Research Article

Investigations on Agrophotovoltaic System Using Different Crops with Special Attention on the Improved Electrical Output

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Abstract
In an Agrophotovoltaic (APV) system, the same plot of land is used for both agriculture and power production. APV systems are currently being investigated for thermal control of solar PV modules using natural transpiration cooling by cultivated crops. The current research focuses on the experimental studies on a 1 kWp APV and 1 kWp reference system with two different crops cultivated beneath the solar PV modules; an experimental setup was designed and built in Nagpur, India. Two crops, *Spinacia oleracea* and *Solanum lycopersicum* (Spinach and Tomato, respectively), were grown below 50% of PV modules, and the thermal and electrical performance of the solar plant was investigated as an APV system. The performance of this APV system was compared with the remaining 50% of PV installation. During this study, the effect of crop height on the performance of the solar plant was also investigated. According to the experiments, the temperature of the solar PV modules in the APV system with Tomato and Spinach was reduced by about 5 °C and 6 °C, respectively, when compared to a reference solar PV system. Additionally, the power plant's production is higher when there is less space between the solar PV module and the crop. To predict the performance of the APV system for any given location and for any given crops a systematic analytical procedure has been formulated. This experimental study shows that for the spinach and tomato crops, a 1 MW APV system would produce 169200 kWh and 187500 kWh more electricity yearly than a reference solar PV plant, respectively. Additionally, the same piece of land would give a comparable crop yield along with improved power generation.

Keywords: Agrophotovoltaic, Agrivoltaic system, Crop cultivation, Green energy, Solar photovoltaic module

1 Introduction

Solar photovoltaics is the most competitive option for electricity generation today, and it is being rapidly explored in every corner of the globe [1]. The standardized manufacturing technique, competitive pricing, and active government support have resulted in large-scale PV deployment around the world. [2] However, a new challenge—a severe land-energy conflict—is envisioned in the near future, leaving aside the other challenges like PV system's high cost, low efficiency, and recycling or disposal. [3] The solution to this problem could be to combine the production of electricity and agriculture on the same plot of land with an agrivoltaic system. Agrivoltaic System refers to the use of land for both agriculture and electricity generation (APV) [4].

Although the concept of an agrophotovoltaic system has been understood for more than 20 years, its real penetration in society, especially in India, is low as a result of a lack of research on numerous elements and a lack of awareness [5]. The research work reported in the literature mainly focused on giving the proof of concept of the APV system [6], [7], few researchers have focused on the prediction of the APV system performance by using various simulation tools like Radiation Interception model and STICS Crop models [8], system advisor model (SAM) [9], PVSyst [10], GECROS – Generic crop growth simulator model [11], CFD package software [12], etc. The simulation studies mainly focused on the prediction of crop growth in the partial and full shade in the APV system [11]. A few studies examined the impact of environmental parameters [13] and microclimatic conditions [12] on the efficiency of agrophotovoltaic systems.

The experimental work on the APV system is also mentioned in literature. These experimental works include the performance analysis of the APV system with the cultivation of crops below PV modules [14], cultivation in inter-row spaces [15], cultivation in the greenhouse covered with the transparent PV modules, straight-line [16] and checkerboard pattern of the solar modules [17], using bifacial PV modules, etc. However, these experimental works mostly focus on the overall crop growth and the yield of the crops in the APV system. Moreover, the majority of the studies were conducted in a few countries like, Italy, France, Japan, South Korea, the United States and China and very insignificant work had been reported in India. Another aspect of the APV system is its inherent thermal control potential of the PV plant by means of evapotranspiration cooling effect of the cultivation. This thermal management of PV modules in APV system is not explored sufficiently in previous studies. Therefore, the present work focused on the experimental performance analysis of the Agrophotovoltaic system with widely used polycrystalline PV modules in the Indian Climatic condition using two popular and widely used crops i.e. Spinach and Tomato respectively. The experimentation was carried out for a 1 kWp Agrophotovoltaic system with the mentioned two crops, the thermal and electrical performance of the Agrophotovoltaic system was considered for the different crop heights. Furthermore, the performance of the plant was estimated using the appropriate theoretical analysis and using machine learning techniques.

2 Materials and Methods

A systematic methodology was utilized to examine the Agrophotovoltaic system's performance under various operating circumstances. Figure 1 depicts the entire methodology used in this study. A thorough literature review was conducted to learn more about PV systems, factors influencing their performance, mounting structures, typical cultivation and farming practices; agriculture in shade, shade tolerant plants, Agrophotovoltaic systems and their classification, and so on. A detailed literature study was reported in [18] by the authors. Two crops were chosen for the experimental study based on the literature review; the experimental setup was designed and installed. The experiments were carried out to compare the electrical and thermal performance of the Agrophotovoltaic system to that of reference PV and open sky farming. Based on the findings, a comprehensive predictive model was created that can be used to calculate the

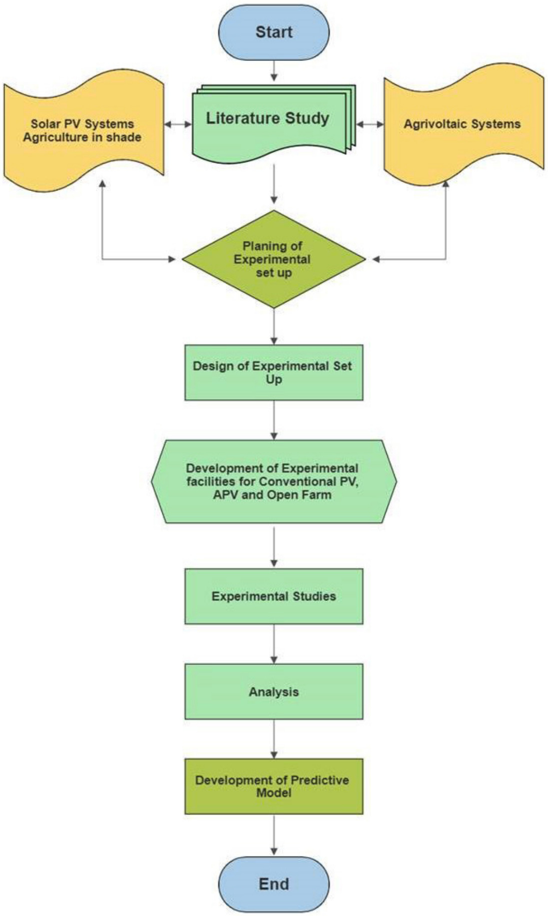

Figure 1: Methodology adopted in the study.

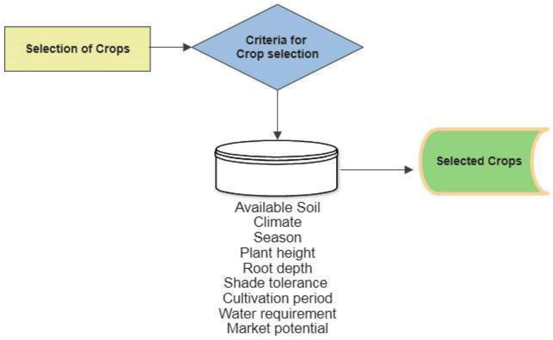

Figure 2: Methodology for crop selection adopted in the present study.

Agrphotovoltaic system's power production for any given location for the chosen crop. Each step's specifics have been covered in Figure 1.

2.1 *Selection of crops for APV system*

Literature reports several criteria for choosing crops suitable for Agrophotovoltaic systems [18]. Some of the major criteria that were followed in the present work are shown in Figure 2. Based on these criteria the two crops were selected for the experimental study in the present work, as shown in Table 1.

Table 1: Details of the crops selected in the present study [19], [20]

Details	Name of the Crop	
	Spinach	Tomato
Requirement of Sunlight	Low moderate	Low moderate
Requirement of Soil	Well-drained, loam	Sandy loam to clay, black soil
Plant height	8–12 Inches	10–18 Inches
Growing period	90 days	70 days

2.2 *Planning of APV farm*

As per the literature study, the different arrangements of APV plants include the cultivation of crops in the inter-row module spacing beneath the module greenhouse APV, Semitransparent PV modules, regular non-transparent PV modules, straight-line pattern, checkerboard pattern, etc. After the thorough literature study, some of the aspects of the APV farm planning were identified and followed as shown in Figure 3.

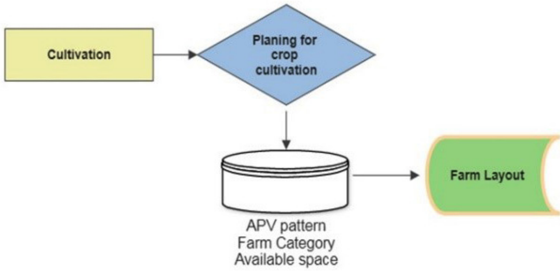

Figure 3: Methodology adopted for farm planning.

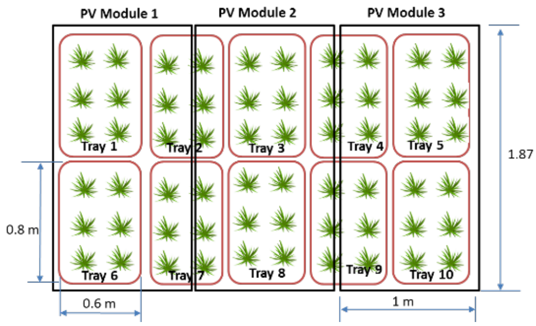

Figure 4: Layout of APV farm.

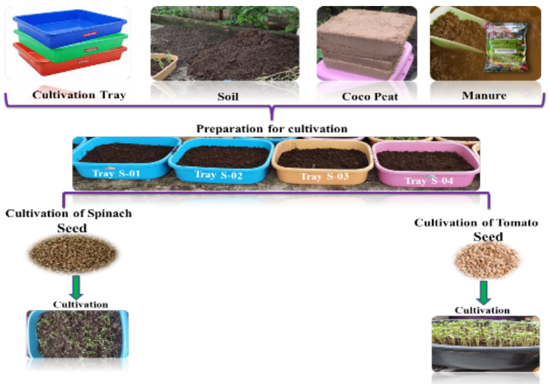

Figure 5: Methodology adopted for cultivation of crops for APV farm.

In the current study, crops were grown beneath the PV modules in a regular straight line pattern for the experimental setup. The standard non-transparent PV modules were opted (details are discussed in section 2.3). The entire footprint of the PV modules was measured, and cultivation trays with the appropriate capacity were selected. The trays had dimensions of 0.8 × 0.6 m. The arrangement of the cultivated crops beneath the PV modules is depicted in Figure 4. Figure 5 shows the stages of crop cultivation.

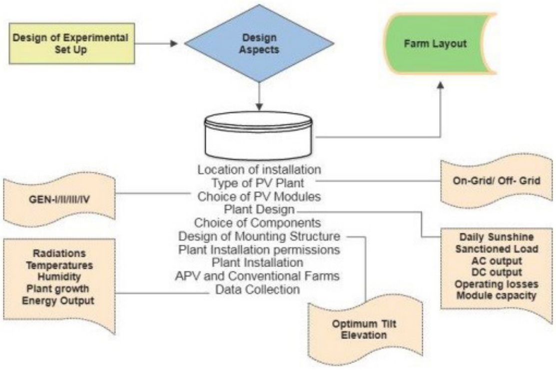

Figure 6: Design of Experimental set up.

2.3 *The experimental setup*

The significant design aspects of the development of the experimental facilities for the performance investigation of the APV system are shown in Figure 6.

The entire experimental facilities were divided into three parts viz; open sky farm, reference PV plant and the Agrophotovoltaic plant. The experimental setup consists of a 2 kWp grid-connected solar PV plant designed with polycrystalline non-transparent PV module using 'HelioScope tool' for Nagpur [21° 08' N, 46.72" E] India as shown in Figure7. The optimum tilt angle for the installation of the solar PV module was computed using standard correlations and used to fabricate the structure of the installation. The structure of the installation was designed in such a way that it will allow to adjust the height of the installation to study the effect of the gap between the crop and the back surface of the PV modules. Figure 8 shows the layout of the experimental setup, Table 2 gives the details of the components used and Figure 9 displays the actual images of the test set.

Table 2: Details of components used in an experimental setup

Sr. No.	Particular	Specification
1	Photovoltaic modules	Luminous 330 Wp, 6 Nos. Polycrystalline Si
2	Inverter	Luminous, 5 kW, 2 separate MPPT
3	Temperature Sensors	K Type thermocouples
4	Pyranometer	Kipp and Zonen, Class B
5	Energy Meters	DC energy Meters, 300 VDC
6	The mounting of the PV module	Inter row spacing –1.5 m, Tilt angle-20° Elevation –1 m & 1.5 m

Figure 7: Design of 2 kWp plant using HelioScope software package.

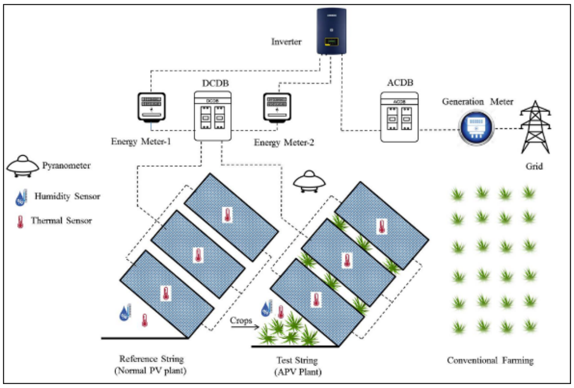

Figure 8: Schematic diagram showing experimental setup.

Figure 9: Photographs showing experimental setup (Legends: 1) Cultivated spinach crops below the PV module, 2) Fully grown spinach crops, 3) View of conventional plant, 4) Agrophotovoltaic system, and 5) ACDB, DCDB, Inverter and energy meters).

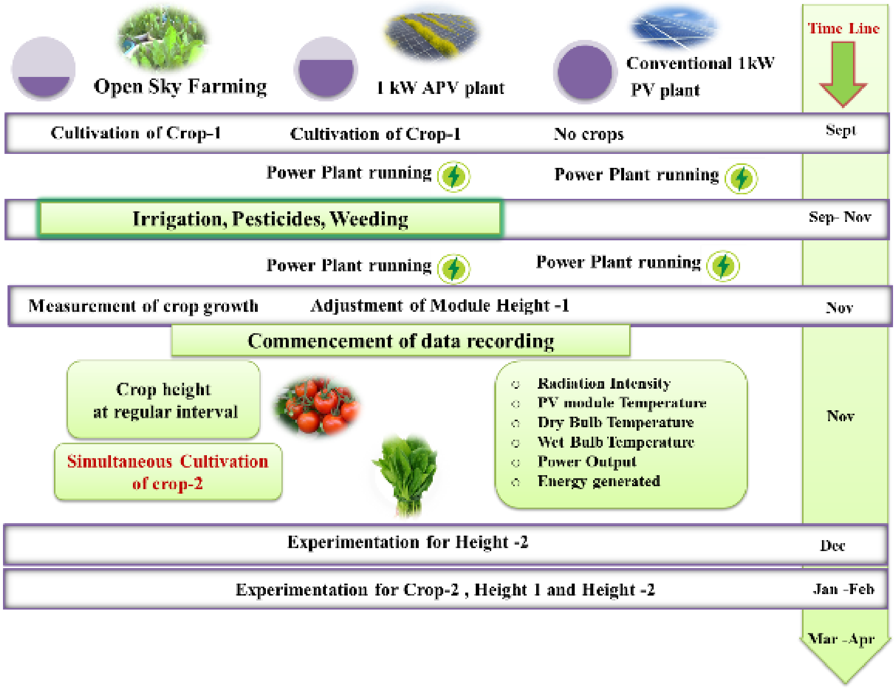

Figure 10: Details of experimental study.

2.4 *Experimentations*

In the experimental studies, radiation intensity, surface temperature of the PV modules, ambient temperature, humidity, crop growth, energy generated by each string and the complete plant were measured. The respective instruments were used to measure the experimental data as shown in Table 2. The power generation from the two strings was measured using two separate DC energy meters and the combined output was measured using a string inverter. The experiments were planned to study the following aspects of the present work.

1) Crop growth in open sky conventional farming and in APV.

2) Effect of cultivation on the microclimate beneath the PV module.

3) Effect of cultivation on PV module temperature.

4) Effect of module temperature on power generation.

5) Effect of different crops on the APV plant performance.

6) Effect of different heights of the crops on the APV performance.

To study the aforementioned aspect, a systematic experimental study was planned as shown in Figure 10. In Figure 10, the timeline indicates the months of the activity, and the horizontal lines indicate the major activity carried out during the experimental study.

As shown in Figure 10, the first crop i.e. Tomato was cultivated in September, and the crops were maintained from September to November by proper irrigation, weeding, pesticide and fertilizers. During this period, the proper functioning of the APV plant and the conventional PV plant was ensured by observing the electrical parameters of the plants. The plants were running and generating a substantial amount of electricity and feeding it to the grid. The growth of the crops in both the APV system and the open sky farm was monitored using measuring tape at regular interval of time. As the crop growth was comparable in both cases and once the crop reached 0.3 m in height (in the first week of November), we began monitoring the performance of the system. At first, the height of PV modules in an agrophotovoltaic plant was adjusted to 1 m from the ground, and the experiments were started from 8 AM to 4.30 PM of each day for a period of one month. In the next month, the module height was adjusted to 1.5 m and the same experiments were repeated. The same procedure was adopted for crop -2 i.e. Spinach. Table 3 gives the uncertainty of the measurements during the experimental studies.

Table 3: Uncertainty analysis

Sr. No.	Measuring Parameters	Instrument Used	Uncertainty (odds 20 to 1)
1	Radiation Intensity	Pyranometer, Model – KippZonen/PM-10 Class-1	± 1.5%
2	Temperature of PV module	Thermocouples Creative, Thermal indicator: DTI-306	± 1.40°C
3	Ambient Temperature	Psychrometer	± 0.1%
4	Current generated by PV module	Energy Meter Everon EV-DSL-01	± 1%
5	Voltage of PV module	Energy Meter Everon EV-DSL-01	± 1%
6	Power produced by PV module	Energy Meter Everon EV-DSL-01	± 1%
7	Units generated	Energy Meter Everon EV-DSL-01	± 1%

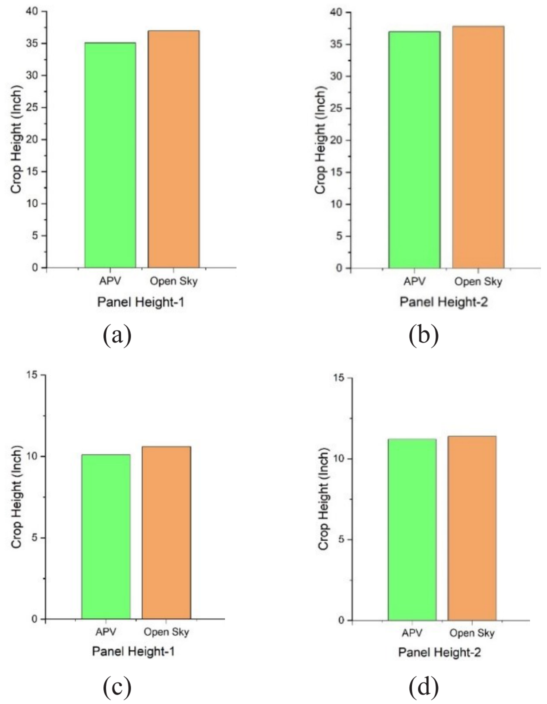

Figure 11: Growth of crops (a) Tomato Height 1 m (b) Tomato Height 1.5 m (c) Spinach Height 1 m and (d) Spinach Height 1.5 m.

3 Findings of Experimental Studies

3.1 *Crop growth in open sky conventional farming and APV*

The crop growth in open sky farm and APV was monitored for both the cases of module height 1 m and 1.5 m as shown in Figure 11. As shown in Figure 11(a)–(d) the growth of both the crops in APV system was comparable with the open sky farming.

3.2 *Effect of cultivation on the microclimate beneath the PV module*

The crops grown beneath the PV modules facilitate transpiration cooling (as discussed in Section 5), which increases the humidity of the atmosphere below the PV module and helps to reduce its temperature.

As shown in Figures 12(a)–(d), the dry bulb temperature beneath the PV module was measured for both conventional and an APV system. Comparing APV systems with reference PV plants, Figure 12(a)–(d) showed lower dry bulb temperatures.

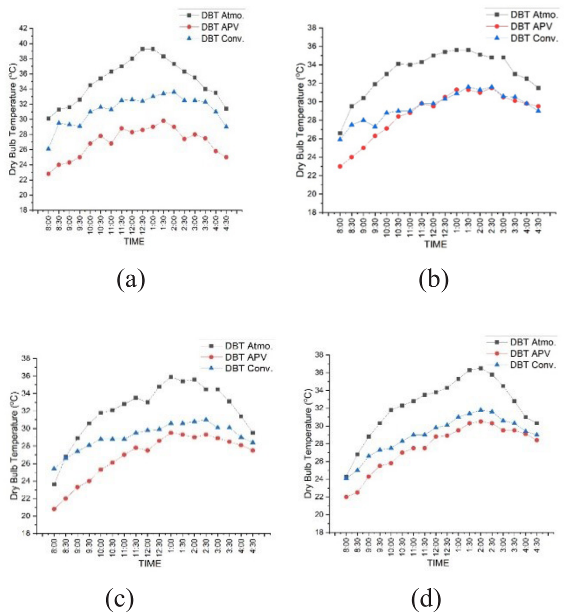

Figure 12: Dry bulb temperature (a) Tomato height 1 (b) Tomato height-2 (c) Spinach height-1 and (d) Spinach height-2.

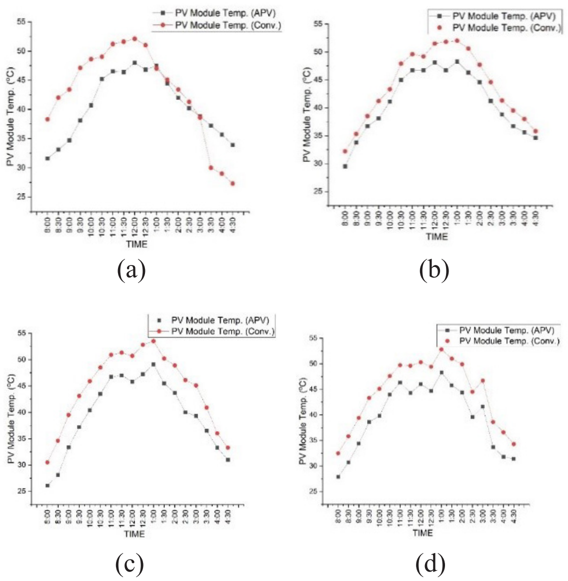

Figure 13: PV module temperature (a) Tomato height-1 (b) Tomato height-2 (c) Spinach height-1 (d) Spinach height-2.

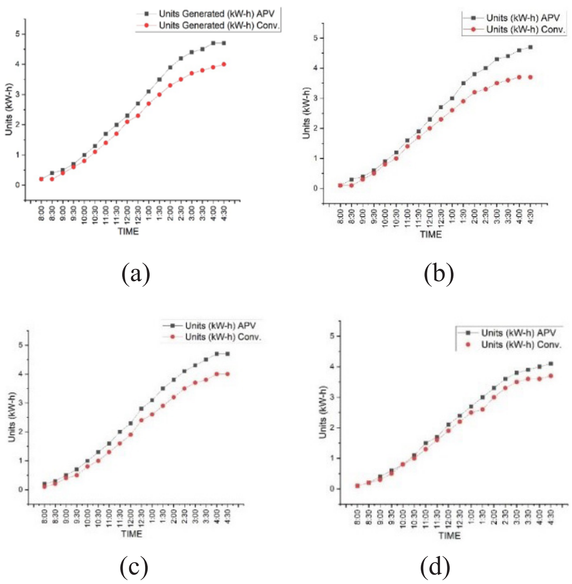

Figure 14: Units generated (a) Tomato height-1 (b) Tomato height-2 (c) Spinach height-1 and (d) Spinach height-2.

3.3 *Effect of cultivation on PV module temperature*

The cultivation of crops below the PV module reduces the temperature of the surrounding atmosphere, which in turn has a consequential effect on the reduction of the PV module's temperature. Figures 14 and 15 shows the temperature of modules in both reference and Agrophotovoltaic plant. Figure 13(a)–(d) show that the module temperature in the Agrophotovoltaic system was lower than the temperature of the reference plant for both crops.

3.4 *Effect of cultivation on power generation*

The power output of the PV module is strongly dependent on its operating temperature. As the temperature of the PV module reduces, its power output increases. This relationship has been observed in the present study. Figure 14(a)–(d) show the power generation by both APV and conventional PV plant. Overall, the experimental studies show that in APV system the PV module temperature reduces by an average of 5–6 °C and consequently the power generation by the PV plant improves by around 13%.

4 Theoretical Analysis of APV System

To predict the performance of the APV system for any given location and for any given crops a systematic analytical procedure has been formulated. The procedure is shown in Figure 18. According to the procedure, at first, the irradiations and the optimum tilt angle for the module installations are estimated. For the estimation of power output, parameters like the plant capacity, crops, crop height, module spacing, etc are required to consider. Based on the results of the current research, a regression model has been created that can predict the temperature of the modules and the system's associated power production.

For the purpose of multilinear regression analysis, the 'Minitab' statistical tool has been used. The PV module temperature (Tpv) is considered as a dependent parameter and the other three parameters viz; Ambient temperature (Ta), irradiance (Ig), and humidity (ω) were considered as independent variables. The experimental data obtained by the 6 months of experiments was considered, and the data was sorted considering the suitable significant data by removing the outliers. The multilinear regression process as given by Minitab guidelines was followed

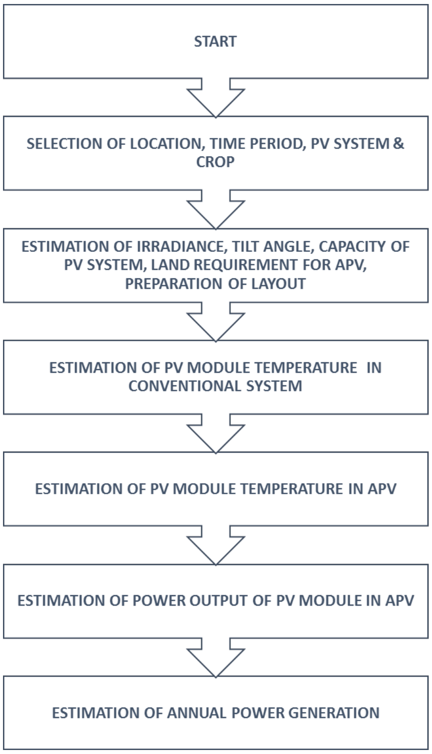

Figure 15: Theoretical estimation of performance of APV Plant.

and the analysis was carried out. The consolidated statistics of the regression model obtained by the MINITAB tool have been shown in Table 4.

Based on the obtained values of regression coefficients, the correlations for the PV module temperatures are obtained as shown in Equations (1)–(8).

For Tomato Height-1
Regression Equation in Uncoded Units

$$Tpv\ Conv\ Expt = -7.39 + 1.206\ Ta + 0.00951\ Ig + 0.1086\ W \quad (1)$$

$$Tpv\ APV\ Expt = -11.70 + 1.187\ Ta + 0.00825\ Ig + 0.1678\ W \quad (2)$$

For Tomato Height-2
Regression Equation in Uncoded Units

$$Tpv\ conv\ Exp = 2.61 + 0.807\ Ta + 0.01722\ Ig + 0.0630\ W \quad (3)$$

$$Tpv\ APV\ Exp = 8.38 + 0.618\ Ta + 0.01578\ Ig + 0.0320\ W \quad (4)$$

For Spinach Height-1
Regression Equation in Uncoded Units

$$Tpv\ conv\ Exp = 26.56 + 0.368\ Ta + 0.01761\ Ig - 0.1862\ W \quad (5)$$

$$Tpv\ APV\ Exp = 13.62 + 01.597\ Ta + 0.01600\ Ig - 0.1278\ W \quad (6)$$

For Spinach Height-2

$$Tpv\ conv\ Exp = 5.32 + 0.8188\ Ta + 0.015396\ Ig + 0.0519\ W \quad (7)$$

$$Tpv\ APV\ Exp = 1.00 + 0.8118\ Ta + 0.01526\ Ig + 0.0512\ W \quad (8)$$

The temperatures obtained by the regression models were compared with the actual values observed in the experimental studies. Figure 16 shows the comparison between theoretical and actual output (a sample case).

Table 4: Statistics of regression analysis

Case	Const.	Ta	Ig	ω	R^2	Adj. R^2	Pred. R^2
Spinach Height-I Conv.	26.56	0.368	0.01761	0.1862	0.8940	0.8893	0.8811
Spinach Height-I APV	13.62	0.597	0.01600	–0.1278	0.9127	0.9089	0.9022
Spinach Height-II Conv.	53.2	0.8188	0.01539	0.0519	0.9298	0.9267	0.9212
Spinach Height-II APV	1	0.8118	0.01526	0.0512	0.9138	0.91	.09048
Tomato Height-I Conv	–7.39	1.206	0.00951	0.1086	0.8380	0.8309	0.8169
Tomato Height-I APV	–11.70	1.187	0.00825	0.1678	0.7616	0.7511	0.7340
Tomato Height-II Conv.	2.61	0.807	0.01722	0.0630	0.8686	0.8628	0.8520
Tomato Height-II APV	8.38	0.618	0.01578	0.0320	0.8417	0.8347	0.8220

Note: Ta is Ambient temperature, Ig is Irradiance, and ω is humidity)

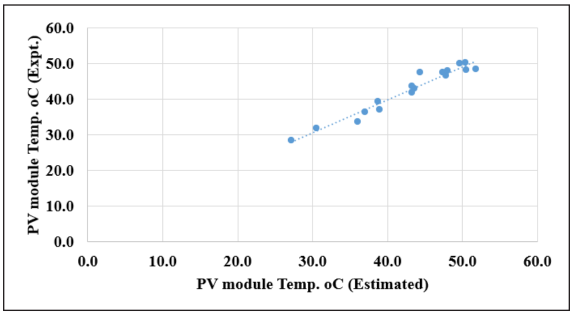

Figure 16: Module temperature experimental and theoretical sample case.

As shown in Figure 16, the predicted values and values by the regression analysis match with each other with reasonable accuracy.

5 Results and Discussions

In the agrophotovoltaic, the crops are planted underneath the solar modules and/or in the inter-row spacing in the Agrophotovoltaic system. In the present research work the crops were cultivated beneath the solar PV module. Most crops have some capacity for transpiration, which allows them to cool and reduce the temperature of their surroundings.

Based on these findings, the subsequent text explains its consequential impact on the power output of the PV module and the effectiveness of the APV system

5.1 *Comparison between predicted and experimental output*

Equation (9) was used to estimate the power output of the solar module based on the temperature coefficient and the module temperature

$$P_{out} = (P_{stc}/1000) \times I_g - (Temp.\ Coeff.(T_{pv} - 25) \times P_{stc} \quad (9)$$

In Equation (9), P_{out} stands for output power of module at T_{pv}, P_{stc} stands for the power at standard test condition, I_g is irradiance, *Temp. Coeff.* is temperature coefficient of PV module for power output and T_{pv} is PV module operating temperature.

The solar PV modules of the same specifications as used in the experimental study have been considered which are of capacity 330 Wp of make Luminous having the temperature coefficient of power is –0.3677%/°C. Subsequently, the electrical units generated by the conventional PV plant and the APV plant were estimated. Figure 17(a)–(d) compares the power produced by the conventional and APV plants based on experimental findings and theoretical estimations.

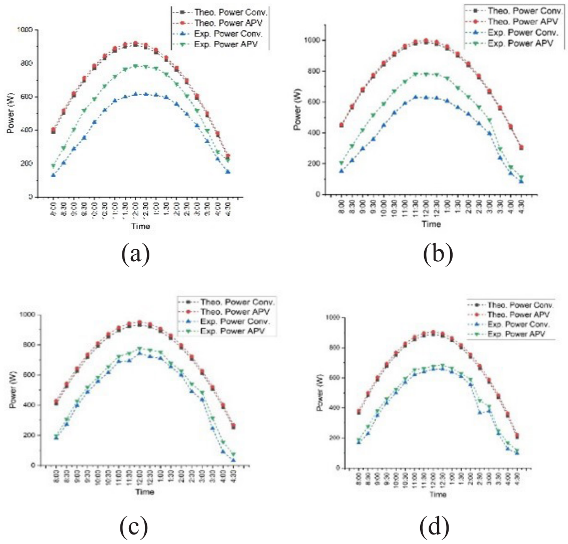

Figure 17: Power output by theoretical and experimental (a) Tomato height-1 (b) Tomato height-2 (c) Spinach height-1 and (d) Spinach height-2.

Figure 18 (a)–(d) compare the power produced by the conventional and APV plants based on experimental findings and theoretical estimations. As shown in Figure 17(a)–(d) and Figure 18(a)–d), the experimental values of power output and the electricity units generated are matching with the theoretical estimation. Similar results were obtained for the Spinach as well.

5.2 *Land Equivalent Ratio (LER)*

In order to quantify land use efficiency, we use the Land Equivalent Ratio (LER). Electricity-crop yield ratio (LER) refers to the total crop yield from both sources. Equation (10) is used to calculate it as follows:

$$LER = \frac{Yield\ of\ APV\ system(Crop1 + Electricity)}{Yield\ (Crop1)} + \frac{Yield\ of\ APV\ system(Crop\ n + Electricity)}{Yield\ (Crop\ n)} \quad (10)$$

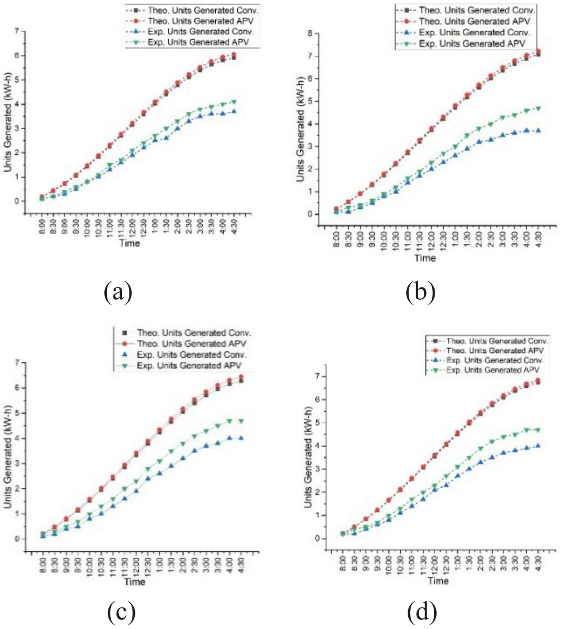

Figure 18: Units generated by theoretical and experimental (a) Tomato height-1 (b) Tomato height-2 (c) Spinach height-1 and (d) Spinach height-2.

LER <1 shows Agrophotovoltaic system is less productive, LER >1 shows increased productivity in the Agrophotovoltaic system as compared to the crop production alone. The LER has been calculated based on the experimental observations of the present study. Figure 19 shows the calculated LER for the Agrophotovoltaic system developed in the present study. As shown in Figure 19, the LER values for all the crops are greater than 1; in comparison with crop production alone, the Agrophotovoltaic system clearly shows increased productivity. Moreover, Tomato crop in Height-1 had the highest LER.

5.3 *Estimation of energy yield by 1 MW APV plant*

Based on the experimental studies, the observations, and the subsequent calculations it has been observed that the electrical efficiency and in turn power output of the solar PV plant is improved by converting it to APV system. In the present study the observations show that on an average the APV system generates 0.4 to 0.6 kWh/ kw/day units of additional energy as compared with the reference solar plant. Based on this calculation, for a 1 MW APV plant for all the crops

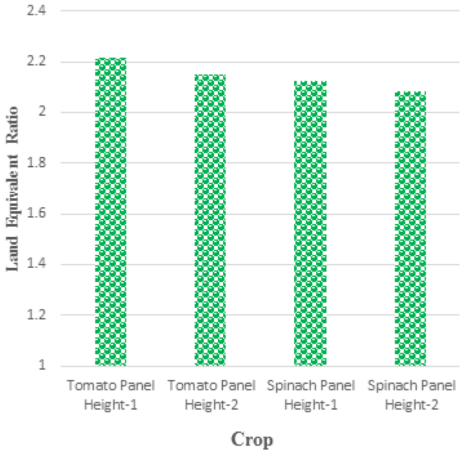

Figure 19: Land equivalent ratio.

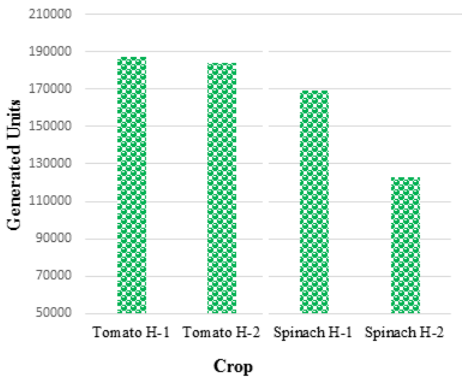

Figure 20: Electricity generation.

have been made. The APV system with tomato crop for module height of 1 m from ground can generate 187500 kWh additional units of electricity per year, as shown in Figure 20. The results are similar for the other crops as well. In addition, the yield of the tomato crop and other crops is comparable to that of open sky farming. This demonstrates the utility of an APV plant not only for dual land use, but also for improved electrical yield. The findings of the present work have been compared with the literature and presented in Table 5.

5 Conclusions

This study aimed to investigate the performance of Agrophotovoltaic (APV) systems across different seasons and crops. It involved conducting experiments

Table 5: Comparison of the findings of the present work with literature

Ref.	Findings			
	Growth of crop in APV system	Reduction in the PV Module Temperature in APV System	Increase in the Power Output of in the APV System	LER of APV System
[21]	No significant different between the open field and the APV system	-	-	-
[22]	Traditional planting and agrivoltaic system received equal irrigation rates	PV panels in an agrivoltaic system were ~8.9 + 0.2 °C cooler in daylight hours.	-	-
[23]	-	Solar module temperature reductions of up to 10 °C	-	-
Present Study	Comparable	Reduction of PV module temperature by 5–6 °C	APV system generates 0.4–0.6 kWh/ kw/day units of additional energy	Increased LER

on a 1 kW APV farm and developing a predictive model for power output estimation. The experiments were conducted for 6 months using Spinach and Tomato crops, comparing their yields to open sky farming. The study analyzed the impact of each crop on the thermal and electrical performance of the PV module and the effect of different module heights in an APV system. A theoretical model was also developed to predict APV plant output for different locations and module types. The study found that the APV system reduced PV module temperature by 10–13%, resulting in a 5–8% increase in energy yield. Crop growth beneath the PV module was comparable to open sky farming. The study concluded that APV systems offer benefits such as effective land use and improved electricity output but recommended further investigation into various aspects of APV systems. These include conducting rigorous experiments at different locations with different crops, exploring combined APV systems with rainwater harvesting and hydroponics, and investigating techno-economic aspects and additional module types. It is also suggested to study the evapotranspiration cooling potential of crops in APV systems considering different geographical zones, crop varieties, climate, and specific sunlight and irrigation requirements.

Author Contributions

R.W.: conceptualization, experimental studies, writing original draft; R.J.: conceptualization, supervision; SJ: conceptualization, experimental design, editing and reviewing. All authors have read and agreed to the published this version of the manuscript.

Conflicts of Interest

The authors declared no conflict of interest.

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