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Sustainable passive cooling strategy for PV module: A comparative analysis

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ABSTRACT

This paper presents the experimental studies of different passive cooling techniques to analyze the electrical power improvement and temperature reduction of a 50 W polycrystalline PV module. Plant cooling, greenhouse cooling, greenhouse + plant cooling, coir pith, and phase change material cooling are the various approaches are used in the analysis. The percentage of electrical power improvement and temperature of various passive cooling techniques are compared with solar modules without cooling. The maximum percentage power improvement (11.34%) was found to be in coir pith cooling with an average maximum power of 36.38 W. The maximum temperature reduction was observed to be 14 °C in case of plant cooling with a greenhouse. Considering the electrical power improvement and temperature reduction, coir cooling and plant cooling were found to be best suited for the given climatic conditions amongst all cooling techniques. The results also showed that the reduction in temperature does not always give rise to the increase in power as it was depicted in the case of greenhouse net cooling and plant cooling with greenhouse. This kind of cooling technique is best suited for agro-based countries in tropical regions.

1. Introduction

Conventional energy sources cannot be relied upon as they are limited [1]. Amongst renewable resources solar energy has increased its growth at an exponential rate. Energy generation is done by the use of solar cells and collectors that convert solar radiation into electricity. Besides being used for electricity generation, solar energy can be used for heating and cooling. Even though there has been tremendous growth in the field of solar PV and thermal collectors, they require auxiliary components such as energy storage which adds to the total cost of the system [2]. Extensive research has been done in the area of performance analysis of Solar PV to obtain more energy per unit area [3]. Studies have also revealed the importance of local climate on solar PV plants [4]. Because of the government's favorable policies in support of solar energy, there has been an increase in the implementation of these technologies [5]. Depending on the type of solar cells and the climatic conditions, a typical PV module converts only 5–20% of the incoming solar radiation into electricity [6]. Enhanced current or voltage parameters are typically used to improve electrical performance

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characteristics in a PV cell or module. By maximizing incoming solar radiation using standard concentrators, current parameters can be improved [6]. Cuce [7] has experimented on the relationship of G and I_{sc} under different humid conditions. The results revealed that the effect of humidity level was found to be minimal [8]. To describe the electrical behavior of a PV cell or module practically and reliably, two resistors must be added to Shockley's ideal diode equation [9]. This method is known as the five-parameter method. It is well known in the literature that cell temperature, which is commonly experienced in hot and temperate climatic situations, has a significant impact on the energy efficiency parameters of PV modules [10].

1.1. *Problem identification and research gap*

Temperature is one of the prominent factors affecting the output power of the Solar PV module [11]. Solar PV efficiency decreases with an increase in temperature. The desirable operating temperature of the solar module is 25 °C, however, in certain scorching and dry climates, the temperature of the module is doubled from STC. It is widely known that the working temperature of PV panels has a significant impact on the already low PV technology efficiency, with a rate of estimated PV panel efficiency degradation ranging from 0.25%/^{0}C to 0.5%/^{0}C as operating temperatures rise [11–13]. There is also a problem of overheating of the Solar PV module, which is usually found in arid and humid conditions [12]. Hence, cooling of solar PV cells is required with no or less consumption such that maximum power output can be delivered.

1.2. *Objective of the study*

In this research, an experimental investigation has been performed to maintain the standard operating temperature of the PV module using various passive heat extracting methods without additional energy use. The concept of passive cooling based on sustainable aspects to encourage the effectiveness of PV technology has been emphasized in this research. The following are the experimental investigation are:

1. To study the various passive PV cooling techniques: plant cooling, greenhouse cooling, greenhouse + plant cooling, coir material, and phase change material.
2. To examine temperature regulation and Power yield improvement of passively cooled modules with the uncooled module.
3. To compare and identify the best passive cooling strategies among the studied techniques.

2. Literature review on active and passive cooling techniques

Ambient temperature, as well as the temperature of the module, also affects a PV module's efficiency, and this is because the module voltage and current depend on the temperature and sunlight [11]. The temperature coefficient of the PV module plays a significant role in output performance. It indicates the degree of the electrical power of the module is affected [12]. To optimize the performance of the panel, it is essential to maintain the operating temperature as low as a minimum, which is called standard test condition (STC) or 25 °C temperature. Thus, taking into account all the above factors, there is a necessity to cool the temperature of the Solar PV module for getting the desired output. Numerous studies have been done in the area of reducing overheating in solar PV panels [13].

2.1. *Active cooling*

Cooling systems consisting of heat-dissipating devices such as fans or pumps for circulating air or water are classified as Active cooling systems. These systems require an external supply of energy for powering devices such as fans, pumps. Nizetic et al. [14] provided an extensive study on active cooling techniques. The study concluded that air-based cooling techniques are greatly hazardous to the environment as they increase the global warming and acidification effects.

2.2. *Passive cooling*

Cooling systems that do not require any external power source are classified as passive cooling systems. These systems use natural methods to provide air or liquid circulation and reduce the heat of the system. Comprehensive and Econo-environmental analysis of

Table 1
Comparison of active and passive cooling techniques.

S.No	Parameter	Active Cooling	Passive Cooling
1	Energy consumption	High	Zero/negligible
2	External energy source	Required	Not Required
3	Movable parts	Present	Absent
4	Coolant flow Rate	High	Low
5	Cost	High	Low
6	Efficiency	High	Low
7	Temperature Regulation	High	Low

Passive cooling techniques based on the Levelized Cost of Energy (LCOE) suggested that there is a wide scope of research necessary in finding Efficient Passive Cooling Techniques with the least environmental impact [15]. Grubisic-Cabo et al. [16], concluded that to take away heat from PV panels, the extracting method needs to act on as much of the panel backside as possible. The numerical study showed that the backside of the panel is closer to cell temperature when compared to the Front side of the panel. Hence it is necessary to cool the backside of the panel. From the literature, it is clear that there are no efficient passive cooling techniques. The pros & cons of the Active and Passive cooling Techniques have been compiled and presented in Table 1 [17–19].

From Table 1, it is understood that though active cooling techniques have higher energy efficiency, the cost associated with it is high which may limit its application for large-scale Solar power plant [20–23]. From the literature, it is clear that there are no efficient passive cooling techniques that can not only provide cooling but also do not consume additional power where each unit of energy consumed plays a very vital role. Hence this work is aimed to study the various passive cooling techniques.

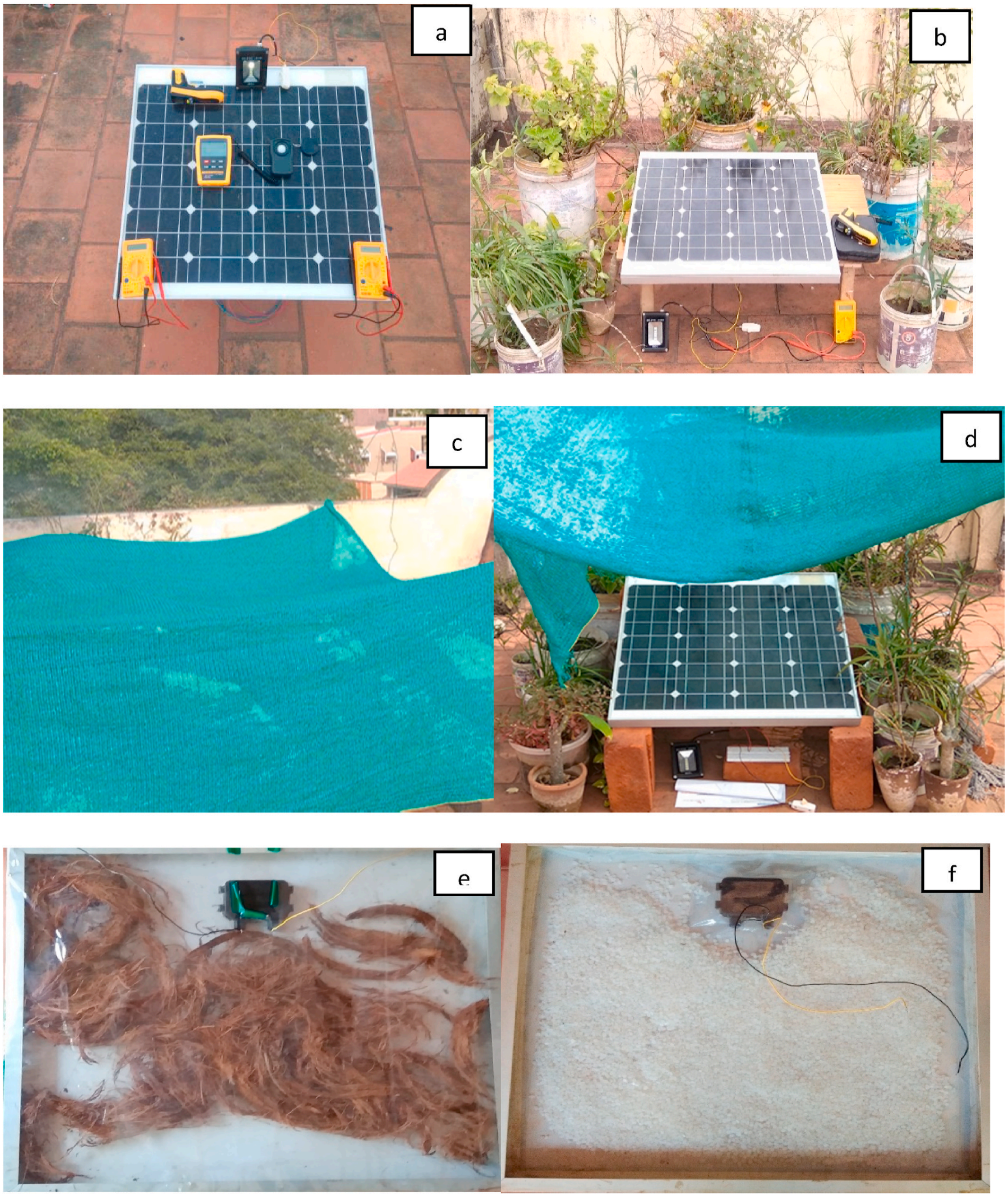

Fig. 1. Experimental setup of PV module
A) without cooling B) with plants C) with greenhouse(net) D) greenhouse (net) and plant E) coir material) Phase change material.

2.3. Research gap and novelty of the work

- Passive cooling outperforms active cooling in terms of overall efficiency considering auxiliary power consumption. So, there is a need to widen the research on passive cooling techniques which doesn't consume power and are sustainable in the long term.
- The following specific cooling techniques like plant cooling, coir cooling, Greenhouse cooling, PCM cooling are still in the experimental stage of research.
- The primary novelty of the research study is the very first investigation of cooling techniques such as plant and coir cooling which is not attempted previously. As far as the author's knowledge coir, greenhouse, and plant cooling has been proposed for cooling PV panel for the first time

3. Experimental methodology

The experimental setup, the materials used and the performance indicators for the analysis are explained in the following section.

3.1. Experimental setup

The experimental setup consists of a solar module of 50Wp power capacity mounted on a stand with optimum tilt, and exposure to sunlight. The solar panel was tilted adequately to ensure maximum reception of solar radiation. The PV modules were initially mounted without cooling arrangement and were tilted at an angle of 15° facing due south to receive the best output of the research location. The Experiment setup was developed with various passive cooling technologies as shown in Fig. 1. The locally available indoor plants which are domestically used were used for plant cooling. These plants decrease the humidity level in the surroundings and improve the efficiency of solar panels. Greenhouse (net) was taken from local plant vendors. This is generally used for Greenhouse farming, to prevent overexposure to sunlight. Coir or coconut fiber is a natural fiber extracted from the husk of coconut and used in products such as floor mats, brushes, and mattresses. Coir is composed of lignin, cellulose, hemicellulose, and ash. The water-soaked coir when placed under the PV panel, at critical temperature absorbs some amount of heat from the module and reduces the temperature of the PV module. Phase Change Materials (PCM) are substances that possess a high heat of fusion that promotes the substance to melt and solidify at a point of temperature (melting point). Paraffin wax is mostly found as a white, odorless, tasteless, waxy solid, with a typical melting point between about 46 and 68 °C (115 and 154 °F) and a density of around 900 kg/m^3. It is insoluble in water.

3.2. Experimental procedure

The research was carried out in the tropical location of Kumbakonam, Tamil Nadu in the northern hemisphere (10.9602° N, 79.3845° E) [15], during the month of May, when is no many variations in climatic conditions and sunlight available for almost 8 h on an average. For the purpose of the study, the effect of other environmental parameters such as the wind, humidity, dust, etc, was not considered. The experiment was carried out under sunlight from 9:00 a.m. to 4:00 p.m. throughout the day. All the temperature measurements were done using an infrared thermometer. A handheld solar power meter was used to measure solar radiation. The experiment was carried out using passive cooling technologies. The experiment was carried out in Kumbakonam which is tropical in nature with dry climatic conditions (Fig. 2).

For every 1 h, the temperature readings of the module were taken. Using digital multimeters, the Vm and Im of the solar panel are measured as different cooling technologies are employed over the solar panel. The specification of the solar module and the sensitivity of the instrument are presented in Table 2 and Table 3.

The uncertainty of the used instruments is determined by calibration, reading observation, atmospheric conditions, and instrument

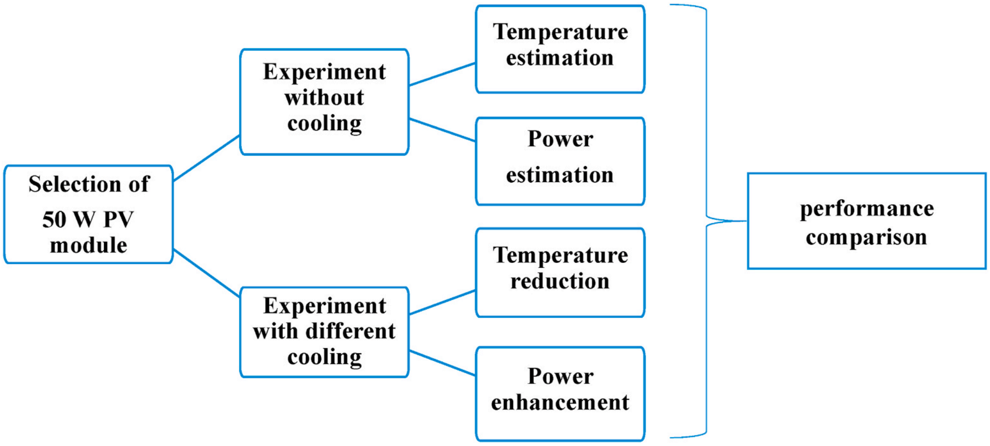

Fig. 2. Flow chart of the experimental study.

selection. It is used to assess the precision of the instruments used in the study. The uncertainty analysis was used to calculate errors associated with temperature, voltage, and current measurements. The overall uncertainty in the analysis is within 2% based on the accuracy and precision of the instrument used. As a result of the aforementioned, there is less uncertainty in the inferences.

3.3. Performance indicators

The efficiency of the PV module is a dependent factor on the power generated by the module at the given instant of time. The maximum power generated by the module at each moment is calculated by the observed values of Im and Vm.

The power delivered by a solar module is given by

$$\mathrm{P_{out}} = \mathrm{Vmp{\cdot}Imp} = FF \times V_{OC} \times I_{SC} \tag{1}$$

Where Pmp is the maximum power output of the Solar panel, Vmp is the voltage at the maximum power point, Imp is the current at the maximum power point, FF is the fill factor of the Solar PV module under consideration, while Voc is the voltage of the panel in the absence of the load and Isc is the current of the panel when the output is short-circuited.

The temperature reduction of the module is calculated using 2

$$\therefore \text{Temperature reduction} = \text{average temperature without cooling -average temperature with cooling} \tag{2}$$

The power enhancement of the module is calculated using 3

$$\therefore \text{\% power improvement} = \text{average power with cooling -average power without cooling} \div \text{(average power without cooling)] x 100\%} \tag{3}$$

4. Results and discussion

4.1. Variation of the electrical parameters

The comparison of the electrical characteristics of PV modules with and without cooling techniques is depicted in Fig. 3. Without cooling, it was observed that the average voltage of 17.8 V was achieved in the experiment. With the cooling, the average voltage of the solar PV module varied from 18.1 V to 20.3 V. With plant cooling, the average voltage was 19.3 V. When Greenhouse cooling was employed; it was observed that the average voltage obtained was 18.1 V. This can be attributed to the fact that the Greenhouse-maintained temperature and did not allow more sunlight to pass through it. When Greenhouse cooling was used along with Plant cooling, there was an improvement of voltage 20 V. This is because there was more provision for sunlight to pass through this setup when compared to the previous arrangement. When coir pith was employed for cooling, the average voltage was 20.3 V. This is because the coir path has moisture retaining property and thus can maintain optimum temperature. When PCM cooling was used, the average voltage of 19.8 V was obtained.

The average current was determined to be 1.76A without cooling. Cooling caused a significant change in current, from a minimum of 0.58 A to a maximum of 1.81 A. Lower current values are linked to greenhouse cooling and greenhouse + plant cooling. This can be attributed to the greenhouse's ability to block direct sun rays.

The average electrical power output of solar PV modules without cooling was found to be 32.6 W. With cooling there was significant variation in power output ranging from 10.82 W to 36.38 W. This can be attributed mainly to the variation of current in various passive cooling techniques. For Coir pith cooling, the average output power was 36.38 W. When the combination of greenhouse and plant cooling was employed, the average output, power was 19.59 W.

Table 4 provides the comparison of % power improvement for various cooling techniques. The maximum power improvement (11.34%) was obtained when coir cooling was used. Plant cooling was the second-best cooling technique, resulting in a (7.34%) increase in power. When compared to plant cooling, which uses air as the medium of coolant, water-soaked coir has better cooling capabilities due to its moisture-retaining capacity. It is worth emphasizing that greenhouse net cooling and the combination of greenhouse + net cooling resulted in % power reduction rather than improvement. The % power reduction was found to be as high as 66.88%–40.03%. Still, unlike, in other cases, it did result in a power improvement. When PCM cooling was incorporated, the % power

Table 2
Specification of the solar module.

S.No	Description	Rating
1	Maximum Power	50 Watt
2	Open circuit Voltage (Voc)	22.3 V
3	Short circuit current (I sc)	3.15 A
4	Voltage at maximum power (VMP)	17.8 V
5	Current at maximum power (IMP)	2.81 A
6	Dimension	0.64 m*0.60 m
7	Fill Factor	0.72
8	Area of the Module	0.384m^2

Table 3
Sensitivity of the instrument.

Instrument	Parameter	Accuracy	Resolution	Range
Multimeter	Current and Voltage	DC Current = 1.8% DC Voltage = ± 0.5%	10 mV 10 mA	0–200V 0–10A
Infra-red thermometer	Temperature	±0.2 °C	0.1 °C	−30 °C–500 °C

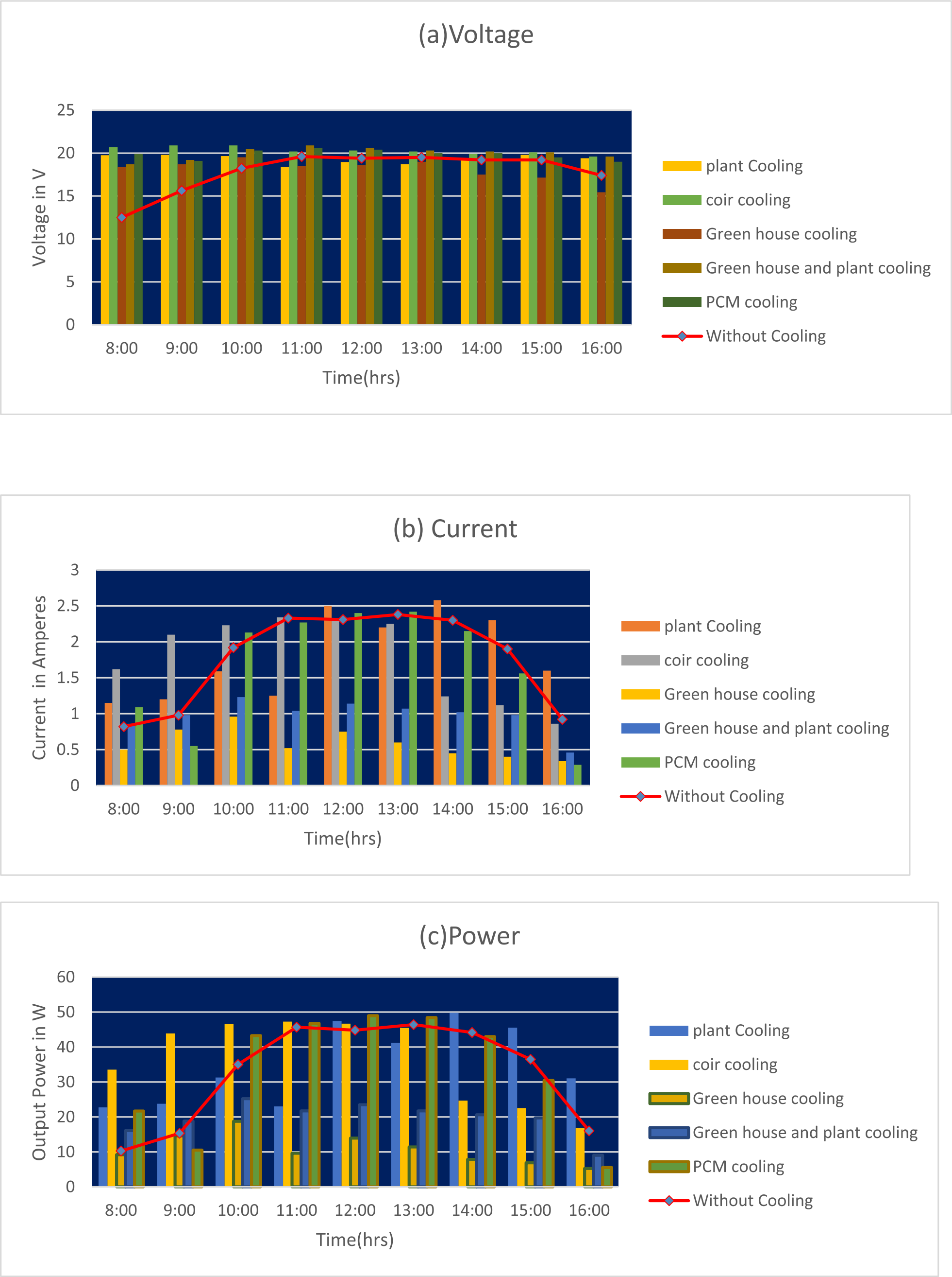

Fig. 3. Comparison of electrical characteristics of PV module with and without cooling techniques.

Table 4
Comparison of % power improvement for various cooling methods with reference PV Panel.

S. No.	Experiment	Peak Voltage (V)	Peak Current (A)	Peak Power(W)	Average voltage(V)	Average current (A)	Average power(W)	% Power improvement (W)
1.	**Without cooling (Reference PV Panel)**	19.6	2.3	46.4	17.8	1.76	32.67	–
2.	Plant cooling	19.8	2.5	49.7	19.3	1.81	35.07	7.34
3.	Greenhouse (net) cooling	19.5	0.9	18.7	18.1	0.58	10.82	−66.88
4.	Greenhouse (net) and plant cooling	20.9	1.2	25.2	20	0.97	19.59	−40.03
5.	Coir cooling	20.9	2.3	47.2	20.3	1.78	36.38	11.34
6.	Phase change material	20.6	2.4	48.9	19.8	1.65	33.16	1.49

improvement is not that significant. This may be due to the type of PCM material chosen for this analysis. However further experiments are needed with advanced nano-based PCM material to arrive at the efficacy of the PCM-based passive cooling techniques.

4.2. Variation of module temperature

Hourly cell temperature readings were used to compare the temperature variation of the PV module. Fig. 4 shows the comparison of module temperature under different passive cooling techniques. As shown in Table 5, the highest temperature of the module without cooling approaches was 69 °C, and the temperature of the module was lowered when cooling techniques were used. The combination of Greenhouse (net)and plant cooling provided the maximum reduction in module temperature (14 °C). This can be attributed to the fact that the plants provided natural air circulation with the obstruction of direct solar radiation. When Greenhouse cooling, the temperature reduction was about 12.1 °C. With the use of Greenhouse (net), plant cooling, and its combination, the average temperature was maintained for a long time compared with the other cooling techniques. It can be concluded from this Green House (Net) can maintain a constant temperature. The best temperature reduction along with the optimal power output was obtained for the plant cooling. It is very interesting to note, even though coir cooling had the least temperature reduction, it had the best electrical power output. So even though coir material has the inherent property of retaining moisture, but still it was not efficient in cooling when compared to other techniques. The general myth that temperature reduction results in an increase in electrical power output are not substantiated with the findings of this study. The temperature reduction in the PCM cooling technique was found to be second best when compared to other cooling techniques.

4.3. Performance comparison with other researchers

The performance comparison of various passive cooling techniques is presented in Table 6. The results presented in this study reveals the effectiveness of the proposed passive cooling methods.

5. Conclusion

One of the trending areas of research is the identification of suitable low-cost passive cooling techniques to reduce the operating

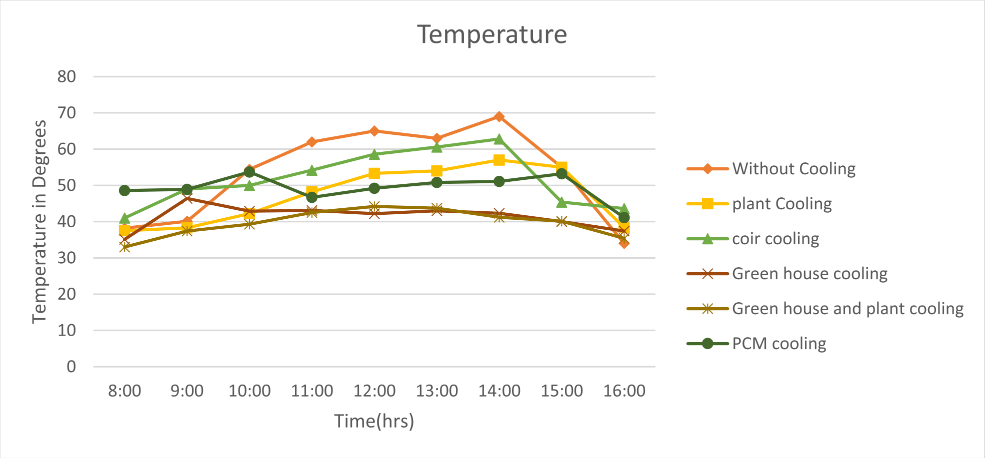

Fig. 4. Comparison of module temperature with and without cooling techniques.

Table 5
Comparison of Temperature reduction for various cooling methods with reference PV Panel.

S. No.	Experiment	Peak temperature (°C)	The average temperature (°C)	The temperature reduction compared to the reference PV panel (°C)
1.	Without cooling (Reference PV Panel)	69	53.4	–
2.	Plant cooling	57	47.1	6.3
3.	Greenhouse (net) cooling	46.4	41.3	12.1
4.	Greenhouse (net) and plant cooling	44.2	39.4	14
5.	Coir cooling	62.8	51.6	1.8
6.	Phase change material	53.7	49.2	4.2

Table 6
Comparison results with other passive cooling reported in the literature.

Author	Type of Panel	Place of Study	Type of cooling	Temperature reduction	Power Enhancements
Grubišić-Čabo et al. [16]	260 W poly crystalline	Split, Croatia	Fin based passive cooling	5 °C	–
Fahad et al. [24]	15 W Poly Crystalline	Saudi Arabia	PCM heat sinks	10 °C	–
Wongwuttanasatian et al. [25]	20 W Polycrystalline	KhonKaen, Thailand	PCM heat sinks	6.1 °C	–
Alagar et al. [26]	170 W CIS	Tamil Nadu, India	Inorganic PCM	9 °C	10%
Salem et al. [27]	50 W Poly Crystalline	Cairo, Egypt	PCM and water mixture	7.4 °C	–
Nasrin and Masoud [28]	10 W Poly crystalline panel	Kermanshah, Iran	Hybrid (Nano enhanced PCM water cooling)	25 °C	48.23%
Fatih et al. [29]	75W poly-crystalline modules	Elazig, Turkey	Finned, PCM, thermo electric modules	2.8 °C	7.72%
Bashir et al. [30]	40W monocrystalline	Mirpur, Pakistan	Back surface water cooling	5.2 °C	20%
This study	50 W Polycrystalline	TamilNadu, India	Coir cooling, Plant Plant cooling, PCM	1.8 °C 6.3 °C 4.2 °C	11.35% 7.34% 1.49%

temperature of a photovoltaic module. Various passive cooling methods are investigated in this experimental study to enhance the performance of the photovoltaic module. The study yielded the following conclusions:

Key findings & major outcome of the study:

1. The maximum power improvement (%) was found in the case of coir cooling (11.35%) and plant cooling (7.34%) respectively. The coir cooling technique provided maximum power improvement along with the optimum temperature reduction.
2. Plant cooling techniques provided better temperature regulation along with considerable power enhancement compared to the uncooled PV module.
3. The results abstained using phase change material is nominal when compared to coir cooling and plant cooling techniques respectively.
4. In the case of Greenhouse (net) cooling, the temperature reduction was very significant but it happened at the cost of less electrical power output. As Greenhouse (net) cooling is concerned, it is advised to employ where the temperature is maximum and unsustainable. Further, the net should be selected with the optimal pore size that allows the maximum amount of light radiation.
5. Based on the practical feasibility and the local environmental conditions, it is advised to employ plant cooling and coir cooling techniques for better performance of the PV module. As plant cooling is concerned, it is better to choose a plant that supports and enhances the cooling of the surrounding and the PV panel. This also prompts the way for atmospheric and nature-based PV cooling solutions which are greener compared to other methods.

Global relevance and practical implications:

6. Passive cooling technologies (plant cooling, coir cooling, PCM, etc.,.) can be implemented in Arid climatic conditions especially in large-scale solar power plants, residential and agricultural sectors for the improvement in performance in a sustainable manner.
7. The plant cooling technique can be implemented for Agrivoltaics where the temperature has to be maintained and also the power generated from the solar plant can be utilized for irrigation purposes and lighting the farm.
8. The coir-based cooling technique has wide scope in tropical countries where coconut is one of the staple foods and leftover coir is available in plenty. This technique is quite efficient, feasible, and also economical in such climatic conditions.

9. The greenhouse cooling technique can be used where temperature regulation is an important criterion. This technique can be integrated with Solar drying applications where electrical power output is of secondary importance when compared to thermal gain.
10. The right selection of material according to their melting point and ease of encapsulation with the PV panel is a key consideration in PCM.

Future scope: Future research can be carried with hybrid passive cooling techniques focused on modeling, optimization, exergy, and life cycle performance. The experimental setup can be further enhanced by adding smart features like IoT sensors, a data logger, and an AI-driven mechanism for the continuous monitoring of the temperature and electrical power output.

Credit authorship contribution statement

Ramkiran B: Conceptualization, Writing – original, Resources, **Sundarabalan CK:** Supervision, Formal analysis, Visualization.**K. Sudhakar:** Supervision,Visualization, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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