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Impact of Crops on the Microclimate and PV System Performance

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ABSTRACT:

Faced by land constraints, Singapore needs to look for viable options to bolster renewable energy consumption whilst trying to prop up local food production. Agrivoltaics is seen as a feasible method where hydroponic farming is integrated underneath solar photovoltaics (PV) systems on a common land. This study aims to investigate the impact crops have on the microclimate and whether it contributes to enhanced PV performance. Situated in the SIT@Dover campus in Singapore, the agrivoltaics setup consists of two identical plots, Plot A and Plot B. Each plot consists of twenty solar panels, erected at a height of 2.5m. Beneath the panels contain two hydroponics growth tables, each capable of housing 180 pots of crops. A HOBO External Temperature/RH Sensor Data Loggers were installed 30 cm above each of the growth tables to record data at 5 min logging intervals. A HOBO U30 USB Weather Station Data Logger records meteorological data at intervals of 5 min. Plot A (control) was intentionally left without crops while Plot B was sowed with 90 *Brassica oleracea* var. *sabellica* pots (50% capacity). The *Brassica oleracea* var. *sabellica* was left to grow in the hydroponics system and harvested on the 32nd day of the crop cycle. Microclimate and energy yield data from the 31st day of the crop cycle were analysed. The 12-h mean temperature from 0700hrs to 1900hrs revealed that the *Brassica oleracea* var. *sabellica* on Plot B reduced the temperature above it by 0.97°C as compared to Plot A. The 12-h mean relative humidity tabulated for Plot A and B was 67.45% and 72.30% respectively. During overhead conditions from 1100 hrs to 1300 hrs, Plot B saw the microclimate temperature lowered by 1.33°C as compared to Plot A while the relative humidity elevated by 6.81% as compared to Plot A. The increase in relative humidity is attributed to the transpiration experienced by the *Brassica oleracea* var. *sabellica* during photosynthesis which shows that plants have the potential to induce cooler microclimatic conditions. The solar PV on Plot B generated 4.36% lesser energy yield as compared to Plot A. The difference is attributed to uneven irradiance captured by the plots due to building shading caused by the morning sun. Cooler microclimate temperature on Plot B does not contribute to improved PV performance primarily due to the large gap between the growth tables and the underside of the solar panels which encourages sufficient convection to take place.

Keywords: Agrivoltaics, Photovoltaics, Microclimate, Crops

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Introduction

With a land area of 725.1 km² (DataGov.Sg, 2023) Singapore faces land scarcity, limiting the number of solar panels it can install in its urbanized landscape. Singapore minimised this constraint by successfully implementing the SolarNova programme which drove solar panel installations on rooftops of residential housing, also known as the Housing Development Board (HDB). It achieved its target of 350MWp in the first quarter of 2020.
Singapore imports over 90% of its food given its limited resources (SFA, 2023). Given that the vast majority of food is imported, Singapore constantly faces a threat of food shortage as a result of food disease outbreaks overseas or changing political landscape in neighbouring countries (SFA, 2023). With the prevalence of COVID-19, the global supply chain has been severely disrupted and has amplified Singapore’s urgency to safeguard its food security. The Singapore Food Agency (SFA) is taking pre-emptive measures to boost local food production to reduce over-reliance on food imports. It aims to produce 30% of its nutritional needs by 2030 through various initiatives such as Research & Development (R&D) grants which enable researchers to study and develop urbanised solutions to suit to Singapore’s use case. The SFA launched a public tender on 23rd February 2021 for seven sites on multi-storey carparks (MSCP) in several HDB estates (SFA, 2023). These sites will be host to vegetable farming and other crops. Previously in September 2020, SFA had launched nine sites for urban farming on MSCPs.

With Singapore’s ambitions to ramp up clean energy and local food production, agrivoltaics is seen as a potential solution to synergise food and energy production on a common plot of land. However, the efficacy and optimal design of the agrivoltaics system for ideal crop quality is an unknown. The study seeks to measure and to investigate the impact crops have on the microclimate and whether it contributes to enhanced PV performance.

Methodology

To investigate the impact of growing crops on the microclimate and whether it contributes to enhanced PV performance. The agrivoltaics was setup with two identical plots, Plot A (Control) and Plot B (*Brassica oleracea* var. *sabellica*).

Beneath the solar panels contain 2 hydroponics growth tables. Plot A (Control) was intentionally left without crops while Plot B (*Brassica oleracea* var. *sabellica*) was sowed with 90 *Brassica oleracea* var. *sabellica* pots (50% capacity). The seedlings were transplanted into the agrivoltaics system on the 8/11/2021 and the matured crops were harvested 4 weeks later on the 10/12/2021.

Two HOBO External Temperature/RH Sensor Data Loggers were installed above each growth table, one at the height of 1m from ground and the other logger was installed at the height of 2m from the ground. Each loggers record data at 5 min logging intervals. A HOBO U30 USB Weather Station Data Logger records meteorological data at intervals of 5 min.

Solar PV Setup

The PV system forms one of two crucial sub-systems which form the agrivoltaics system **Figure 1**.

At a 5° west-facing tilt and elevation of 2.5m from the concrete platform, the 16 kWp solar PV system spans across two plots: Plot A(left) and Plot B (right), capturing solar irradiance from the sun and converting into electricity. The PV system comprises of 40 solar modules with 4 strings of 10 modules each. Each module is connected to a power optimizer which maximises the performance of each module under shading. The gap between Plot A and Plot B is 2m.

A Huawei FusionSolar system was setup to provide new generation string inverters with smart management technology to create a fully digitalized smart PV solution for our agrivoltaics system. The smart PV panel systems are setup to cover the entire crop's growing bed at a height of 2.5m above the ground. The Huawei Solar Inverter would help to record daily data such as PV output, Total Energy consumption, Consumed from PV(kW) and Irradiance(W/m2).

Figure 1: 16kWp Solar PV system across Plot A (L) and Plot B (R)

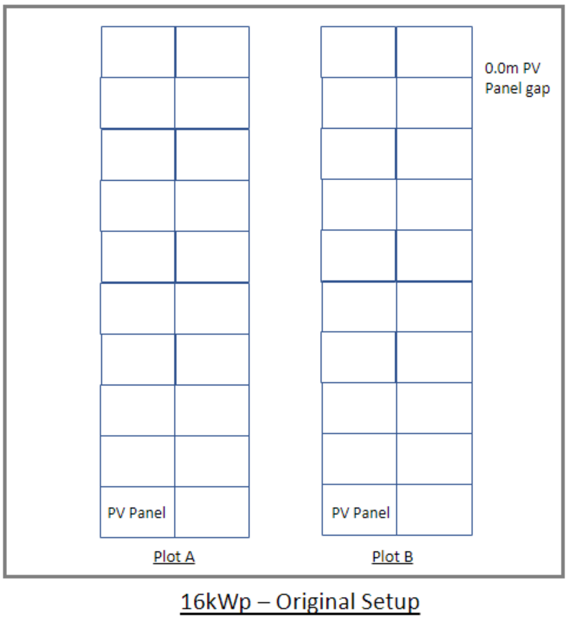

Figure 2: Layout of all the PV panels configurations for Plot A and Plot B (Top View)

Hydroponics Setup

The hydroponics system forms the other sub-system to complete the agrivoltaics setup. Unlike conventional soil-based farming, hydroponics technology makes use of nutrient solution to grow crops (Jones, J.B, 1997). The Nutrient Film Technique (NFT) technology is implemented for this setup to grow the crops. NFT incorporates the continuous flow of chilled water mixed with nutrients in gutters to deliver and facilitate the absorption of essential nutrients through the roots of crops. The nutrient solution depth is typically maintained between *1 to 2 mm* in the gutter by varying the flow rate of the nutrient solution. **Figure 3** is a simplified visualization of the NFT gutter cross-section. **Figure 4** is the NFT bench setup in SIT@Dover agrivoltaics site.

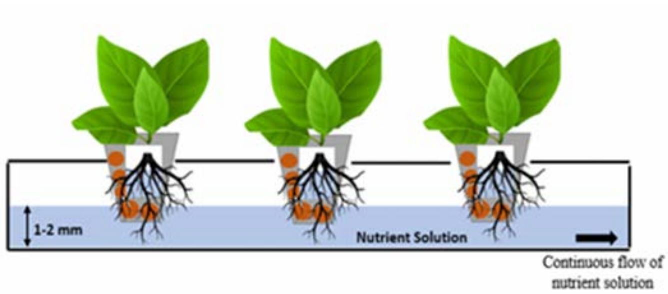

Figure 3: Nutrient Film Technique (NFT) visualization

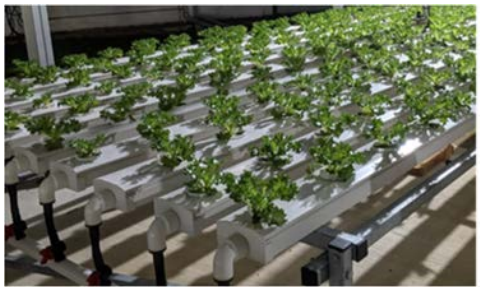

Figure 4: NFT bench in SIT@Dover

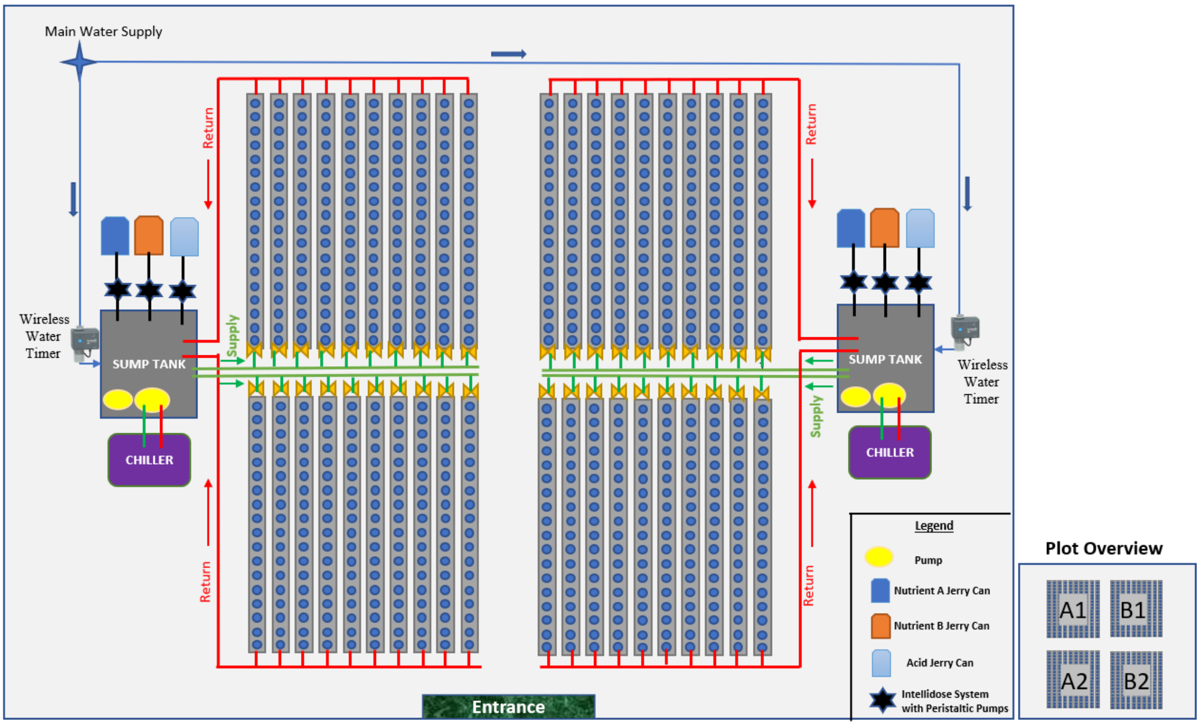

Figure 5: Hydroponic system diagram

Microclimate Sensors

The agrivoltaics setup consist of many sensors such as temperature and relative humidity sensors (TRH). Table 1 shows the overview of the Microclimate sensors used. **Figure 6 and 7** show the overview of the TRH sensors.

A HOBO Temperature/RH Data logger measuring instrument was setup in the centre of each plot where the data logger would be surrounded by growing crops. The loggers are placed at a height of 1m and 2m from the ground and above the crop's growth tables.

Table 1. Overview of Microclimate Sensor

Sensor	Specifications	Parameter/s	Purpose
HOBO External Temperature/Relative Humidity Sensor Data Logger (MX2302A)	▪ Accuracy: +/- 0.2C° and +/- 2.5% Relative Humidity ▪ Range: -40 to 70°C ▪ Resolution: 0.02°C	Temperature (°C) & Relative Humidity (%)	Measures the microclimate ambient temperature and humidity at different heights (1m & 2m)

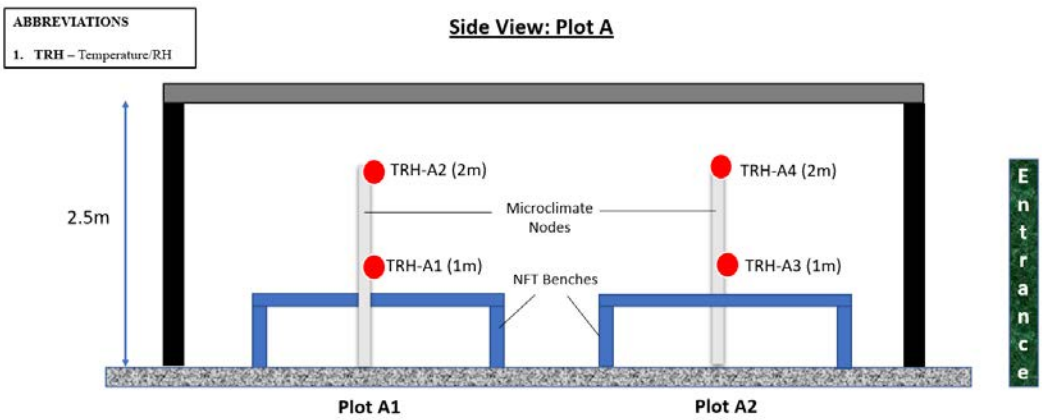

Figure 6: Layout of all the Measurement Sensors design configurations for Plot A (Side View)

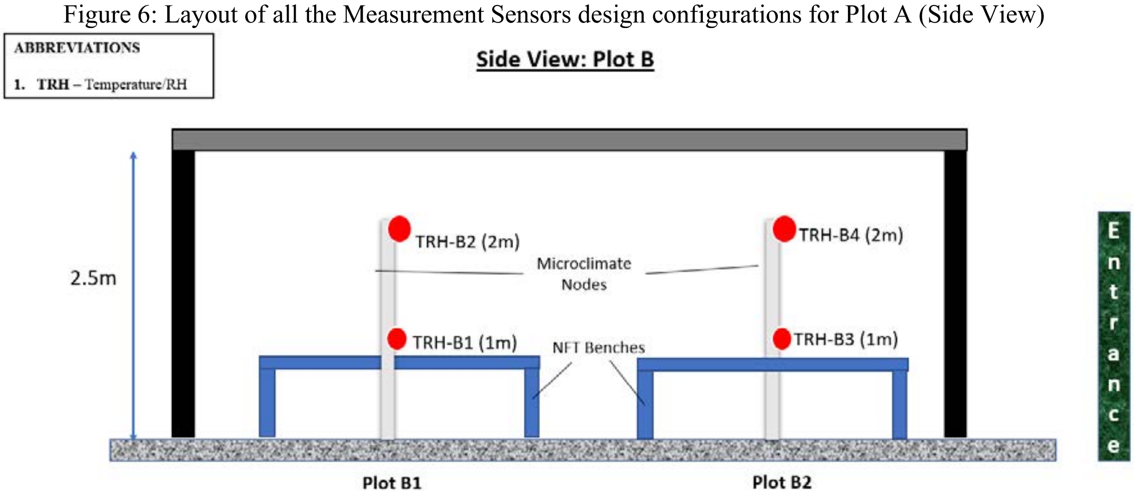

Figure 7: Layout of all the Measurement Sensors design configurations for Plot B (Side View)

Results and Discussion

This section discusses and analyses the recorded data on the 4th week of the experiment and during the period of 0700 – 1900 hours daily when natural daylight is available and maximum transpiration is in progress.

In order to have the best data comparison between Plot A (Control) and Plot B (*Brassica oleracea* var. *sabellica*). The authors have decided to use the data collected on the 4th week (03/12/2021 – 10/12/2021). This is because on the 4th week, the crops are near its full-grown size with maximized leaf size as they are near their harvest date. With the leaf size at its maximum, we will be experiencing maximum transpiration process during the last week of the experiment. Therefore, we will be able to identify and compare the microclimate in Plot A (Control) and Plot B (*Brassica oleracea* var. *sabellica*) to see if it contributes to enhance PV Performance.

Microclimate Analysis

Throughout the experiment, it has been observed that the average temperature of Plot A (Control) has been higher than Plot B (*Brassica oleracea* var. *sabellica*) for both TRH sensors recorded at the height of 1m and 2m from the ground. However, it is also observed that the difference in the average temperature between Plot A and Plot B recorded at the height of 2m from ground is significantly lesser.

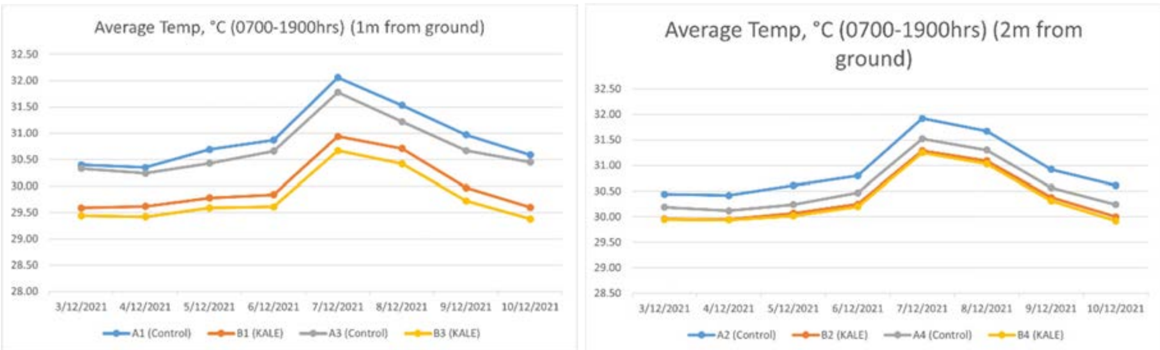

Figure 8: Average Temperature of Plot A(Control) V.S Plot B (Brassica oleracea var. sabellica).

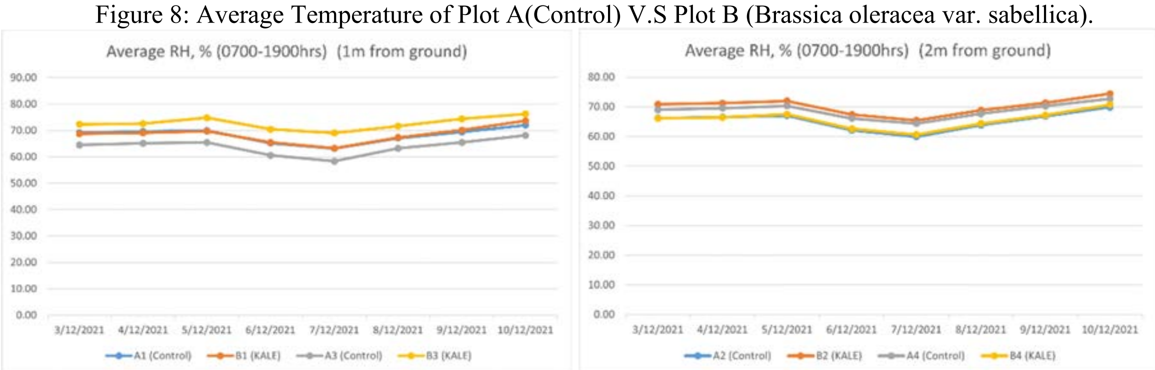

Figure 9: Average RH of Plot A(Control) V.S Plot B (Brassica oleracea var. sabellica).

In contrast with the results from table 8. Table 9 seems to show that the average relative humidity at the height of 1m from the ground and at the height of 2m from the ground are very close. With only slight noticeable differences is the average relative humidity recorded at the height of 1m from the ground.

PV Performance Analysis

The pattern and trend of the energy yield between Plot A (Control) vs Plot B (*Brassica oleracea* var. *sabellica*) was observed to be highly similar. However, it was observed that the energy yield during the period of 3/12/2021 to 10/12/2021 for Plot A was 206.72 kWh and Plot B (*Brassica oleracea* var. *sabellica*) was 200.40 kWh. Plot A (Control) has a slightly more energy at 6.32 kWh during the 8 days period.

Corresponding to the findings from the energy yield data. A similar trend was observed for the average temperature and relative humidity data collected at the height of 2m from ground which is also the closes sensors to our PV panels. It was observed that the average temperature and the average relative humidity for Plot A (Control) and Plot B (*Brassica oleracea* var. *sabellica*) was very similar with insignificant differences as compared to the average temperature and relative humidity data collected at the height of 1m from the ground where the microclimate recorded significant differences near the crops growing bed in Plot B (*Brassica oleracea* var. *sabellica*), recording lower average Temperature and a higher relative humidity than Plot A (Control).

The findings suggest that the average temperature and relative humidity seem to normalize to the surrounding environment as the microclimate rises from 1m to above 2m from the ground. This would have result in little to no impact on the performance of the PV panels setup at 2.5m from the ground. For this instance, both Plot A and Plot B will not be experiencing any significant increase in overall energy production as none of the Plots recorded any significant reduction in temperature base on the data.

It was also observed that the site location was selected within the campus which is surrounded by adjacent taller buildings that could be one of the external factors that could have some form of influence in the total solar yield data collected.

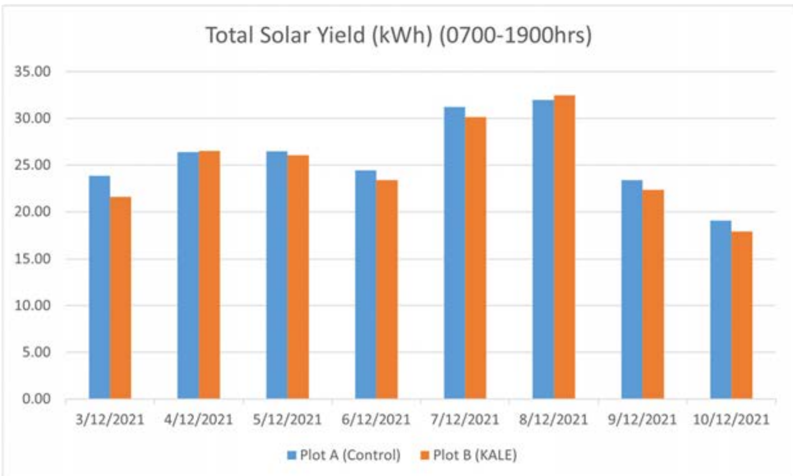

Figure 10: Total Daily Solar Yield(kWh) Plot A(Control) V.S Plot B (Brassica oleracea var. sabellica).

Solar Module Efficiency

Corresponding with the earlier results collected, the solar module efficiency (Table 2) seeks to affirm that the growing crops has little to no noticeable effect on the agrivoltaic system efficiency.

It is to note that due to the absence of the irradiance sensor on plot B, the ratio method is adopted to have an estimate of the actual irradiance for Plot B.

$$Efficiency\ (\%) = \left[\frac{Yield}{Input\ Energy}\right] x\ 100\% \qquad (1)$$

$$Input\ Energy\ (kWh) = Irradiation\ (kWh/m^2)\ x\ 40\ m^2. \qquad (2)$$

Table 2. Solar Module Efficiency - Plot A vs Plot B

	Output			Input			Efficiency	
Date	Yield - Plot A (kWh)	Yield - Plot B (kWh)	Ratio (A/B)	Irradiation (kWh/m²)*	Input Energy (kWh) - Plot A	Input Energy (kWh) - Plot B [ESTIMATED BASED ON RATIO]	Efficiency - Plot A (%)	Efficiency - Plot B (%)
3/12/2021	23.83	21.61	1.10	3.95	158.00	152.47	15.08	14.17
4/12/2021	26.38	26.52	0.99	4.42	176.80	170.61	14.92	15.54
5/12/2021	26.47	26.05	1.02	4.43	177.20	171.00	14.94	15.23
6/12/2021	24.42	23.37	1.04	4.03	161.20	155.56	15.15	15.02
7/12/2021	31.21	30.14	1.04	5.32	212.80	205.35	14.67	14.68
8/12/2021	31.97	32.47	0.98	5.46	218.40	210.75	14.64	15.41
9/12/2021	23.38	22.36	1.05	3.99	159.60	154.01	14.65	14.52
10/12/2021	19.06	17.88	1.07	3.17	126.80	122.36	15.03	14.61
Total / Average	206.72	200.40	1.04				14.88	14.90

Limitations

This study demonstrated the positive influence of the *Brassica oleracea* var. *sabellica* on the parameters of the agrivoltaics microclimate however there were no notable effects on PV performance. One of the limitations of this study was the fixation of the PV elevation at 2.5m which meant that the system's height could not be tinkered with to introduce additional experiments to conduct the experiments at varied heights. Additionally, the PV panels are installed at a 5° west-facing tilt (sunlight exposure) allowed ample sunlight for the crop's growth(based on Daylighting simulations). However, optimum crop growth required shading, and this led to our subsequent study of the effect of PV gaps on crop growth (Data was not included in this report). Lastly, more plant species (Jericho lettuce and Thai basil) with varying leaf areas could be sowed into the agrivoltaics system to ascertain the correlation between leaf area and the extent of influence on the microclimate parameters in our subsequent report.

Conclusion

In line with our government's goal to be 30% self-sustaining by 2030, *Brassica oleracea* var. *sabellica*(cold-hardy vegetables) was selected this experiment. This is because we would like to test out the feasibility of growing crops that are not typically grown in our tropical climates in our agrivoltac system.

In this experiment, the results have clearly shown that the growing crops in Plot B does have a positive impact on its microclimate. The average temperature record at 1m height from ground was significantly lower in Plot B as compared to Plot A at the same height.

However, the pattern and trend of the average temperature and relative humidity recorded at the 2m from the ground **Figure 8 and Figure 9** suggested that the positive microclimate impact from Plot B will gradually fade and normalize with the surrounding environment as it continues to rise.

Corresponding with the average temperature and relative humidity recorded, the solar module efficiency (Table 2) has reaffirmed that due to the vast amount of space between the crops growing bed and the PV panels, the microclimate from Plot B (*Brassica oleracea* var. *sabellica*) had little to no impact on enhancing the PV performance.

However, to provide a different and potentially more comprehensive perspective in terms of understanding the actual moisture exchange between the crops and the environment while helping to monitor the water requirements of our crops, we will be measuring the Absolute Humidity (AH) for our subsequent report.

Acknowledgement

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