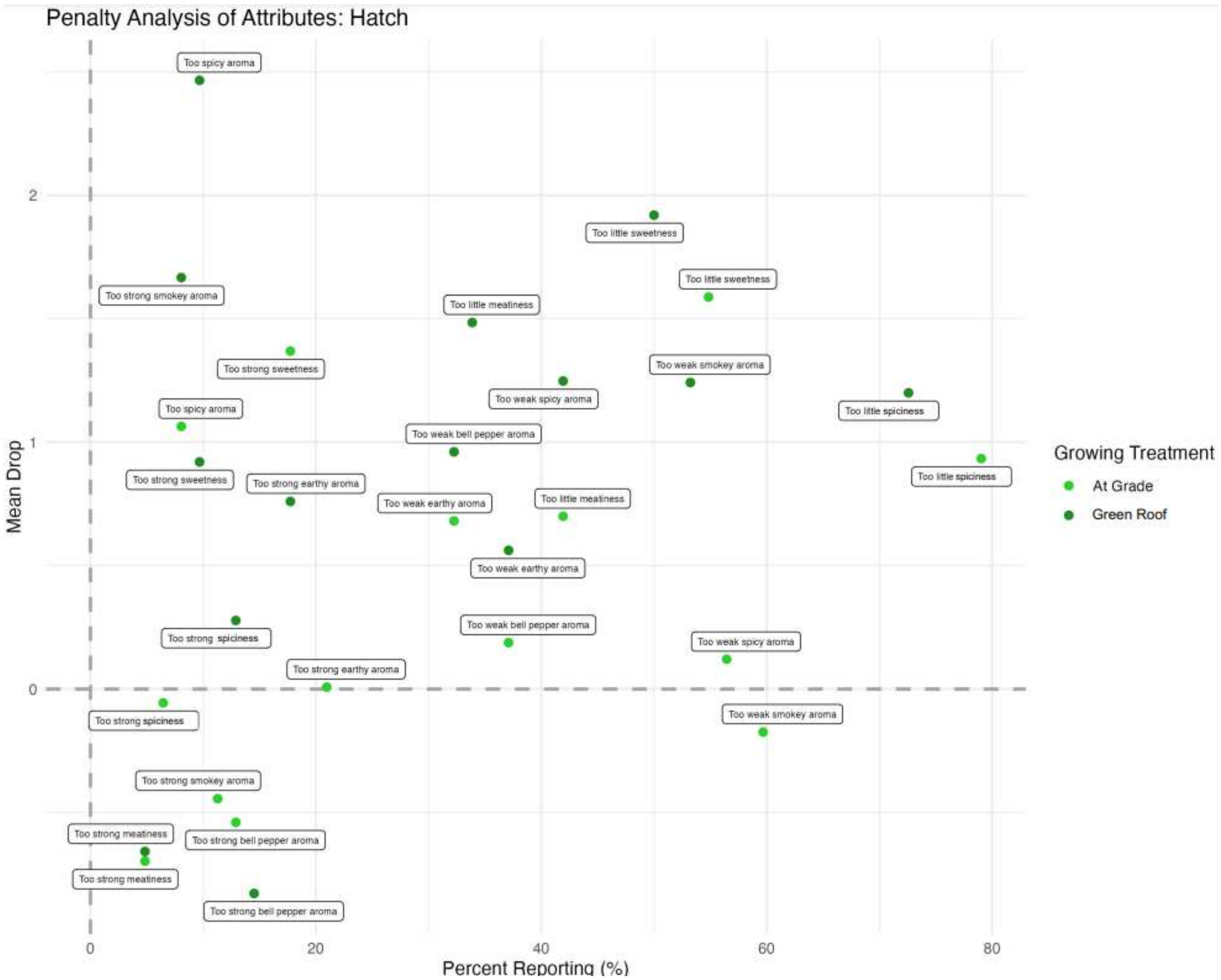


Figure 28. Penalty analysis and mean drop for ‘Hatch’ green roof and at-grade peppers. The mean drop (y-axis) is calculated by taking the main hedonic score for each group and subtracting it from the JAR group. The percentage of panelists that rated an attribute is indicated on the x-axis. Attributes in the top right corner of the plot (>50% Reporting and > 1 unit Mean Drop) demonstrate a higher impact on overall liking.

The penalty analysis for the ‘Mosco’ samples shows that only the at-grade samples had attributes with high impact on overall liking (Figure 29). The upper right quadrant of the ‘Mosco’ penalty analysis demonstrates high impact from the ratings “too little sweetness” (58.1%, 1.3 units), “too weak smokey aroma” (62.9%, 1.2 units), and “too weak spicy aroma” (61.3%, 1.2 units). This suggests that panelists would prefer sweeter at-grade ‘Mosco’ peppers with a more intense smokey and spicy aroma. The green roof ‘Mosco’ samples did not have any attributes with a mean drop >1 and more than 50% of panelists reporting. Future research could explore how the growing environment of a green roof impacts the phytochemical composition of ‘Mosco’ chile peppers to better understand the differences in consumer acceptance for sweetness, smokey aroma, and spicy aroma.

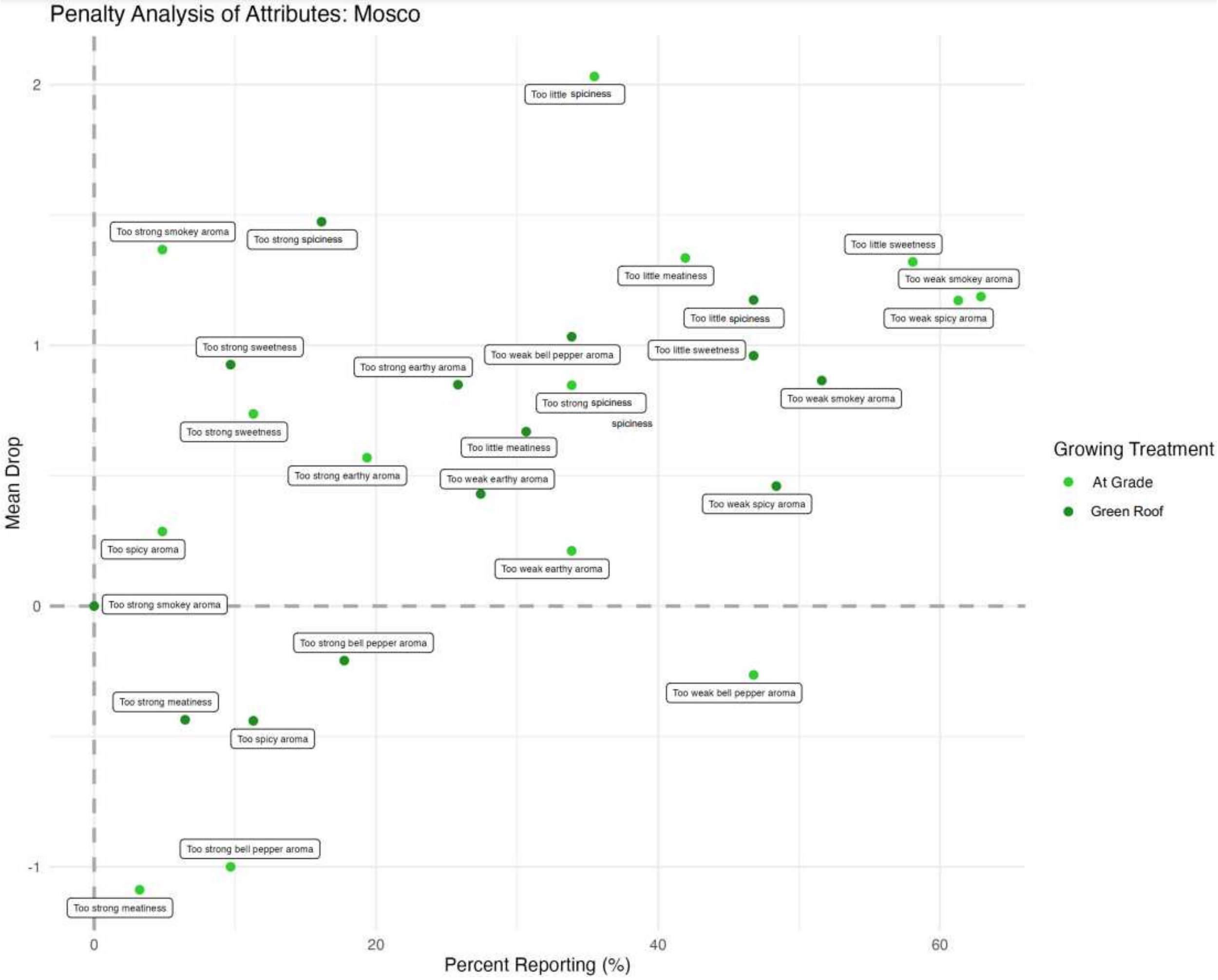


Figure 29. Penalty analysis and mean drop for ‘Mosco’ green roof and at-grade peppers. The mean drop (y-axis) is calculated by taking the main hedonic score for each group and subtracting it from the JAR group. The percentage of panelists that rated an attribute is indicated on the x-axis. Attributes in the top right corner of the plot (>50% Reporting and > 1 unit Mean Drop) demonstrate a higher impact on overall liking.

3.3.4 Limitations

Limitations of this study include panelist sample size, time, resources, and the harvesting of chile peppers over a 2-month period. Due to limited time and resources, this study was conducted over the course of one day rather than several days, limiting the number of panelists that could be included in the study. Due to timing and resource limitations, this study was not able to utilize an incomplete block design (serving less samples per panelist) or replicated evaluations (Lawless & Heymann, 2010). Although chile peppers were harvested based on minimum size and ideal color (green) over a 2-month time period, the exact ripeness of chile peppers cannot be determined without destroying the fruit. Therefore, variation in pepper ripeness may have had an impact on consumer perceptions, particularly for sweetness in this study. Attributes were selected from previous research (Patel et al., 2016; Uppili et al., 2023; Yang et al., 2020) focused on other pepper cultivars since there is not an existing lexicon for the two cultivars in our study.

3.4 Conclusion

This study explored the potential impact of two growing environments on consumer acceptance of roasted ‘Hatch’ and ‘Mosco’ chile peppers. Panelists rated samples using a 9-point hedonic scale for overall liking and a JAR scale for seven different attributes. The results demonstrated that there was no significant difference in overall liking and panelist acceptance of the various attributes based on growing environment. Panelists seemed to desire a stronger spiciness in roasted ‘Hatch’ and ‘Mosco’ peppers than provided, so urban farmers may benefit from altering growing environments to increase capsaicinoid levels. Attribute ratings of the green roof ‘Hatch’ and ‘Mosco’ peppers were correlated with a slight increase in overall liking when compared to the respective peppers grown at grade.

This study was a first exploration into sensory attributes and consumer acceptance for these peppers. JAR data from this study is nuanced and complex without many clear patterns of consumer acceptance. Future research could investigate the descriptive attributes of roasted chile peppers and build a standardized lexicon of flavor, aroma, and texture attributes in order to provide more specific and accurate language for researchers to use in future sensory studies.

Additional exploration into the impact of different growing environments on consumer acceptance of these attributes may help chile pepper breeders develop peppers that meet the expectations and preferences of consumers. It may be possible to make changes to urban growing environments such as reducing irrigation, providing shade, or using different fertilizers to intensify various attributes preferred by consumers. Research should explore the impact of these changes on consumer acceptance to support farmers in growing a highly desirable product. Results from this study show that as green infrastructure and urban agriculture expand, urban farmers can select ‘Hatch’ and ‘Mosco’ chile peppers for crop production with the confidence that growing them on a green roof will not negatively impact consumer acceptance.

CHAPTER 4: RESULTS AND FUTURE RESEARCH OF CHILE PEPPER (*Capsicum annuum* L.) PRODUCTION IN ROOFTOP AGRIVOLTAICS

Rooftop agrivoltaics (RAV) is a system that combines the use of photovoltaics (PV) with green roofs to produce renewable energy and food crops in the same space on urban rooftops. RAV has the potential to support the current agriculture system facing challenges from climate change and bringing fresh produce to food insecure populations in urban areas. Chile peppers are a suitable selection for exploring crop production in RAV due to their preference for partial shade and adaptations for hot, arid climates.

This research demonstrated that bifacial and opaque silicon-based PV provide too much shade for optimum chile pepper production in an RAV system. With these panel types, it would be best to select even more shade tolerant crops rather than chile peppers, which prefer 30-40% shade. Growing chile peppers in this RAV system resulted in a shade response with low plant biomass and reduced yield. A 40% shade cloth was used to simulate semi-transparent PV in the second season. Chile peppers grown under the shade cloth had optimum plant growth metrics as well as high yield production suggesting that chile peppers are a suitable crop to be grown in a semi-transparent RAV system. Yield production was high for all cultivars in both the full sun and shade cloth plots suggesting that chile peppers are a good selection for green roof crop production. Water use was reduced in the shade cloth, bifacial, and opaque plots compared to the full sun and at-grade plots for at least a portion of the season suggesting that RAV could reduce irrigation requirements of chile peppers. Chlorophyll content of chile peppers was generally highest in full sun, however the results in other treatments were mixed over the course of two growing seasons. We observed that pest pressure was reduced in the shade cloth plot suggesting that moderate levels of shade could reduce incidences of pests and therefore the need for pesticides.

Future research should explore how chile peppers perform in an RAV system with semi-transparent PV to understand if the results seen in this simulated semi-transparent PV environment are similar. Stomatal conductance results can vary by time of day and climate, so additional research could examine stomatal conductance and plant water use more closely to better understand the impact of RAV on irrigation requirements of chile peppers. Chlorophyll content is an indicator of photosynthetic capacity, which is connected to fruit production. The results in this study are mixed regarding chlorophyll content based on different shade treatments and fruit production. More research is needed to further characterize chlorophyll content and to understand how RAV impacts this plant metric. RAV may be a more suitable for some chile pepper cultivars compared to others based on different adaptations to shade and drought, so more exploration could focus on testing different cultivars to select optimum cultivars for RAV. Finally future research could investigate how moderate levels of shade can impact the presence of different pests, thus potentially reducing the need for pesticides.

The just-about-right (JAR) sensory evaluation conducted on ‘Hatch’ and ‘Mosco’ roasted chile peppers grown at-grade and on a green roof demonstrated that there was no significant difference in overall liking between treatments for each cultivar. These results provide urban farmers with the confidence to select both ‘Hatch’ and ‘Mosco’ chile peppers for green roof cultivation. Seven attributes were evaluated on a JAR scale and none of these attributes were rated at-JAR by 75% of panelists. This suggests that the panelists preferred or expected a higher intensity of each of these attributes, or that the attributes were not the best attributes to describe these specific roasted chile peppers. For some attributes, the green roof sample of each cultivar received more at-JAR ratings than the at-grade sample of the respective cultivar, suggesting that the green roof growing environment may have affected the panelist acceptance of these attributes.

Future sensory research could explore creating a lexicon for ‘Hatch’ and ‘Mosco’ roasted chile peppers. The attributes selected for the sensory evaluation were found in previous research on other types of peppers because previous sensory research was not found for ‘Hatch’ and ‘Mosco’ peppers. Creating a lexicon for these specific peppers would provide future researchers with the proper language to use in sensory evaluations moving forward. Phytochemical composition of fruit can be impacted by different growing environments, so it would be useful to explore this in conjunction with sensory evaluation of ‘Hatch’ and ‘Mosco’ roasted chile peppers to better understand the impact of the different growing environments on consumer acceptance. It may provide more insight into the increase of at-JAR ratings for green roof grown samples compared to at-grade samples for certain attributes. Finally, exploring consumer expectations of chile peppers could be key to better understanding preferences for spiciness in these roasted chile peppers since the term ‘chile pepper’ can refer to many different chile peppers with a wide range of spiciness.

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