Hindawi
International Journal of Photoenergy
Volume 2023, Article ID 4720545, 12 pages
https://doi.org/10.1155/2023/4720545

Research Article

Thermal and Electrical Performance of Uncooled, Nature-Cooled, and Photovoltaic Thermal Module

Pushpendu Dwivedi,[1] **Sujay Ashwinraj Ganesh**,[2,3] **Kumarasamy Sudhakar**,[1,2,4] **Archana Soni**,[1] **and S. Shanmuga Priya**[5]

[1]*Energy Centre, Maulana Azad National Institute of Technology, Bhopal, 462003, M.P, India*
[2]*Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Malaysia*
[3]*Centre for Automotive Engineering (Automotive Centre), Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia*
[4]*Centre for Research in Advanced Fluid & Processes (Fluid Centre), Universiti Malaysia Pahang, 26300, Paya Besar, Pahang, Malaysia*
[5]*Department of Chemical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India*

Correspondence should be addressed to Kumarasamy Sudhakar; sudhakar@ump.edu.my and S. Shanmuga Priya; shan.priya@manipal.edu

Received 21 March 2022; Revised 19 October 2022; Accepted 24 November 2022; Published 3 February 2023

Academic Editor: Qiliang Wang

The experimental study is aimed at analyzing photovoltaic module's thermal and electrical performance (PV) with back surface cooling under Malaysian tropical climate conditions. The performance of a passively cooled PV module integrated with biomaterial (moist coconut fiber) was compared with a photovoltaic thermal (PVT) system with water circulation at the rate of $0.02\,kg\,s^{-1}$ and a reference PV module. The study observed that the passively cooled PV module succeeded in reducing the module surface temperature by more than 20%. However, the PVT system reduced the temperature only by less than 17%. The electrical energy efficiency was improved remarkably in the passively cooled PV module by almost 11%, but the PVT system managed to increase the electrical efficiency by 9%, approximately. It can be concluded that nature-inspired coconut fiber-based cooling can be one of the potential alternatives to active cooling methods.

1. Introduction

For decades, fossil fuels have been used to meet humans' energy demands, primarily through electricity production. The role of crude oil and natural gases has become more questionable for decades as they come with the price. Energy production through fossil fuels has caused as much detrimental impact on the environment as harvesting them. As mentioned by Alobaid et al. [1], heavy carbon emissions and accelerated global warming have resulted from extensive fossil fuel usage. Not only are they a nonrenewable energy source, but also fossil fuels are unreliable and potentially put our environment at stake. Solar energy is one of the many forms of renewable energy mentioned by Owusu and Asumadu-Sarkodie [2] which is being used as an alternative to produce carbon-free energy and mitigate negative climate change. As noted by Kirpichnikova et al. [3], solar energy is a very sustainable and reliable source of energy as it is eternally available at the same time, eco-friendly. Incorporating solar energy by installing solar panels either in the household or to meet industrial needs has proven effective and encouraging.

About 5 to 20% of sunlight is in contact with the PV module, generating electrical energy. In contrast, the remainder of the sunlight is either radiated back to the atmosphere or absorbed into the panel through conduction as heat [4]. Consequently, the heat will cause a dramatic increase in the surface temperature of the PV module. As the temperature of the panel increases, it rises more from its nominal operating cell temperature (NOCT), directly plummeting the efficiency of the PV module. The temperature coefficients of power for mono and multicrystalline PV modules are rated at -0.4% to -0.5% per degree Celsius. The negative sign indicates that for every 1°C increase of PV module temperature above its operating temperature under standard test conditions (solar irradiance of 1 kW/m^2, air mass of 1.5, and operating module temperature of 25°C) as mentioned in Sun et al. [5]. Active and passive cooling techniques were both introduced in light of this problem faced by the PV module systems. As mentioned by Zhang et al. [6], the cooling techniques serve to lower the PV module surface temperature to suitable levels that improve the PV modules' efficiencies. Active cooling methods promote cooling the PV module at the expense of energy consumption, either from the PV module itself or from external energy sources, as mentioned by Olawole et al. [7]. Conversely, passive cooling techniques avoid the usage of energy; instead, they rely on natural convection or conduction process to remove the heat away from the PV module. To further utilize the energy from the PV module, a photovoltaic-thermal (PVT) system is introduced which functions as a cross-over between a PV module and a thermal collector that carries heat through the fluid, as mentioned by Kallio and Siroux [8]. The PVT system produces electricity from the PV module and valuable heat that is obtained by the cooling fluid circulation. This outcome is an increase in the system's overall efficiency and the PV module's electrical efficiency.

Energy analysis is based on the first law of thermodynamics, in general are applied for the performance evaluation of solar module Tsai and Yang [9]. Exergy analysis, on the other hand, is based on the second law of thermodynamics that accounts for the quality of energy or the usefulness of the energy as reported by Kallio and Siroux [8]. The exergy analysis relies on the amount of exergy losses experienced by a system. Exergy losses result from the difference between the exergy input and output. Unlike energy, exergy can be destroyed, and the value of exergy destruction determines the availability of work in a particular system.

1.1. Problem Statement and Novelty of the Study. Although the primary goal of all the cooling techniques is to increase the PV module's efficiency, a significant difference exists in the results achieved by the proposed cooling methods when they are being analyzed in terms of thermal and electrical performance. To overcome several challenges with the active cooling system, affordable, energy-efficient, and sustainable cooling solution is vital for future.

1.2. Objective of the Study. This research focuses on the development and experimental testing of low-cost, sustainable cooling method for PV module. The primary purpose of this study is to analyze the thermal and electrical performance of an uncooled and nature-cooled PV module and PVT system. Not only that, but this study is also aimed at comparing the performance and identifying the best cooling technique for Malaysian tropical climate conditions.

2. Background of PV Cooling

Figure 1 briefly illustrates the various factors influencing the module performance and cooling techniques.

2.1. Active and Passive Cooling Techniques. Popovici et al. [10], highlighted the influence of the fins' height and the inclination angle on the cooling. Heat sink fins made of copper were attached to the module's rear surface to facilitate a fixed air velocity of 1.5 ms^{-1}. The height of the fins was changed from 0.01 m to 0.05 m by 0.01 m increments, whereas the angle of inclination was also changed from 45°, 90°, to 135°. The fins' height of 0.03 m and 45° gave the most significant temperature drop. Peng et al. [11] studied the usage of ice cubes to act as a heat sink at the rear surface of the PV module as it faced a light source on the ground. Ice cubes were evenly spread on the back surface, and the light intensity representing the solar irradiation varied between 160 W/m^2, 300 W/m^2, and 400 W/m^2. Qasim et al. [12] assessed the effectiveness of a hybrid passive cooling system using fins and phase change material (PCM). The study was carried out in two phases in which the first phase tested the effectiveness of the number of fins along with the PCM whereas the second phase of the study was carried out by varying the configuration of PCM used. From the study, it was seen that 11 fins integration with PCM showed the best electricity conversion from the first phase, whereas the second phase showed that one PCM configuration is better than two PCM configurations. Elbreki et al. [13] investigated the effect of the number of lapping fins and the thickness that would be ideal in facilitating the cooling effect of the PV module. The different numbers of fins were used with respective pitches to investigate the temperature reduction of the PV module. The PV module's temperature was reduced to 39.73°C from 64.3°C by attaching 18 lapping fins and 27.7 mm fin pitch to the back surface of the module. Abdollahi and Rahimi [14] carried out experimental work on the cooling of the PV module using a combination of phase change material (PCM) and water circulation. Using a unique PCM container designed for maximum heat transfer, the water circulation was set such that cold water flows into the duct behind the PV module from below, and the hot water exits the duct from above and enters the PCM container to release the sensible heat absorbed to become cold water, and the circulation continues. From this, it was found that nano-PCM showed better results than a standard PCM in the proposed technique. Table 1 briefly compares the results of a similar experimental study by various researchers.

3. Experimental Methodology

The complete experimental methodology is illustrated in Figure 2.

3.1. Description of the Experimental Set-Up. In this experiment, three identical solar modules were used, each with a different configuration. The PV modules' specifications are listed in Table 2. The first module used was integrated with a hybrid photovoltaic thermal (PVT) system at the module's

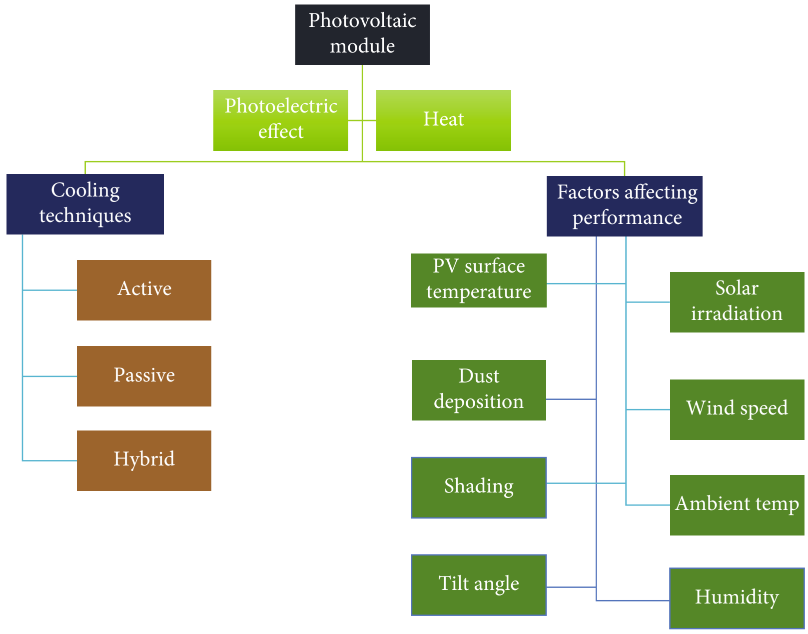

Figure 1: Factors influencing module performance and cooling techniques.

rear surface with an oscillatory flow design. In contrast, the second module was combined with a moist coconut pith that was compacted and encapsulated with a polyurethane sheet at the back of the module's surface. The last module was kept as a reference module. Figure 3 provides the schematic arrangement of the experimental setup.

3.2. Experimental Procedure. Before the experimental procedure, a preliminary experiment was conducted to detect and troubleshoot any problems and irregularities. During the initial testing, the experimental setup was inspected for problems, one of which was a leakage in the piping system of the PVT-integrated PV module. This was rectified by applying silicon gum to seal and secure the leakages. Also, during the trial run, the water flow rate was adjusted using the water flow meter and Arduino software. Based on the literature reviews, a flow rate of $0.02\,kg\,s^{-1}$ was adjusted to flow through the oscillatory flow design of the PVT system throughout the experiment. The weather forecast was checked for the upcoming days to be sunny, which was suitable for the investigation to be conducted. The actual experiment was successfully conducted for two consecutive days, from 9 am to 5 pm. All three PV modules were tested on the frames with the same orientation, and the experiment was conducted as per the preliminary. For the PVT system, a water storage tank was constantly filled to ensure that the water flow at the PVT system's inlet was constant. The other two panels were also tested on the frame unobstructed. For this experiment, the data measurement and recordings were conducted every 1 hour throughout the experiment period from 9 am to 5 pm. The electrical values, such as the current and voltage, were measured across a load using the TENMA Resistance Decade Box. Hence, the collected data for this experiment primarily included the output voltage (V), output current (A), PV module surface temperature (T_m), ambient temperature (T_{amb}), solar irradiation (G), wind speed (v_{wind}), and air humidity (RH). For the further analysis of energy performance from the respective panels, additional data were collected such as the temperatures of the water inlet ($T_{w,in}$) and water outlet ($T_{w,out}$) were recorded with the K-type thermocouple for the PVT integrated PV module. The temperature readings of the water inlet and outlet were taken from the average of six (6) individual readings from the respective boxes A and B. For the PV module integrated with the coconut coir fiber, the PV module front (T_{front}) and back surface temperature (T_{back}) was recorded using the K-type thermocouple.

For the electrical components of the PV module, proper apparatus arrangement and method are required to obtain the most accurate and precise reading. For the voltage reading, the multimeter/voltmeter can be placed parallel to the load to measure the potential difference between the two terminals. For the current, however, the circuit must be broken and connected in series with an ammeter and load. By doing this, the current will flow through the multimeter/ammeter to the load, and the value of the current can be obtained. In this study, a clamp meter was employed to take the current reading by simply clamping it over the desired wire. It is rather convenient and time savvy to use than an ammeter. Therefore, the voltage and current output of all three PV modules in this experiment were measured simultaneously using the voltmeter and ammeter, respectively.

3.3. Thermal and Electrical Performance Parameters. The performance indicators are the means used to examine the performance of PV modules [21]. The system's energy efficiency will be used to analyze the data collected from the experiment. The energy efficiency of a PV module is the

Table 1: Review of similar experimental work.

Author	Methodology	Outcome	Type of cooling technique
Abdollahi and Rahimi [14]	Integration of PCM at the back of the PV module	The nano-composed PCM is more efficient than the plain PCM. The nano-composed oil showed the highest efficiency of 44.74, 46.63, and 48.23% at the solar irradiation of 410, 530, and 690 W/m^2, respectively	Passive cooling
Arifin et al. [15]	Cooling effect of fins on PV modules	This study showed that 15 fins made of copper showed the highest decrease in temperature (10.2°C) and efficiency (2.74%)	Passive cooling
Lubon et al. [16]	Effect of two active water-cooling methods; water film and water spray	It is seen that water film obtained better results than water spray with a 19.1% increase in power from the reference rather than 9.3% (water film)	Active cooling
Hadipour et al. [17]	Efficiency of PV module using active water cooling using steady spray water, pulsed-spray water cooling	The results show that the maximum electrical power output of the PV panel increases about 33.3% by using steady-spray water cooling	Active cooling
Liu et al. [18]	Experiment using different tube designs, tube diameters, water inlet temperature, and flow velocity	The average surface temperature of PVs decreases as tube diameter and flow velocity increase, while tube spacing and water inlet temperature decrease	Active PVT cooling
Rajasekar et al. [19]	Integrating coconut coir into the PVT system while using earthen pot water to flow through the system	The results show that using earthen pot water to cool the coir pith increased the overall efficiency by 64%. The temperature of the pot water is 5–8°C lower than the surrounding air temperature	PVT with biomaterial
Shahsavar et al. [20]	PVT system with sheet-, plain serpentine tube, rifled serpentine tube, grooved serpentine tube collector, finned and unfinned collector	PVT systems achieved better performance compared to the PV module without cooling	Active cooling (magnetite nanoparticles)

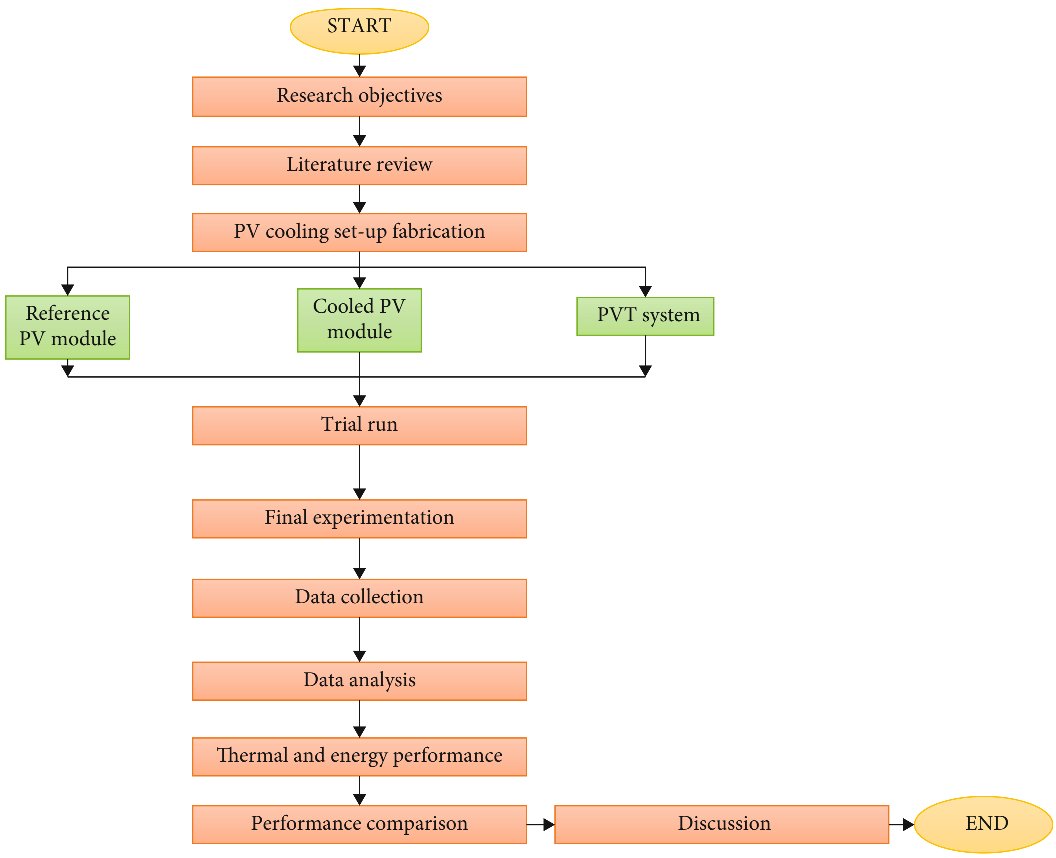

Figure 2: Flowchart highlighting the methodology of the study.

Table 2: Specification of the photovoltaic (PV) module.

Description	Characteristic/value
Model	*VE*-30-36*P*
Technology	Polycrystalline
Maximum power, P_{max} (W)	30
Open circuit voltage, V_{OC} (V)	21.97
Short circuit current, I_{SC} (A)	1.75
Maximum power point voltage, V_{MPP} (V)	18.31
Maximum power point current, I_{MPP} (A)	1.64
Dimensions of the module (cm)	34.8 × 67.4 × 3

ratio of the PV module's electrical output to the total surface area of the PV module and the solar irradiation incident on it. The maximum power point (MPP) result can be calculated using the formula provided by Kumar et al. [22].

$$P_{max} = V_{oc} \times I_{sc} \times \text{FF}, \quad (1)$$

where V_{OC} and I_{SC} are the open-circuit voltage and short-circuit current, respectively. The fill factor is the performance used to determine the capacity of a PV cell, as mentioned by Ballal et al. [23].

FF can be calculated by the following formula:

$$\text{Fill Factor(FF)} = \frac{V_{MPP} \times I_{MPP}}{V_{oc} \times I_{sc}}, \quad (2)$$

or

$$V_{MPP} I_{MPP} = \text{FF} \times V_{oc} \times I_{sc}. \quad (3)$$

Therefore, the electrical energy efficiency (%) of the PV module is the ratio of the PV module's MPP output to the solar power it generates and it can be calculated by,

$$\eta_{el,\,energy} = \frac{P_{max}}{G \times A} = \frac{V_{mp} \times I_{mp}}{G \times A} = \frac{V_{oc} \times I_{sc} \times \text{FF}}{G \times A}, \quad (4)$$

where A is the solar irradiation's total exposed surface area (m^2) of the PV module and G is the solar irradiation incident on the module surface (W/m^2).

For the case of a PVT system, the overall performance is a combination of the system's electrical and thermal energy output as mentioned by Abdul-Ganiyu et al. [21]. Hence, the thermal gain of the PVT can be calculated by

$$Q = \dot{m}_w c_{pw} (\Delta T), \quad (5)$$

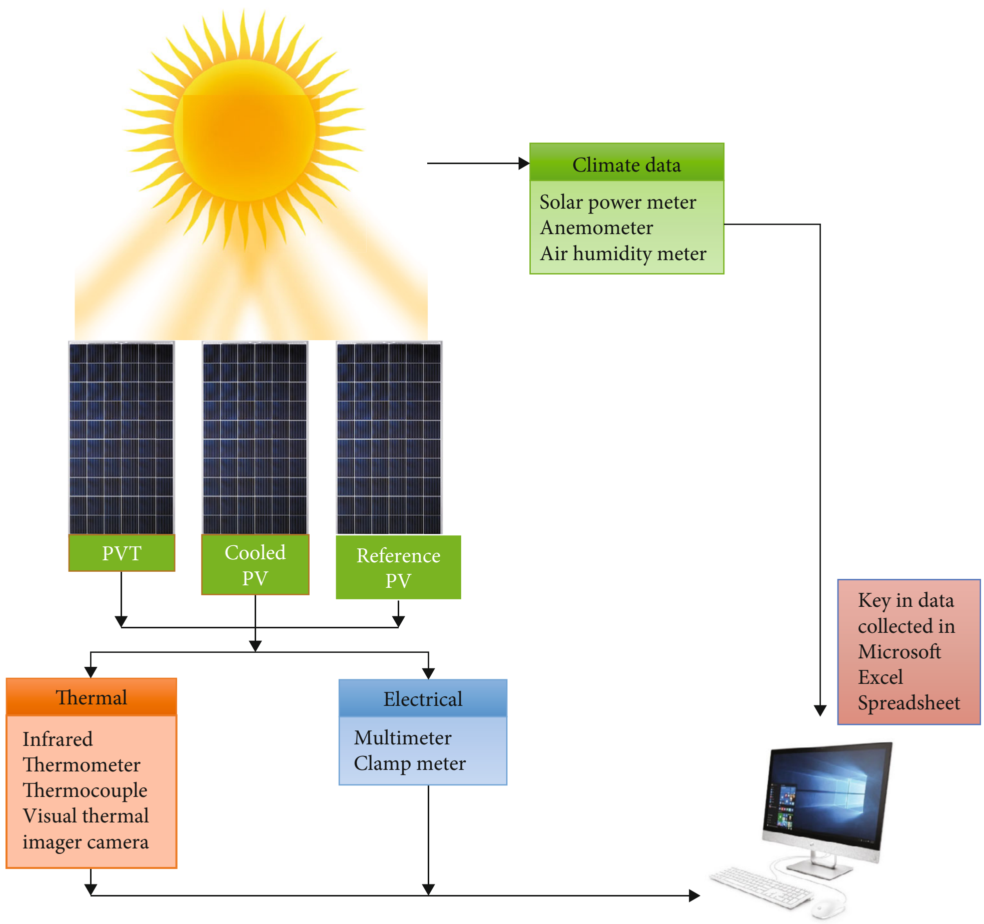

Figure 3: Schematic diagram of the experimental setup.

where $\dot{m}_w$ is the water mass flow rate (kg s^{-1}), c_p is the specific heat capacity of water (J/kg/°C), and ΔT (°C) is the temperature difference between the outlet and inlet water temperature of the PVT system, expressed as

$$\Delta T = T_{\text{out}} - T_{\text{in}}. \tag{6}$$

Throughout the analysis of the study, the specific heat capacity of water, c_p, was assumed to be constant at 4.18 kJ/kg/°C. The PVT system's thermal energy efficiency (percent) can be expressed as the ratio of the PVT system's thermal energy output to the solar irradiation incident on the PV module's total exposed surface area, given as

$$\eta_{\text{th, energy}} = \frac{Q}{G \times A}, \tag{7}$$

$$\eta, \text{PVT} = \frac{P}{G \times A} + \frac{Q}{G \times A}. \tag{8}$$

The overall efficiency (%) of the PVT system can be expressed by combining equations (5) and (8), as given by

$$\eta, \text{PVT} = \frac{(P + Q)}{G \times A}. \tag{9}$$

For the performance of the PV module, the following assumptions were used in this experiment:

(i) The PV module back surface temperature, $T_{\text{back,equals}}$, the coconut coir fiber temperature

(ii) The heat transfer coefficient is constant for the front and back surfaces of the PV module

(iii) The pump work was neglected in calculating output power from the PVT system

4. Results and Discussion

In this section, the data collected from the three PV modules were analyzed and discussed critically. Data collected from the climatic condition will also be examined concerning the performance of the PV modules.

4.1. Weather Parameter Analysis. The characteristics of a PV module are primarily influenced by the environmental factors that affect it. These environmental parameters will physically influence the PV performance. In this experimental study, two significant parameters controlling the PV module performance are solar irradiation and ambient temperature,

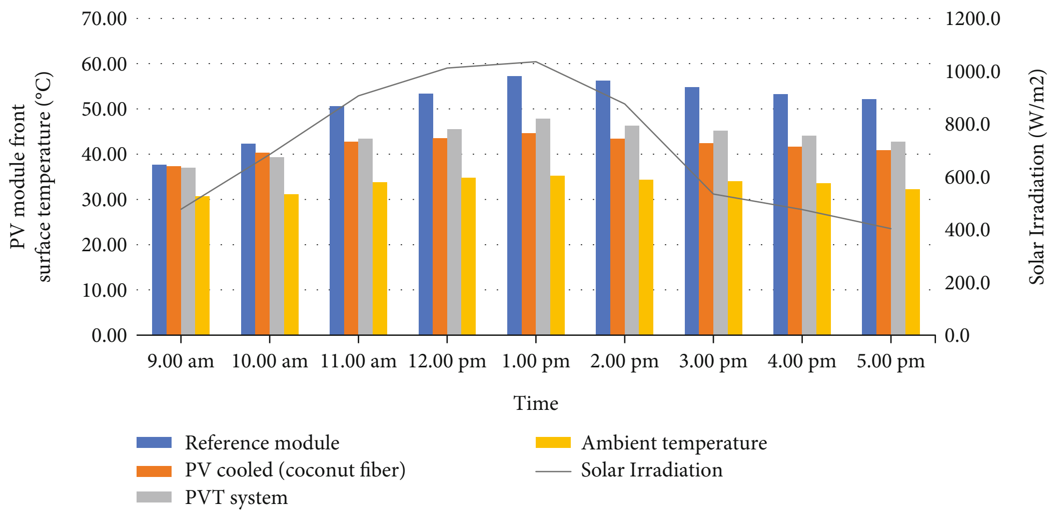

Figure 4: Variation of solar irradiation, ambient temperature, and PV module front surface temperature.

which go hand in hand. Figure 4 shows a parabolic trend of the solar irradiation and ambient temperature for the PV module temperatures On the day of the experiment, the solar irradiation and ambient temperature were recorded from 9.00 am until 5 pm, respectively. The peak solar irradiation and ambient temperature obtained from the experiment were 1036 W/m^2 and 35.2°C. As aforementioned, these stated environmental parameters significantly affect the PV module's performance by increasing and decreasing the PV module front surface temperature. It should be noted that a PV module's performance will be hampered as its front surface temperature rises due to the heat energy absorbed from solar irradiation during power production [13]. As the surface temperature increases, the PV module will operate at a temperature beyond its nominal operating cell temperature (NOCT) of about 25°C, which consequently causes inefficiency. From Figure 4, it can be inferred that all three PV modules' front surface temperatures have a linear relationship with solar irradiation. However, the noticeable difference is the variation in module surface temperature between the three PV modules. This is accomplished by using the two different cooling techniques described above to improve the back surface of the PV modules. The highest temperature recorded by the passively cooled PV module integrated with damp coconut fiber, PVT system, and reference module is 44.6°C, 47.8°C, and 57.2°C, respectively, at 1.00 pm. From the readings, it is clear that the passive cooled PV showed the lowest increment in module surface temperature, followed by the PVT system and the reference module. By integrating damp coconut, the temperature of the PV module surface was decreased by 22.03% and 23.46%, whereas the PVT system reduced the PV module surface temperature by 16.43%.

4.2. Electrical Performance. The I-V curve depicts a PV module's power output in relation to the solar irradiation incident on it and the temperature of the PV module. The voltage corresponds to the current, while the module temperature corresponds to the solar irradiation [24]. Figure 5 shows the I-V characteristic curve of the PV modules during the experimental testing. An increase in solar irradiation throughout the day causes an increase in current output, whereas an increase in PV module temperature results in a voltage drop corresponding to the results obtained. The short circuit current and open circuit voltage recorded for the passively cooled PV module integrated with coconut fiber, PVT system, and reference module are 1.7 A and 17.34 V, 1.68 A and 17.22 V, and 1.64 A and 16.8 V, respectively. These values are close to the PV module datasheet rating of 1.75 A and 21.97 V for the I_{SC} and V_{OC}, respectively, as stated in Table 2. Similar trends can be seen where the passively cooled PV module shows the highest maximum power output, followed by the PVT system and the reference module. The maximum power output is observed when the solar irradiation is at its peak. From both results, the maximum power point (MPP) for the passively cooled PV module with coconut fiber, PVT system, and reference module is 24.21 W, 20.21 W, and 14.65 W, respectively. Since the coconut fiber integrated PV module showed the lowest increase in surface temperature, it is evident that the voltage was not as affected as the PVT system. Therefore, a higher voltage from the passively cooled PV module and the steady current output resulted in a greater power output relative to the PVT system.

Power output is a product of the output voltage and current of the PV module. Corresponding to the I-V curve, the PV module will record the highest power output at the peak solar irradiance of the day. Figure 6 shows the power output of the PV modules with respect to the module's front surface temperatures calculated hourly on both days of the experiment. From the figure, the peak power outputs of the passively cooled PV module integrated with coconut fiber, PVT system, and reference panel are 24.21 W, 20.21 W, and 14.65 W, respectively. The passively cooled PV module

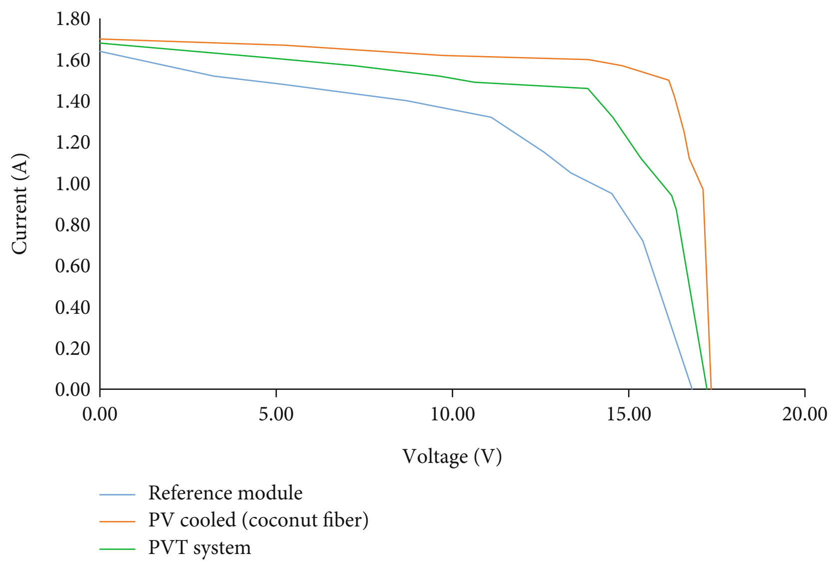

Figure 5: Comparison of output current and voltage between PV modules.

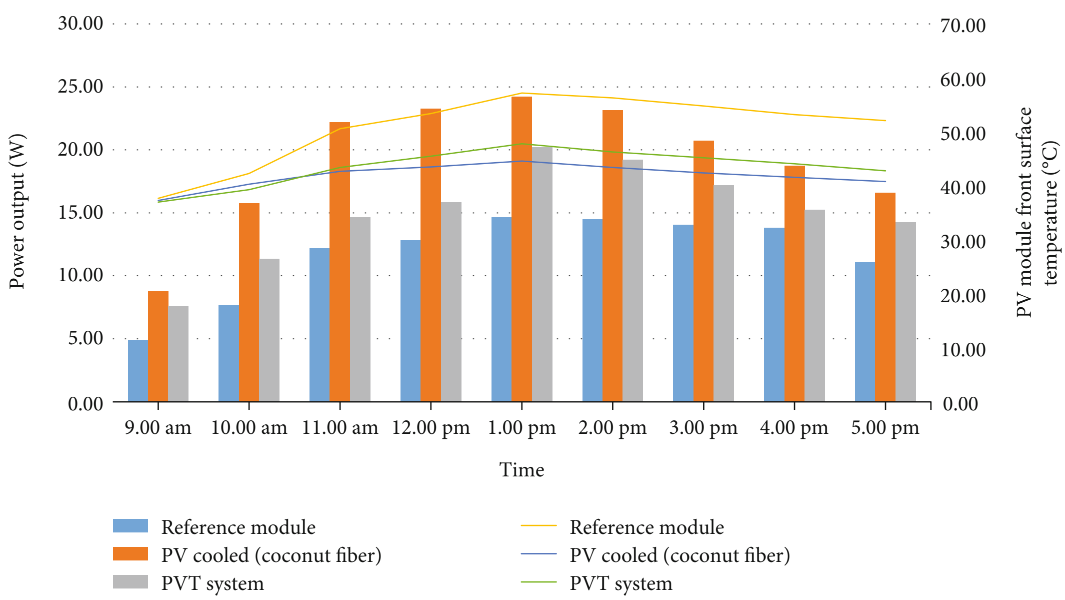

Figure 6: Comparison of power outputs and module temperature of uncooled, cooled, and PVT modules.

integrated with coconut fiber increased the power output by 65.26% on an experimental day. The PVT system, however, only managed to increase the power output by 37.95%. The passively cooled PV module increases power output significantly more than the PVT system. This can be explained by the fact that as more sensible heat is removed from the back of the PV module, the front surface temperature drops, resulting in higher voltage output. To put it another way, the convection that carries water molecules away from the back of the PV module increases heat loss from the back surface and, as a result, from the front cover of the passively cooled PV module compared to the PVT system.

4.3. Efficiency Parameters. The efficiency is a characteristic of how well a PV module responds to the solar irradiation intake by producing current. It measures the percentage of solar irradiation that is converted to electricity and wasted as heat. As mentioned in the literature work, the two energies that are produced by a PV module include heat and electrical energy, in which heat energy is dominating output than the latter. The electrical efficiencies of the three PV modules and the thermal and overall efficiencies of the PVT system are depicted in Figure 7. During peak solar irradiation, the electrical efficiencies of the passively cooled PV module integrated with coconut fiber are 9.96% higher than

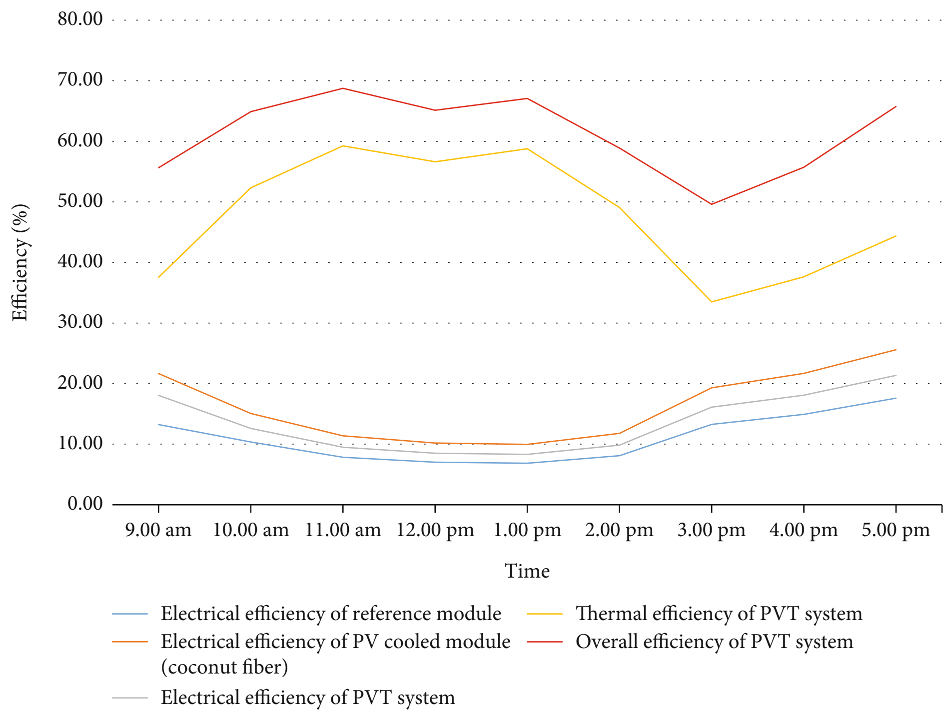

Figure 7: Comparison of electrical, thermal, and overall efficiency of uncooled, cooled, and PVT modules.

the PVT system, which has an electrical efficiency of 10.42 percent. The PV module's efficiency was increased by 45.4 percent using moist coconut fiber passive cooling, whereas the PVT system only increased the electrical efficiency by 21.46 percent. In a similar energy efficiency context, the PVT system, however, can be categorized into two types of efficiency reading, namely, electrical and thermal efficiency. This is because, other than electric current, the PVT system also provides heat energy. Water flowing in the thermal collector at the PV module's back surface is responsible for collecting the heat energy produced by the PV module. From the figures, the thermal efficiencies of the PVT system during the peak solar irradiation are 58.77%. When combined with the electrical efficiency, it is evident that the overall energy efficiency of the PVT system surpassed the electrical efficiency of the passively cooled PV module with a value of 67.06%. This is because, in the passively cooled PV module, water molecules from the moist coconut fiber absorb the sensible heat from the PV module and escape to the atmosphere through the perforation in the polyethylene sheet encapsulation. This indefinitely removes all the valuable heat energy that can be utilized. In the case of the PVT system, the fitting of the thermal collector, as its name suggests, collects the available heat energy from the PV module instead of wasting its potential. Moreover, as mentioned earlier, heat energy is produced greater than electrical energy in a PV module. Therefore, this statement can be validated by the PVT system's thermal efficiency, which is always a greater value than the electrical efficiency in both figures.

4.4. Performance Comparison. The moist coconut fiber acts as a heat sink on the PV module's back surface, which is critical for removing sensible heat from the module. Water molecules are directly in contact with the PV modules' back surface with the coconut fiber's help due to the coconut fiber's high water-holding capacity, lowering the back surface temperature of the module. This allows heat energy generated on the PV module to be rapidly transferred from the front to the back surface through conduction. Following this, the sensible heat will be absorbed by the water molecules present in the coconut fiber. Finally, when the water molecules have absorbed sufficient heat energy, they will act as a heat removal agent by evaporating through the perforations present on the polyethylene sheet encapsulation. In short, the water molecules will carry away the sensible heat energy from the PV module to the atmosphere by convection. Furthermore, for the PVT system, the oscillatory flow thermal collector system is responsible for the heat removal from the PV module. As the water flows through the thermal collector attached to the back surface of the PV module, heat energy from the front surface is conducted to the back and the collector by an aluminum plate attached between the thermal collector and the PV module back surface. The function of the aluminum plate is to provide a uniform heat transfer from the front to the back surface, subsequently, to the thermal collector. As the module temperature increases, more sensible heat will be removed by the water flowing in the thermal collector at a constant flow rate of $0.02\,kg\,s^{-1}$. Although both cooling techniques had some common characteristics of the heat removal mechanism, the passively cooled PV module managed to significantly lower the temperature of the PV module compared to the PVT system. Table 3 shows the performance of all the PV modules that gave the best results.

Table 3: Summary of performance.

PV module	Module temperature (°C)	Electrical efficiency (η_{el}, %)	Thermal efficiency (η_{th}, %)	Overall efficiency (η_{Ov}, %)
Reference	56.70	5.70	—	5.70
Cooled	41.70	10.47	—	10.47
PVT system	48.70	8.46	58.00	67.06

Table 4: Comparison of results with the other studies.

Researchers	Type of study	Back surface attachment	Efficiency improvement (%)
Grubišić-Čabo et al. [25]	Experimental	Perforated fins (random arrangement)	2
Hamdan et al. [26]	Experimental	Phase change material (PCM)	2.6
Arifin et al. [15]	Experimental	Heat sink with fins	2.4
Elbreki et al. [13]	Experimental	Lapping fins and planar reflector	1.39
Kiwan et al. [27]	Modeling and Simulation	Phase change material (PCM)	1-2
This study	Experimental	Biomaterial (moist coconut fiber)	3.11

To further validate the effectiveness of the passively cooled PV module integrated with moist coconut fiber, a series of comparisons can be made with other researchers who have conducted passive cooling of the PV module by enhancing the back surface of the PV module using similar or different mediums. Table 4 shows the comparison between different passive cooling techniques and their increment in efficiency to the current study.

The commonly found back surface attachment for a passively cooled PV module uses fins or phase change material (PCM). In this experiment, adding biomaterial to the PV module significantly increased efficiency over the others.

5. Conclusion

This investigation is aimed at comparing the performance of uncooled, cooled PV modules and PVT systems with thermal and electrical performance. The rule of thumb is that the PV module's performance can be enhanced by lowering its front surface temperature. With that being said, the results obtained from this experiment can be summed up in the following way:

(i) The temperature reduction at the peak solar irradiation for the passively cooled PV module surface was 22.03%, while the temperature reduction for the PVT was 16.43%. The passively cooled PV module is more effective than PVT system in terms of temperature reduction

(ii) The PV module that was passively cooled had an electrical efficiency of 10.47%. The PVT system had an electrical efficiency of 8.4%. The peak thermal efficiency of the PVT system was 58.77%

(iii) The passively cooled PV module integrated with moist coconut fiber displayed the lowest module temperature (41.7°C), followed by the PVT system

(iv) The passively cooled PV module produces a more significant temperature reduction and better energy efficiency (10.47%) in this experimental study

(v) The PVT system, however, had the highest overall efficiency (67%) as it also produced valuable thermal energy in this study

With these performance analysis parameters, the coconut fiber-based cooling system is more efficient than the PVT and other related works. It can be concluded that nature-inspired coconut fiber-based cooling can be one of the potential alternatives to active cooling methods.

5.1. Limitations. During this experimental work, certain restrictions have been detected, which caused a slight drawback.

(i) The water element used in the PVT system was solely dependent on a tap water source. This is to be noted as the tap water source is also significantly influenced by the ambient temperature. This may have caused the temperature fluctuations in the PVT systems' water inlet

(ii) Next, another limitation seen was the air humidity. Despite being sunny, the air humidity varied. This means that the atmosphere's water content was not consistent on an experimental day. However, it is essential to note that air humidity was a minor factor influencing this experiment and, therefore, can be deemed insignificant

5.2. Future Scope. Future work should consider analyzing the studied system's exergy efficiency and exergy loss.

Data Availability

The data used to support the findings of this study have not been made available because of funder obligation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Pushpendu Dwivedi and Sujay Ashwinraj contributed equally to this work as first authors.

Acknowledgments

The corresponding author is grateful for the financial support of Universiti Malaysia Pahang (https://www.ump.edu.my) through grant PGRS210349. Mr. Pushpendu Dwivedi is grateful to MeitY for providing PhD fellowship under the Visvesvaraya PhD scheme of the Ministry of Electronics & Information Technology, being implemented by Digital India Corporation. The research work is also based on the outcome of long-term research collaboration between Universiti Malaysia Pahang, Malaysia, MANIT-Bhopal, India, and MIT-Manipal, India.

References

[1] M. Alobaid, B. Hughes, D. O'Connor, J. Calautit, and A. Heyes, "Improving thermal and electrical efficiency in photovoltaic thermal systems for sustainable cooling system integration," *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 6, pp. 305–322, 2018.

[2] P. A. Owusu and S. Asumadu-Sarkodie, "A review of renewable energy sources, sustainability issues and climate change mitigation," *Cogent Engineering*, vol. 3, no. 1, article 1167990, 2016.

[3] I. M. Kirpichnikova, K. Sudhakar, I. B. Makhsumov, A. S. Martyanov, and S. Shanmuga Priya, "Thermal model of a photovoltaic module with heat-protective film," *Case Studies in Thermal Engineering*, vol. 30, article 101744, 2022.

[4] P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, and I. Kirpichnikova, "Advanced cooling techniques of P.V. modules: a state of art," *Thermal Engineering*, vol. 21, article 100674, 2020.

[5] V. Sun, A. Asanakham, T. Deethayat, and T. Kiatsiriroat, "A new method for evaluating nominal operating cell temperature (NOCT) of unglazed photovoltaic thermal module," *Energy reports*, vol. 6, pp. 1029–1042, 2020.

[6] C. Zhang, C. Shen, S. Wei, Y. Wang, G. Lv, and C. Sun, "A review on recent development of cooling technologies for photovoltaic modules," *Journal of Thermal Science*, vol. 29, no. 6, pp. 1410–1430, 2020.

[7] O. C. Olawole, E. S. Joel, O. F. Olawole et al., "Innovative methods of cooling solar panel: a concise review," *Journal of Physics Conference Series*, vol. 1299, no. 1, article 012020, 2019.

[8] S. Kallio and M. Siroux, "Energy analysis and exergy optimization of photovoltaic-thermal collector," *Energies*, vol. 13, no. 19, article 5106, 2020.

[9] H. L. Tsai and C. J. Yang, "PV model with energy balance equation for commercial PV modules," *In Applied Mechanics and Materials*, vol. 284, pp. 1163–1167, 2013.

[10] C. G. Popovici, S. V. Hudişteanu, T. D. Mateescu, and N. C. Cherecheş, "Efficiency improvement of photovoltaic panels by using air cooled heat sinks," *Energy Procedia*, vol. 85, pp. 425–432, 2020.

[11] Z. Peng, M. R. Herfatmanesh, and Y. Liu, "Cooled solar PV panels for output energy efficiency optimisation," *Energy Conversion and Management*, vol. 150, pp. 949–955, 2017.

[12] M. A. Qasim, H. M. Ali, M. N. Khan et al., "The effect of using hybrid phase change materials on thermal management of photovoltaic panels - an experimental study," *Solar Energy*, vol. 209, pp. 415–423, 2020.

[13] A. M. Elbreki, K. Sopian, A. Fazlizan, and A. Ibrahim, "An innovative technique of passive cooling PV module using lapping fins and planner reflector," *Case Studies in Thermal Engineering*, vol. 19, article 100607, 2020.

[14] N. Abdollahi and M. Rahimi, "Potential of water natural circulation coupled with nano-enhanced PCM for PV module cooling," *Renewable Energy*, vol. 147, pp. 302–309, 2020.

[15] Z. Arifin, S. Suyitno, D. D. D. P. Tjahjana, W. E. Juwana, M. R. A. Putra, and A. R. Prabowo, "The effect of heat sink properties on solar cell cooling systems," *Applied Sciences*, vol. 10, no. 21, p. 7919, 2020.

[16] W. Lubon, G. Pełka, M. Janowski et al., "Assessing the impact of water cooling on PV modules efficiency," *Energies*, vol. 13, no. 10, article 2414, 2020.

[17] A. Hadipour, M. Rajabi Zargarabadi, and S. Rashidi, "An efficient pulsed- spray water cooling system for photovoltaic panels: experimental study and cost analysis," *Renewable Energy*, vol. 164, pp. 867–875, 2021.

[18] Y. Liu, Y. Chen, D. Wang et al., "Experimental and numerical analyses of parameter optimization of photovoltaic cooling system," *Energy*, vol. 215, article 119159, 2021.

[19] R. Rajasekar, P. Prasannaa, and R. Ramkumar, "Efficiency of solar PV panel by the application of coconut fibres saturated by earthen clay pot water," *Environmental Technology*, vol. 42, no. 3, pp. 358–365, 2021.

[20] A. Shahsavar, P. Jha, M. Arıcı, S. Nižetić, and Z. Ma, "Energetic and exergetic performances of a nanofluid-based photovoltaic/thermal system equipped with a sheet-and-grooved serpentine tube collector: indoor experimental tests," *Solar Energy*, vol. 225, pp. 918–933, 2021.

[21] S. Abdul-Ganiyu, D. A. Quansah, E. W. Ramde, R. Seidu, and M. S. Adaramola, "Investigation of solar photovoltaic-thermal (PVT) and solar photovoltaic (PV) performance: a case study in Ghana," *Energies*, vol. 13, no. 11, p. 2701, 2020.

[22] P. Kumar, A. K. Shukla, K. Sudhakar, and R. Mamat, "Experimental exergy analysis of water-cooled PV module," *International Journal of Exergy*, vol. 23, no. 3, pp. 197–209, 2017.

[23] R. Ballal, S. Sagar, and G. Kumar, "PV module, irradiation, shading, fill factor," *PV module, Irradiation, Shading, Fill factor*, vol. 5, pp. 1–4, 2015.

[24] H. Ibrahim and N. Anani, "Variations of PV module parameters with irradiance and temperature," *Energy Procedia*, vol. 134, pp. 276–285, 2017.

[25] F. Grubišić-Čabo, S. Nižetić, D. Čoko, I. Marinić Kragić, and A. Papadopoulos, "Experimental investigation of the passive cooled free-standing photovoltaic panel with fixed aluminum fins on the backside surface," *Journal of Cleaner Production*, vol. 176, pp. 119–129, 2018.

[26] M. Hamdan, M. Shehadeh, A. Al Aboushi, A. Hamdan, and E. Abdelhafez, "Photovoltaic cooling using phase change material," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 12, pp. 167–170, 2019.

[27] S. Kiwan, H. Ahmad, A. Alkhalidi, W. O. Wahib, and W. Al-Kouz, "Photovoltaic cooling utilizing phase change materials," *E3S Web of Conferences*, vol. 160, article 02004, 2020.