ASEAN Journal for Science and Engineering in Materials

Journal homepage: https://ejournal.bumipublikasinusantara.id/index.php/ajsem

Enhancing Photovoltaic Efficiency through Paraffin–Pomegranate Phase Change Composites: An Experimental Approach with Bibliometric Analysis toward Sustainable Thermal Management Aligned with Sustainable Development Goals (SDGs)

Ali M Jawarneh, Faris M. AL-Oqla, Mohamad Otair*

The Hashemite University, Zarqa, Jordan

*Correspondence: E-mail: jawarneh@hu.edu.jo

ABSTRACT

Overheating remains a major limitation to photovoltaic (PV) efficiency in high-temperature environments because excessive surface heat reduces electrical conversion and accelerates material degradation. This study integrates bibliometric and experimental approaches to develop a novel phase change composite (PCM) by combining paraffin with green composite materials (GCMs) derived from agricultural waste (pomegranate peel, sumac, and starch). Five PV panels with different PCM/GCM mixtures were tested under identical conditions to identify the most effective formulation. The optimal composition (57% paraffin and 43% pomegranate peel) achieved a melting point of 72°C and thermal conductivity of 0.1617 W/m.K, resulting in a 16.65% increase in daily energy output (240.98 Wh). Infrared imaging confirmed uniform temperature distribution and elimination of hot spots. The optimal condition was achieved because the fibrous pomegranate structure increased the melting point and stabilized the paraffin matrix, creating a porous network that improved heat absorption and distribution. This enhanced thermal regulation reduced surface temperature and hot spots, resulting in higher PV efficiency and energy output. This sustainable and low-cost innovation supports sustainable development goals (SDGs).

ARTICLE INFO

Article History:
Submitted/Received 06 Aug 2025
First Revised 27 Sep 2025
Accepted 10 Nov 2025
First Available online 11 Nov 2025
Publication Date 01 Sep 2026

Keyword:
Enhanced efficiency,
Global sustainability,
Green Composite Materials (GCMs),
Phase Change materials (PCMs),
PV cooling.

1. INTRODUCTION

Global climate change and the depletion of fossil fuel reserves have intensified the demand for alternative and sustainable energy sources. The solar energy sector has therefore experienced remarkable growth in recent years, emerging as one of the most promising renewable resources (Rozon *et al.*, 2023). However, despite the rapid development of photovoltaic (PV) systems, their efficiency is significantly limited by overheating under prolonged solar radiation. When the temperature of a PV panel exceeds 25 °C, the electrical conversion efficiency decreases, which leads to reduced output, material degradation, and a shorter lifespan of PV modules (Rozon *et al.*, 2023). Therefore, developing effective and sustainable thermal management techniques for PV systems in high-temperature regions remains a major scientific and technological challenge.

Phase change materials (PCMs) have attracted growing attention due to their ability to store and release large amounts of thermal energy during melting and solidification, providing a passive mechanism for temperature regulation (Sharma *et al.*, 2009). Organic PCMs such as paraffin are preferred for their chemical stability, non-corrosive behavior, and availability, whereas inorganic PCMs such as metal salts and hydrates possess higher latent heat capacities but suffer from corrosion and phase separation issues (Sharma *et al.*, 2009). Improving PCM formulations to enhance stability, thermal conductivity, and cost efficiency has thus become an important research direction in renewable energy and materials science (Sharma *et al.*, 2009).

Several studies have explored PCM-based PV cooling systems to reduce heat accumulation and improve power generation. For instance, the energy and environmental performance of PV–PCM systems under Mediterranean climates demonstrated improved thermal regulation but high initial energy costs (Foteinis *et al.*, 2023). Cooling with nanoemulsions increased overall system efficiency to 84% compared with 80% for water cooling (Liu *et al.*, 2023). Adjusting the tilt angle of PCM heat sinks reduced PV temperatures by up to 12% (Abdulmunem *et al.*, 2021). The use of tubular PCM enclosures and hybrid water-PCM systems further reduced module temperatures by 6.4–7.5 °C (Savvakis *et al.*, 2020; Abdollahi & Rahimi, 2020). Natural water circulation combined with nano-enhanced PCMs achieved up to 48% higher energy efficiency than conventional PCMs (Sudhakar *et al.*, 2021). Radiation-based PCM modules, thermoelectric generator (TEG) integration, and composite enhancements using graphene and magnesium oxide have also shown significant potential (Karthikeyan *et al.*, 2020; Soares *et al.*, 2020; Darkwa *et al.*, 2019; Rajvikram *et al.*, 2019; Li *et al.*, 2019).

Recent reviews have classified PCMs into four major systems (pure, composite, feather, and hybrid), highlighting that composite PCMs yield the best thermal performance when integrated with additives such as graphene nanoplatelets or magnesium oxide (El Kassar *et al.*, 2024; Ma *et al.*, 2019). Nonetheless, the cost, durability, and environmental impact of PCM-based cooling systems remain major barriers to large-scale application (Tao *et al.*, 2019). To improve sustainability, bio-based PCMs such as BioPCM M51 Q25 derived from plant extracts have been proposed, leading to a 3.4% annual increase in power generation efficiency (Nijmeh *et al.*, 2020). However, these studies still rely heavily on synthetic materials, leaving an important gap in the exploration of green composite materials (GCMs) as natural thermal enhancers for PCMs (Reji Kumar *et al.*, 2024).

GCMs, often derived from renewable fibers or agricultural by-products, are increasingly being considered for environmentally responsible engineering applications because they offer high strength-to-weight ratios, biodegradability, and cost efficiency. Incorporating such natural materials into PCMs may reduce thermal leakage, stabilize the matrix, and improve heat distribution without the environmental drawbacks of synthetic additives. Despite these advantages, the integration of GCMs into PCMs for PV cooling has not yet been systematically investigated.

Recent experimental studies on nano- and hybrid PCMs show the potential of material enhancement to improve energy efficiency. Adding SiO_2 nanoparticles to paraffin increased its thermal conductivity from 0.24 W/m·K to 0.45 W/m·K (Bharathiraja *et al*., 2024). Vermiculite–paraffin and pearlite–paraffin composites provided better temperature control and solar panel efficiency (Govindasamy & Kumar, 2023). In Iraq's climate, paraffin–beeswax mixtures reduced film temperature by 4 °C and improved panel performance by 1% (Mohammed *et al*., 2024). Furthermore, finned eutectic PCMs have been shown to effectively reduce module temperature and improve conversion efficiency (Homlakorn *et al*., 2022).

A bibliometric analysis conducted using Scopus data from 2013 to 2024 confirms a steady global increase in PV–PCM research, with the most common keywords being "thermal management," "latent heat storage," and "nano-enhanced PCMs." However, there is a striking absence of studies on bio-based or agricultural waste composites, indicating a clear research gap and opportunity for innovation (El Kassar *et al*., 2024; Reji Kumar *et al*., 2024).

The objective of this study is twofold: (1) to experimentally evaluate the thermal and electrical performance of PV panels integrated with paraffin–GCM mixtures and (2) to identify the optimal composition that maximizes energy output and heat regulation efficiency. Additionally, a bibliometric review is employed to contextualize the research within global PCM–PV trends and to validate its contribution to sustainable energy innovation. This research supports Sustainable Development Goals, especially SDG 7for Affordable and Clean Energy and SDG 12 for Responsible Consumption and Production, by transforming agricultural waste into functional materials for renewable energy systems. The novelty of this study lies in introducing a new paraffin–green composite system that integrates pomegranate peel, sumac, and starch (three agricultural wastes abundant in Jordan) as thermal additives to improve PCM properties. This integration increases the melting point, enhances conductivity, stabilizes paraffin, and ensures uniform heat transfer. Unlike previous works that relied on synthetic or nano-based additives, this research pioneers the use of natural waste fibers to improve the efficiency and sustainability of PV cooling.

2. METHODS

The experimental setup consisted of five identical photovoltaic (PV) panels, whose specifications are presented in **Table 1**. Each panel had a nominal peak power of 20 W, a maximum power voltage of 18 V, and a maximum power current of 1.11 A. The short-circuit current was 1.22 A, while the open-circuit voltage reached 21.6 V. The maximum system voltage was 1000 VDC, and the physical dimensions of each panel were 410 × 320 × 17 mm. To facilitate thermal regulation, an aluminum container (41 × 32 cm) with internal fins, shown in **Figure 1**, was attached to the back of each panel. The aluminum container was filled with a mixture of paraffin as the base phase change material (PCM) and green composite materials (GCMs) to evaluate their influence on thermal behavior and electrical output (Sharma *et al*., 2009).

All materials used in this research were locally sourced. Paraffin was selected as the PCM, while sumac, starch, and pomegranate peel were chosen as GCMs derived from agricultural waste. Each sample weighed 1.700 kg. Sumac is a tangy red spice made by grinding dried sumac berries, while pomegranate peel was dried and ground into a fine powder. Starch was used in powdered form. Nine different mixtures were prepared by varying the proportions of paraffin and the green additives (**Table 2** and **Figure 2**). Three mixtures were prepared for each GCM type (pomegranate peel, sumac, and starch), maintaining a total mass of 1.7 kg per sample to ensure consistency. The purpose of these variations was to determine the optimal PCM-GCM ratio that provides the best thermal performance and energy efficiency.

Table 1. Specifications of the solar panel.

Nominal Peak Power	Maximum Power Voltage (Vmp)	Maximum Power Current (Imp)	Short-Circuit Current (Isc)	Open-Circuit Voltage (Voc)	Maximum System Voltage	Size (mm)	No.
20 W	18 V	1.11 A	1.22 A	21.6 V	1000 VDC	410 × 320 × 17	202010110

Figure 1. An aluminum container with internal fins attached to the back of the solar panel.

Table 2. Different loadings of green composite materials (GCM)

Mixture	Abbreviation	Paraffin Content (kg)	Fiber Content (kg)	Total Mass (kg)	% Paraffin	% Fiber
Paraffin 87% and Pomegranate 13%	M-1	1.479	0.221	1.7	87%	13%
Paraffin 74% and Pomegranate 26%	M-2	1.258	0.442	1.7	74%	26%
Paraffin 57% and Pomegranate 43%	M-3	0.969	0.731	1.7	57%	43%
Paraffin 87% and Sumac 13%	M-4	1.479	0.221	1.7	87%	13%
Paraffin 74% and Sumac 26%	M-5	1.258	0.442	1.7	74%	26%
Paraffin 57% and Sumac 43%	M-6	0.969	0.731	1.7	57%	43%
Paraffin 87% and Starch 13%	M-7	1.479	0.221	1.7	87%	13%
Paraffin 74% and Starch 26%	M-8	1.258	0.442	1.7	74%	26%
Paraffin 57% and Starch 43%	M-9	0.969	0.731	1.7	57%	43%

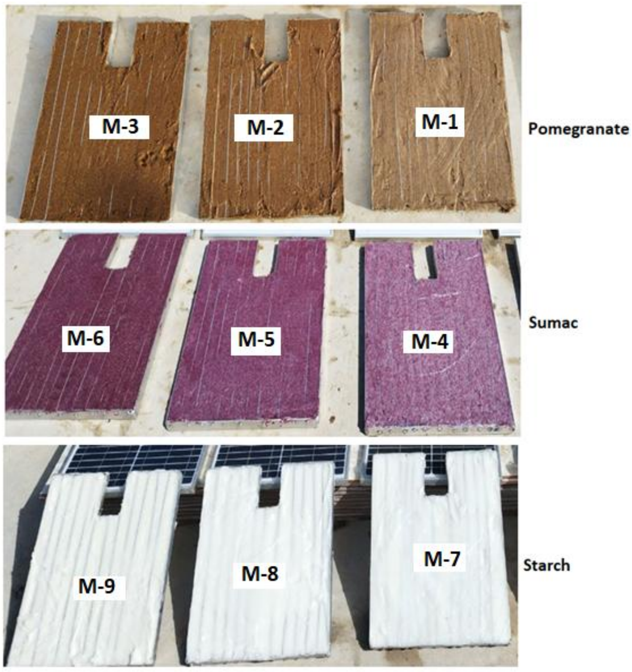


Figure 2. Nine different mixtures made from paraffin and various additives (pomegranate, sumac, and starch) in varying proportions.

The melting point is a key selection criterion for PCMs, as it determines the temperature range at which energy storage and release occur. PCMs with tunable melting points are essential in solar applications requiring stable heat absorption and discharge. Paraffin has a baseline melting point of 37 °C and thermal conductivity of approximately 0.3 W/m·K. To enhance these properties, the mixtures were tested using an electric oven to determine their melting points. For each mixture, three heating tests were conducted, and the average melting temperature was calculated. The data in **Table 3** show that increasing the proportion of GCM additives consistently raised the melting point of the paraffin composite. Among all formulations, Mixture 3 (57% paraffin and 43% pomegranate) exhibited the highest melting point of 72 °C, followed by Mixture 9 (starch-based) at 61.3 °C. These findings demonstrate that the thermal properties of paraffin composites are strongly influenced by both the type and concentration of bio-based additives (Foteinis *et al*., 2023).

Solar irradiance was measured throughout April and May using a calibrated pyranometer positioned horizontally to capture total global radiation. **Figure 3** illustrates the daily radiation profiles during both months. The cumulative daily radiation was obtained by summing the values across each month, resulting in a total of 760 MJ/m^2 in April and 840 MJ/m^2 in May. These irradiance values provided the environmental parameters for assessing the system's thermal performance under realistic outdoor conditions (Rozon *et al*., 2023).

Thermal conductivity, thermal diffusivity, and volumetric heat capacity of the GCMs (pomegranate peel, sumac, and starch) were measured using a Hot Disc thermal analyzer. The results are summarized in **Table 4**. Pomegranate peel exhibited the highest thermal conductivity (0.1617 W/m·K) and thermal diffusivity (0.3704 mm^2/s), followed by sumac and starch. Conversely, sumac displayed the highest volumetric heat capacity (0.7664 MJ/m^3·K), indicating a greater ability to store heat. Pomegranate peel's superior conductivity and diffusivity make it the most effective additive for rapid heat transfer, while sumac's high heat capacity makes it advantageous for thermal energy storage. Starch demonstrated balanced properties between the two. These measurements guided the selection of the most effective composite formulation for PV panel integration (Govindasamy & Kumar, 2023; Mohammed *et al.*, 2024).

Table 3. Melting points for various GCMs

Materials	Abbreviation	Test 1 (°C)	Test 2 (°C)	Test 3 (°C)	Average (°C)
Paraffin 87% and Pomegranate 13% (Mixture 1)	M-1	40	39	41	40
Paraffin 74% and Pomegranate 26% (Mixture 2)	M-2	58	53	57	56
Paraffin 57% and Pomegranate 43% (Mixture 3)	M-3	74	70	72	72
Paraffin 87% and Sumac 13% (Mixture 4)	M-4	44	40	49	44
Paraffin 74% and Sumac 26% (Mixture 5)	M-5	46	48	54	49.3
Paraffin 57% and Sumac 43% (Mixture 6)	M-6	54	51	58	54.3
Paraffin 87% and Starch 13% (Mixture 7)	M-7	44	45	50	46.3
Paraffin 74% and Starch 26% (Mixture 8)	M-8	50	55	57	54
Paraffin 57% and Starch 43% (Mixture 9)	M-9	59	63	62	61.3

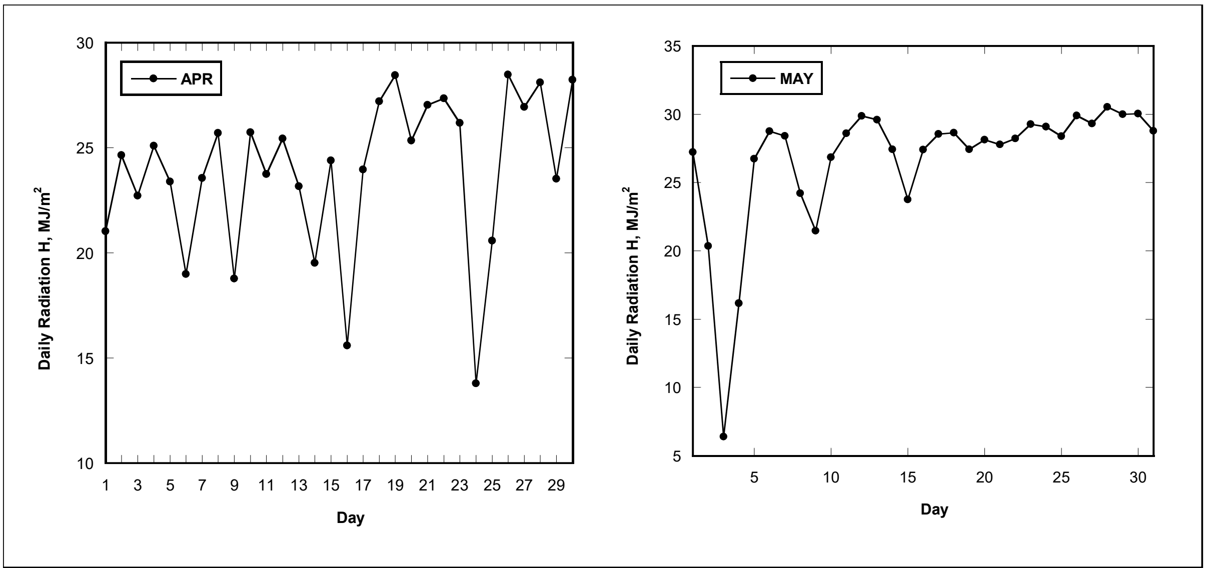


Figure 3. Daily solar irradiation for April and May.

Table 4. Thermal conductivity, thermal diffusivity, and volumetric heat capacity of green composite materials.

Material	Thermal Conductivity (W/m·K)	Thermal Diffusivity (mm²/s)	Volumetric Heat Capacity (MJ/m³·K)
Pomegranate Peel	0.1617	0.3704	0.4365
Sumac	0.1374	0.1793	0.7664
Starch	0.1250	0.2535	0.4932

3. RESULTS AND DISCUSSION

The performance of photovoltaic (PV) panels enhanced with various phase change composite materials was evaluated to determine the influence of green composite additives (pomegranate peel, sumac, and starch) on thermal regulation and power generation. Each composite mixture (M-1 to M-9) combined paraffin with one of the selected bio-based materials at different ratios. The results are discussed in terms of power output, temperature regulation, and material performance, leading to the identification of the most efficient mixture (M-3). The discussion also interprets these findings through the lens of sustainable development goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), emphasizing the environmental and energy efficiency benefits of utilizing agricultural waste in energy systems.

Figure 4 illustrates the bibliometric growth trend of global photovoltaic (PV) research based on Scopus database records from 1923 to 2025. The analysis reveals an exponential increase in the number of publications over the past two decades, reflecting rapid technological advances and intensified global interest in solar energy systems. Research output began to accelerate notably after 2010, coinciding with the expansion of renewable energy policies and improvements in PV efficiency. The sharp rise from 13,864 documents in 2017 to over 25,000 in 2024 demonstrates the ongoing momentum toward sustainable energy innovation and aligns with global efforts to achieve SDG 7: Affordable and Clean Energy. The sustained publication volume in 2025 indicates that PV research continues to be a dominant focus within the renewable energy domain, emphasizing its critical role in the transition to low-carbon energy systems. This bibliometric analysis has been well-used in many areas (Nandiyanto *et al*., 2025; Solehuddin *et al*., 2025; Mubarokah *et al*., 2024; Maryanti *et al*., 2022).

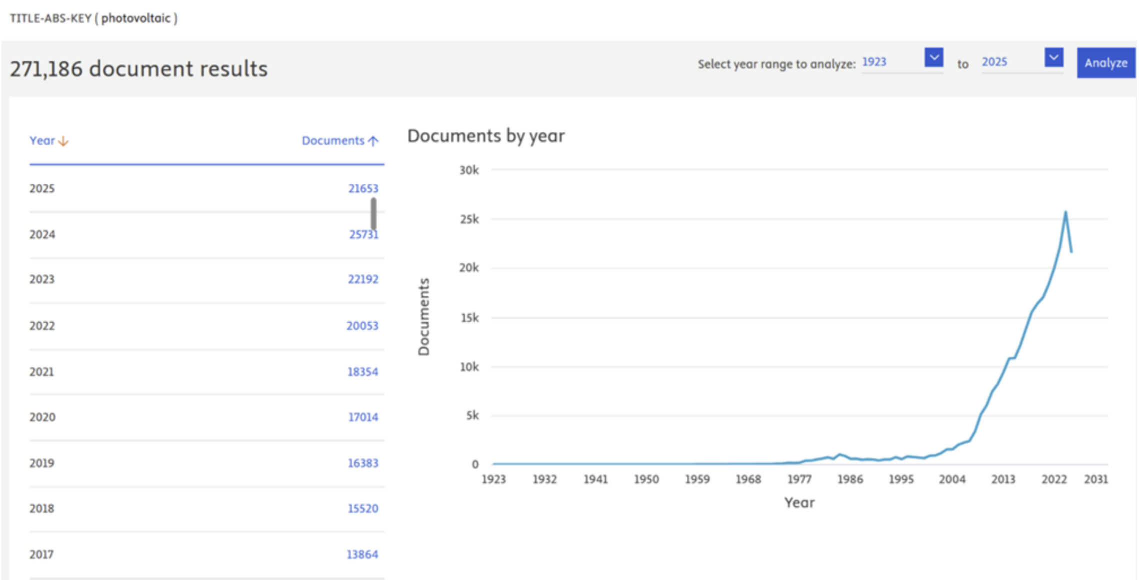


Figure 4. Bibliometric trend of global photovoltaic (PV) research publications from 1923 to 2025 based on Scopus data, showing exponential growth in scientific output and reflecting increasing global attention toward sustainable energy development. Data was taken in November 2025.

3.1. Photovoltaic Output Power Performance

The output power of each PV panel configuration was monitored at half-hour intervals using a digital multimeter with a sensitivity range of ±0.025% to ±1%. The current and voltage data were used to calculate instantaneous output power. Among the three additive groups (pomegranate (M-1, M-2, M-3), sumac (M-4, M-5, M-6), and starch (M-7, M-8, M-9)), each group demonstrated distinct behavior influenced by the proportion of the green composite material. The systematic comparison allowed a comprehensive understanding of how thermal and structural properties of different agricultural additives affect PV performance (Foteinis *et al*., 2023).

3.2. Effect of Pomegranate Peel

Figure 5 illustrates the energy output of PV panels integrated with varying percentages of pomegranate peel. The output increased consistently with higher pomegranate content. The M-3 mixture, composed of 57% paraffin and 43% pomegranate peel, achieved the highest total energy yield of 196.8 Whr over the test day. This was followed by M-2 (74% paraffin, 26% pomegranate) with 194.1 Whr and M-1 (87% paraffin, 13% pomegranate) with 186.4 Whr. The results clearly indicate that incorporating more pomegranate peel enhances heat regulation, leading to higher power generation.

The superior performance of the M-3 composite can be attributed to its increased melting point (72 °C) and improved heat distribution due to the fibrous microstructure of the pomegranate peel. The bio-fibers within the PCM matrix enhance the structural integrity and provide more uniform heat transfer pathways. This facilitates better temperature stability on the rear surface of the PV module, which in turn increases the efficiency of energy conversion. The gradual energy release during the melting phase of the PCM prevents excessive heating of the panel and minimizes efficiency losses typically caused by thermal stress (Sharma *et al*., 2009).

The results also suggest that agricultural waste, such as pomegranate peel, can serve as an effective thermoregulating filler for PCMs, offering an eco-friendly, low-cost, and sustainable alternative to synthetic additives. This approach supports the circular economy by repurposing organic waste for renewable energy technologies, contributing directly to SDG 12.

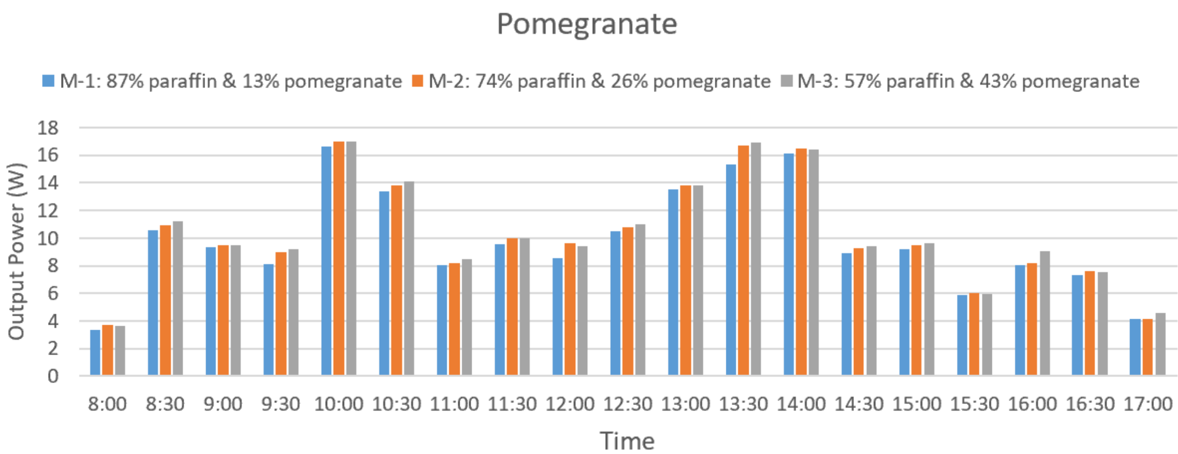


Figure 5. Output power from samples with varying percentages of pomegranate peels.

3.3. Effect of Sumac

The effect of adding sumac powder as a green composite material is shown in **Figure 6**. The panels with sumac additives exhibited more complex behavior compared to the pomegranate. The M-5 mixture (74% paraffin, 26% sumac) recorded the highest total energy yield at 263.5 Whr, followed by M-6 (57% paraffin, 43% sumac) at 260.5 Whr, and M-4 (87% paraffin, 13% sumac) at 252.7 Whr.

Unlike the pomegranate composites, the increase in sumac percentage did not result in a linear improvement in performance. This non-linear trend can be explained by the relatively lower thermal diffusivity (0.1793 mm^2/s) of sumac compared to pomegranate peel (0.3704 mm^2/s). When the concentration of sumac becomes too high, the internal heat conduction rate decreases, preventing effective energy transfer from the PV surface into the PCM layer. Thus, although sumac possesses a higher volumetric heat capacity (0.7664 $MJ/m^3 \cdot K$), which enables greater energy storage, excessive loading may limit thermal circulation and delay the release of stored heat (Govindasamy & Kumar, 2023).

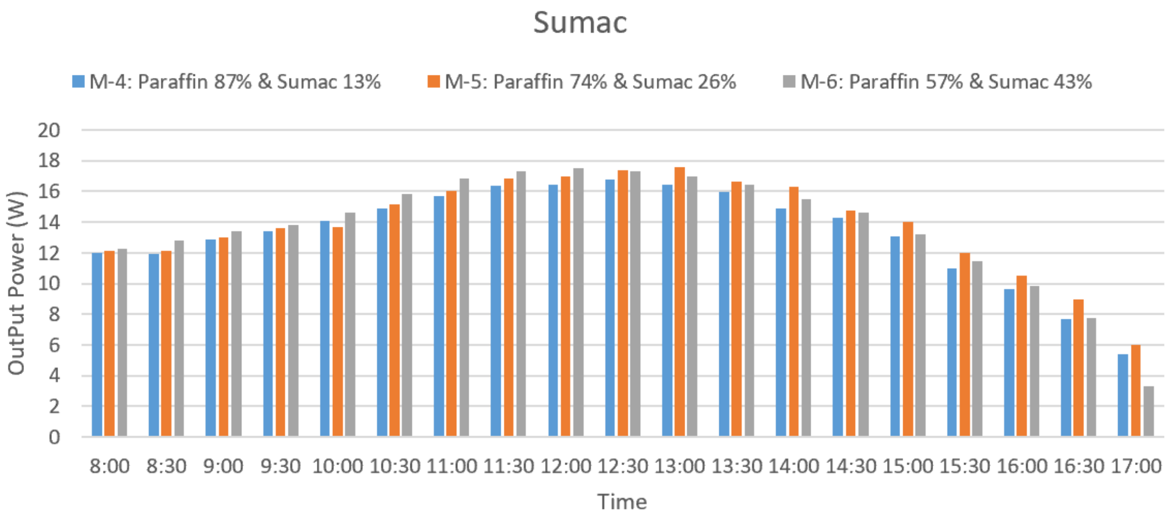


Figure 6. Output power from samples with varying percentages of sumac.

In practical terms, a medium proportion of sumac (as in M-5) achieves a balance between energy storage and heat conduction. This result is valuable for applications requiring stable nighttime heat release or intermittent cooling. However, in regions with intense solar radiation where rapid heat dissipation is essential, sumac may not perform as effectively as pomegranate-based composites.

3.4. Effect of Starch

The impact of starch on PV energy output is presented in **Figure 7**. Among the starch-based mixtures, M-8 (74% paraffin, 26% starch) produced the highest energy yield at 257.4 Whr, followed by M-7 (87% paraffin, 13% starch) at 253.4 Whr, and M-9 (57% paraffin, 43% starch) at 247.8 Whr. These results demonstrate that increasing starch content beyond an optimal limit does not further enhance PV output.

This pattern can be attributed to starch's moderate thermal conductivity (0.125 $W/m \cdot K$) and diffusivity (0.2535 mm^2/s), which provide balanced but not superior heat transfer properties. Moderate amounts of starch enhance the PCM's stability without excessively hindering heat flow. However, high starch concentrations may create thicker thermal barriers, reducing the material's ability to absorb and discharge heat efficiently. As such, starch is most effective as a stabilizing agent rather than as the primary thermal conductor. Its performance supports prior findings that natural polysaccharide-based materials provide structural reinforcement and prevent leakage in paraffin composites but do not significantly enhance conductivity (Mohammed *et al*., 2024).

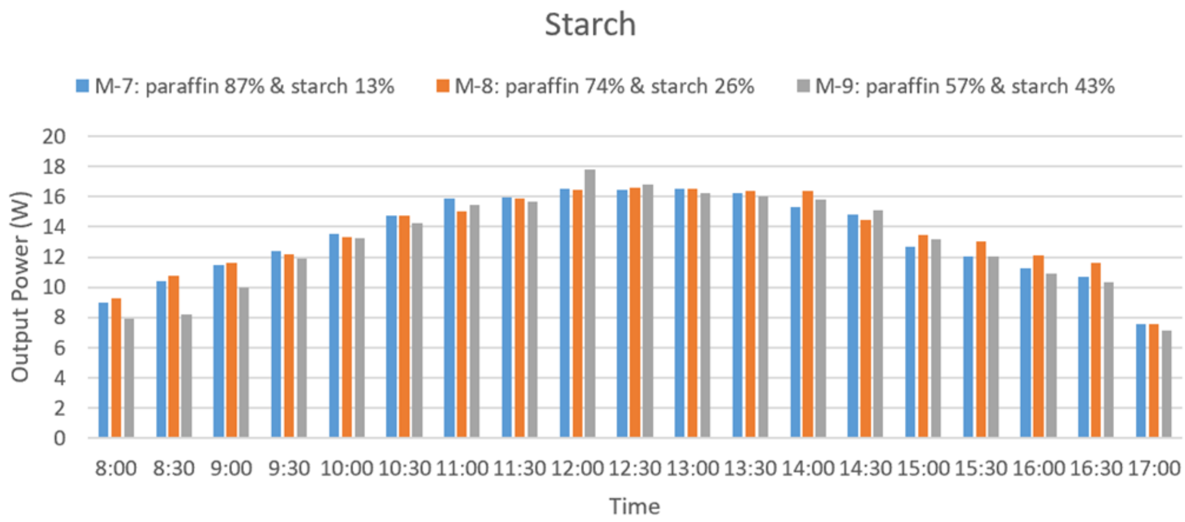


Figure 7. Output power from samples with varying percentages of starch.

3.5. Comparison of Best Samples (M-3, M-5, M-8)

A direct comparison among the three best-performing mixtures (M-3 (pomegranate), M-5 (sumac), and M-8 (starch)) was conducted under identical experimental conditions. **Figure 8** shows the five solar panels used in the study: a reference panel (without PCM), a paraffin-only panel, and three panels containing the paraffin-based composites.

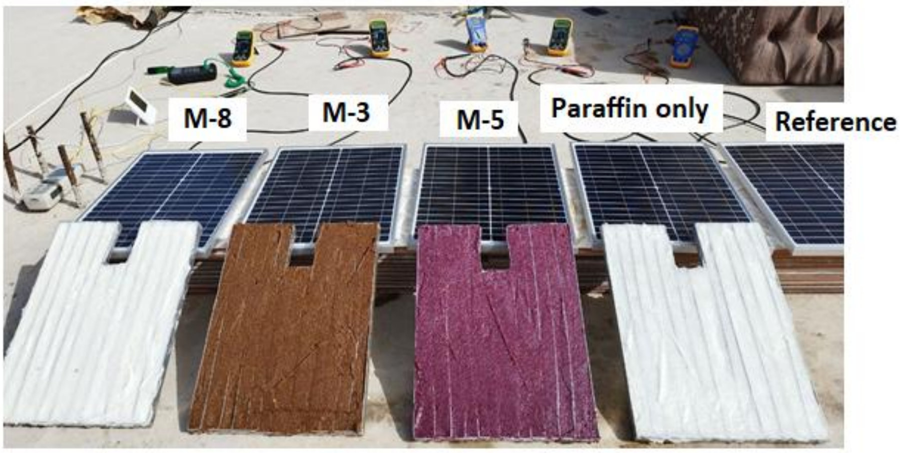


Figure 8. Five solar panels used in the experiment.

Figure 9 depicts the output power profiles measured at half-hour intervals throughout the day. The reference PV panel consistently showed the lowest power output, confirming the adverse impact of overheating on photovoltaic efficiency. The paraffin-only panel demonstrated an improvement over the reference, validating paraffin's capacity to absorb heat during its phase transition. However, all three PCM–GCM mixtures significantly outperformed both the reference and paraffin-only configurations, highlighting the contribution of green additives in improving heat regulation and efficiency.

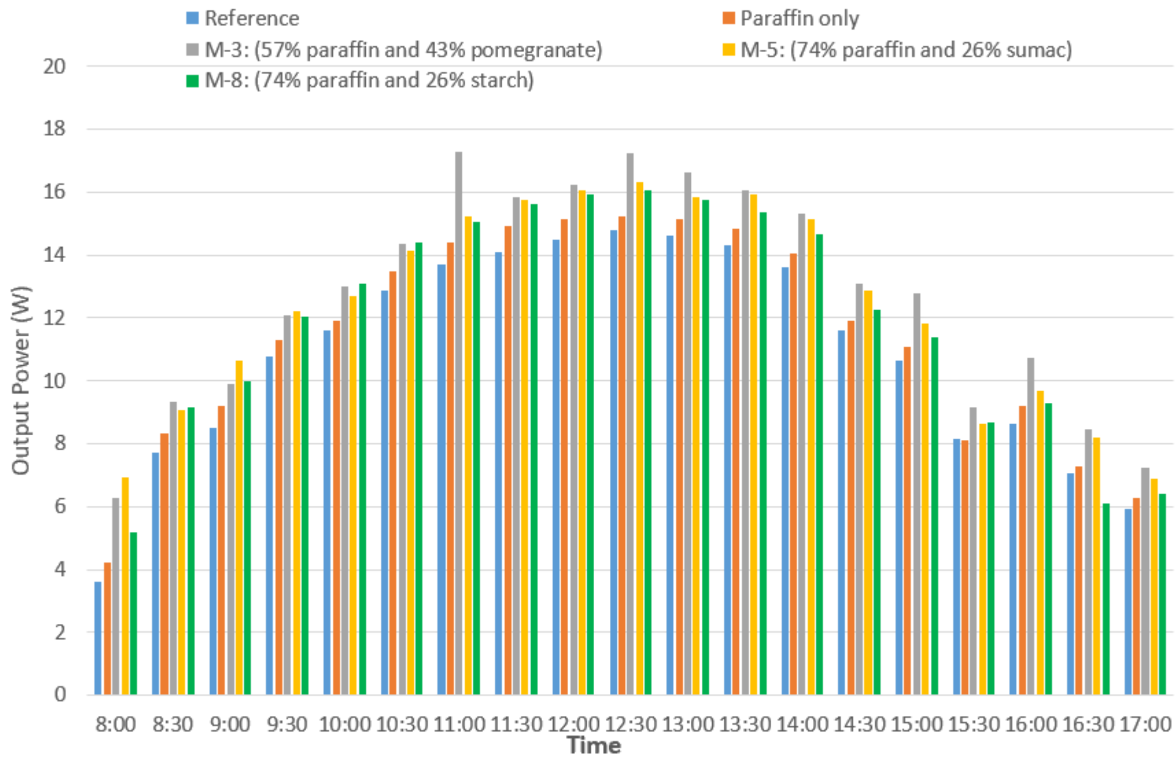


Figure 9. Output power (W) of different solar panel setups measured at half-hour intervals throughout the day.

The M-3 panel, consisting of 57% paraffin and 43% pomegranate peel, achieved the highest peak output power of 17.30 W at 11:00 AM, maintaining a consistently higher performance throughout the day. The M-5 panel (74% paraffin and 26% sumac) reached a peak of 16.30 W at 12:30 PM, ranking second overall. Meanwhile, the M-8 panel (74% paraffin and 26% starch) peaked at 14.40 W at 10:30 AM.

The data indicate that paraffin-based PCMs containing bio-waste composites exhibit substantial improvements in power generation efficiency compared to conventional setups. Notably, M-3's superior output can be explained by its optimized combination of high thermal conductivity, elevated melting point, and porous microstructure, which collectively promote uniform temperature distribution. The fibrous matrix formed by pomegranate peel aids in minimizing temperature gradients, ensuring steady energy conversion and reducing thermal stress on solar cells.

3.6. Daily Output Power and Energy Yield Analysis

To further quantify the impact of each configuration, **Figure 10** compares the total daily energy output (Whr) for all panels under uniform conditions. The reference PV panel generated the lowest total output of 206.59 Whr, while the paraffin-only panel reached 215.96 Whr. The panels with composite mixtures outperformed both, with M-3 (pomegranate) achieving the highest total output of 240.98 Whr, followed by M-5 (sumac) at 233.99 Whr and M-8 (starch) at 226.43 Whr.

These results clearly show that integrating bio-based additives enhances both heat management and energy efficiency. The presence of pomegranate peel not only improves the heat absorption–release cycle but also delays the onset of thermal saturation, allowing the PV panel to maintain a higher operational efficiency during midday peaks. The improvement of 16.65% in daily energy output for M-3 compared to the reference demonstrates its capability to mitigate temperature-induced efficiency loss—a well-known limitation in PV systems exposed to high-temperature environments (Rozon *et al*., 2023).

The observed ranking (M-3 > M-5 > M-8 > paraffin-only > reference) provides empirical validation that material selection and composite formulation critically determine PCM effectiveness. The success of M-3 also reinforces the concept that enhancing the **melting point** and **thermal diffusivity** through natural fillers can achieve significant efficiency gains without compromising material sustainability.

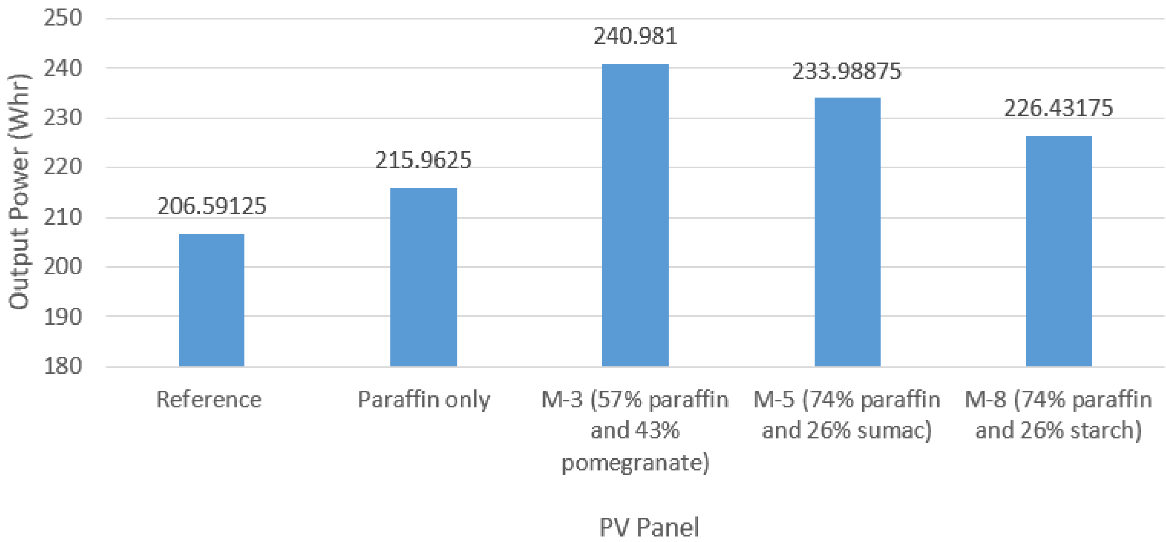


Figure 10. Measured daily output power (Whr) of solar panels tested under identical conditions.

3.7. Percentage Increase in Output Power

The comparative enhancement in energy output among different PV configurations is illustrated in **Figure 11**. Four systems were evaluated relative to the reference panel: the paraffin-only configuration and three paraffin–GCM mixtures (M-3, M-5, and M-8). The paraffin-only system achieved a modest 4.54 % increase in total output power, confirming that even conventional PCM provides basic thermal buffering. The addition of green materials, however, produced substantially higher performance.

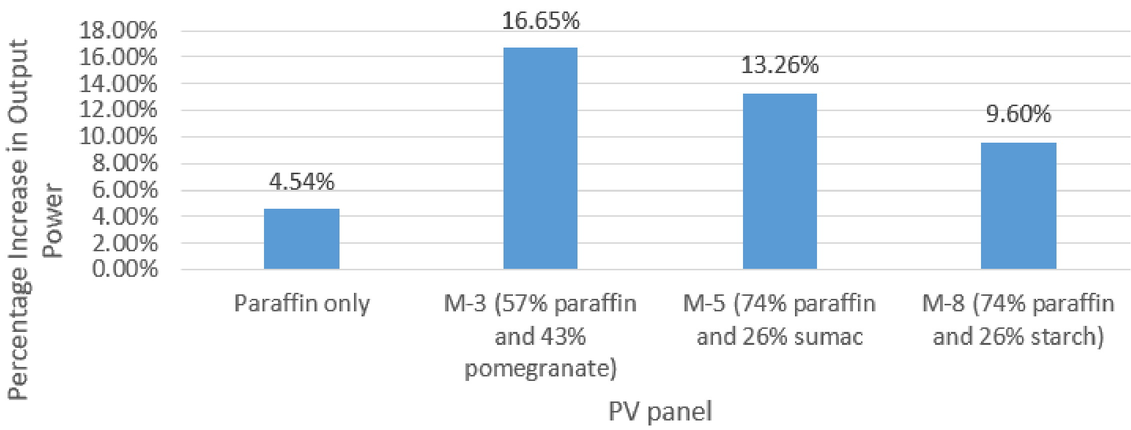


Figure 11. Percentage increase in output power for different solar panel configurations compared to the reference panel.

Among the composites, M-3 (57 % paraffin, 43 % pomegranate) exhibited the greatest improvement, recording a 16.65 % increase in output power compared to the reference. M-

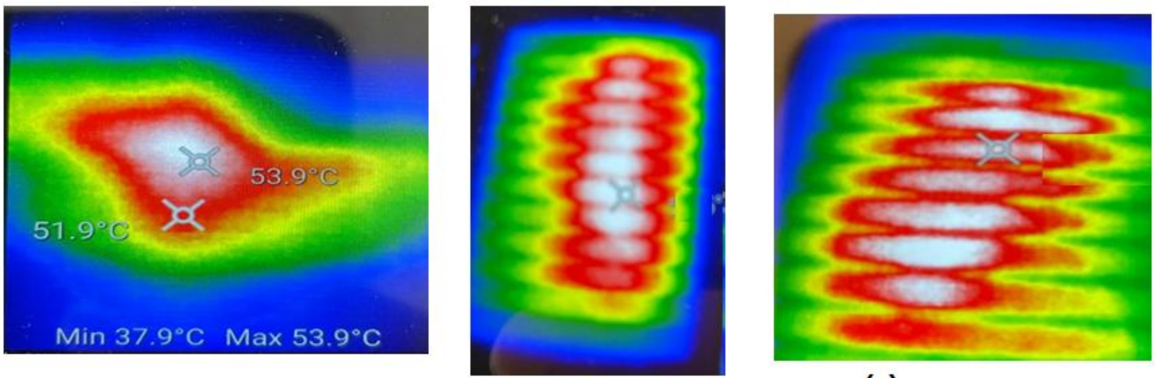
5 (74 % paraffin, 26 % sumac) followed with 13.26 %, while M-8 (74 % paraffin, 26 % starch) achieved a 9.60 % enhancement. These findings confirm that incorporating bio-waste-derived GCMs significantly enhances PV energy yield by improving thermal stability and maintaining a lower operating temperature.

The improvement in M-3's efficiency can be attributed to synergistic thermal interactions between paraffin and pomegranate peel. The fibrous structure of pomegranate facilitates micro-porous channels within the PCM, enhancing heat distribution and delaying the rate of temperature rise. As the composite absorbs and releases latent heat more uniformly, the surface temperature of the PV panel remains within an optimal operational range. This directly prevents thermal degradation of cell voltage, which typically drops by 0.4 % – 0.5 % for every 1 °C temperature rise (Foteinis *et al*., 2023). Consequently, better heat management leads to a measurable increase in electrical conversion efficiency.

These outcomes also align with the theoretical expectation that composites with higher effective melting points provide extended thermal buffering capacity under high irradiance. M-3's elevated melting point (72 °C) allows it to remain solid for a longer duration, absorbing excess heat when the panel surface surpasses 40 °C—conditions that commonly occur in arid and tropical climates. Hence, its application could be especially beneficial for solar installations in regions like the Middle East, North Africa, and South Asia, where overheating severely limits PV efficiency (Rozon *et al*., 2023).

3.8. Surface Temperature Distribution and Infrared Imaging

The improvement in electrical performance was corroborated by thermal imaging analysis using an IR281 infrared camera, which provided surface temperature distribution maps for three representative PV panels: the free (reference) panel, the paraffin-only panel, and the M-3 composite panel (57 % paraffin, 43 % pomegranate) (see **Figure 12**). The device, with a sensitivity of 0.04 °C and resolution of 206 × 156 pixels, enabled precise detection of hot-spot formation across the panel surfaces.



(a) (b) (c)

Figure 12. Surface temperature distribution: (a) free panel, (b) paraffin-only panel, (c) M-3 panel (57 % paraffin and 43 % pomegranate).

The thermal images reveal notable differences among the configurations. The free panel (**Figure 12a**) displayed pronounced temperature non-uniformity, with localized regions exceeding 70 °C. Such hot spots result from uneven current flow and poor heat dissipation, ultimately reducing PV lifespan. The paraffin-only panel (**Figure 12b**) exhibited improved uniformity owing to the latent-heat absorption during the paraffin's phase transition, though residual non-uniformity remained.

The M-3 panel (**Figure 12c**) achieved the most homogeneous temperature distribution, demonstrating effective suppression of hot spots. The composite's improved performance stems from its optimized mixture: paraffin absorbs heat while the embedded pomegranate fibers distribute it evenly through the matrix. This reduces temperature gradients between adjacent cells and enhances the module's durability. The resulting uniform thermal profile directly corresponds to the panel's higher and more stable electrical output throughout the day.

The findings support previous reports that PCM-based cooling systems can mitigate thermal stress in PV panels by 10 %–20 % when properly engineered with high-conductivity fillers (Govindasamy & Kumar, 2023). The inclusion of agricultural-waste fillers offers an additional advantage: the micro-porous structure of dried organic fibers enhances convective heat transfer without substantially increasing composite density or cost.

3.9. Quantitative Comparison of Surface Temperatures

Figure 13 presents the hourly variation of surface temperatures for the three PV systems between 10:00 AM and 4:00 PM. Measurements were conducted simultaneously to ensure comparable environmental conditions.

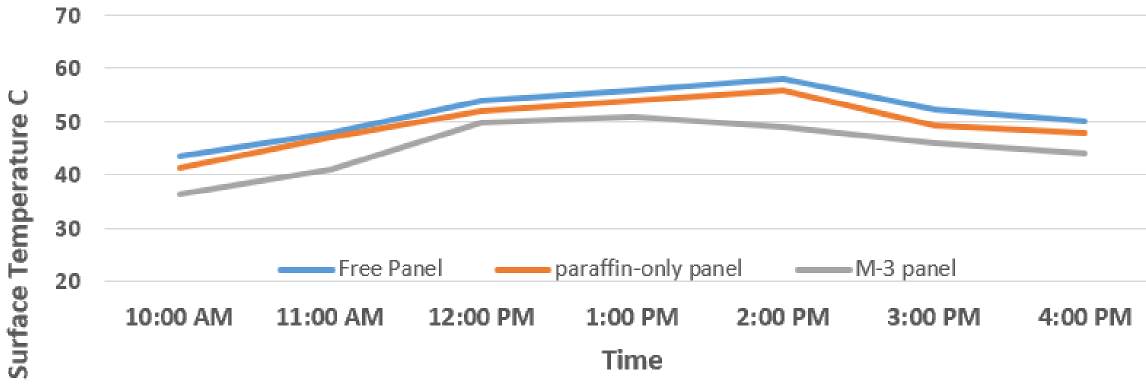


Figure 13. Surface temperature comparison of PV panels.

Throughout the observation period, the M-3 panel consistently exhibited the lowest surface temperature, maintaining an average of 54.2 °C ± 0.5 °C, compared with 59.8 °C for the paraffin-only panel and 65.7 °C for the free panel. The difference of 5 – 10 °C between M-3 and the reference underscores the composite's superior cooling capability. Notably, the temperature reduction corresponds closely with the observed 16.65 % increase in electrical output, reaffirming the strong correlation between effective thermal control and PV efficiency (Sharma *et al*., 2009).

The consistent performance of M-3 during peak irradiance hours (11:00 AM – 2:00 PM) highlights the stability of its phase-transition behavior. While the paraffin-only PCM tends to liquefy rapidly around 37 °C, losing its capacity for further heat absorption, the addition of pomegranate peel raises the composite's functional range. The porous biomass network acts as a scaffold, slowing the melting process and extending the material's latent-heat absorption phase. This prevents premature saturation and allows continuous temperature buffering throughout the day (Mohammed *et al*., 2024).

Moreover, the fibrous texture of the pomegranate peel promotes capillary action, redistributing molten paraffin within the matrix during the phase transition. This dynamic movement enhances internal convection and reduces the risk of leakage—a common challenge in PCM applications. As a result, the M-3 formulation maintains physical integrity during multiple heating–cooling cycles, demonstrating promising durability for long-term PV applications.

3.10. Mechanism of Thermal Enhancement in M-3 Composite

The thermal enhancement mechanism of the M-3 composite can be understood as a synergistic balance between *latent-heat storage* and *conductive heat spreading*. Paraffin provides high latent-heat capacity, while the pomegranate peel introduces micro-scale roughness and interfacial pathways for heat flow. Although pomegranate has lower intrinsic conductivity (0.1617 W/m·K) than paraffin (0.3 W/m·K), its structural integration creates a composite network that reduces effective thermal resistance.

This phenomenon can be explained through the *percolation model* of heat transfer in composite materials, where dispersed fibers or particulates form conductive bridges across the matrix. The pomegranate's carbonaceous and lignocellulosic components act as semi-conductive domains, facilitating phonon transfer and enhancing overall conductivity. At the same time, the elevated melting point (72 °C) ensures prolonged operation in the solid–liquid equilibrium zone, enabling consistent heat absorption under high-temperature conditions (El Kassar *et al*., 2024).

Another critical advantage of the M-3 formulation is its reduced tendency for thermal cycling fatigue. Repeated melting and solidification often cause phase segregation in conventional PCMs. However, the porous structure of the pomegranate peel confines paraffin within micro-pores, preventing separation and maintaining homogeneous performance over successive days. This stability is crucial for real-world PV applications where panels experience continuous thermal cycling.

3.11. Innovation and Broader Implications

The integration of pomegranate peel into PCM technology represents a novel advancement that addresses two major challenges in solar energy systems: thermal inefficiency and waste valorization. By utilizing agricultural by-products, the M-3 composite not only improves energy yield but also contributes to reducing organic waste disposal and associated carbon emissions. This dual benefit aligns directly with SDG 7 (Affordable and Clean Energy) by enhancing renewable-energy efficiency, and SDG 12 (Responsible Consumption and Production) by promoting circular-economy principles.

From an engineering standpoint, the M-3 composite offers a cost-effective, environmentally sustainable, and scalable solution for PV thermal management. The materials—paraffin and pomegranate peel—are inexpensive and abundantly available, particularly in regions where both solar irradiance and agricultural production are high. This makes the technology accessible to developing countries seeking to improve solar power reliability without costly synthetic additives.

Furthermore, the measurable 16.65 % gain in electrical output translates into substantial long-term energy benefits. Assuming an average daily insolation of 5 kWh/m² and a 200 W panel, applying the M-3 composite could yield an additional 33 Wh per day per module. Across large solar farms, this improvement scales into megawatt-hour levels of extra generation annually, representing both economic and environmental advantages.

In addition, the composite's ability to mitigate hot-spot formation enhances PV module lifespan by reducing thermal stress and preventing micro-cracks in the encapsulant layers. Extending module service life by even 5 % can offset significant replacement costs and lower the life-cycle carbon footprint of solar installations.

3.12. Summary

The experimental results demonstrate a clear correlation between composite formulation, surface temperature regulation, and energy output. Key findings include:

(i) Thermal Uniformity: Infrared imaging confirmed that the M-3 composite achieved the most uniform surface temperature distribution, effectively eliminating hot spots.

(ii) Power Enhancement: M-3 delivered the highest output increase (16.65 %) compared with the reference system, followed by M-5 (13.26 %) and M-8 (9.60 %).

(iii) Material Optimization: The optimal ratio of 57 % paraffin to 43 % pomegranate maximized both conductivity and melting-point stability.

(iv) Sustainability: The reuse of agricultural waste materials supports circular-economy practices and reduces environmental impact.

Collectively, these findings validate the hypothesis that integrating green composite materials into PCMs can effectively mitigate PV overheating and significantly enhance power output. The success of the M-3 formulation establishes a foundation for future research on multi-component PCMs that combine mechanical stability, high thermal storage capacity, and environmental sustainability.

4. CONCLUSION

This study demonstrated that integrating pomegranate peel with paraffin (M-3: 57% paraffin, 43% pomegranate) significantly enhances photovoltaic (PV) efficiency and thermal regulation. The M-3 composite achieved a 16.65% increase in daily energy output and the most uniform surface temperature distribution, reducing hot spots and prolonging panel life. Utilizing agricultural waste as a green composite material offers a sustainable, low-cost solution for solar cooling applications, aligning with SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) by promoting renewable efficiency and waste valorization in energy systems.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

6. REFERENCES

Abdollahi, N., and Rahimi, M. (2020). Potential of water natural circulation coupled with nano-enhanced PCM for PV module cooling. *Renewable Energy, 147*, 302–309.

Abdulmunem, A. R., Samin, P. M., Rahman, H. A., Hussien, H. A., Mazali, I. I., and Ghazali, H. A. (2021). Numerical and experimental analysis of the tilt angle's effects on the characteristics of the melting process of PCM-based as PV cell's backside heat sink. *Renewable Energy, 173*, 520–530.

Bharathiraja, R., Ramkumar, T., Karthick, L., and Mohanraj, M. (2024). Performance investigation on flat plate solar water collector using a hybrid nano-enhanced phase change material (PCM). *Journal of Energy Storage, 86*, 111163.

Darkwa, J., Calautit, J., Du, D., and Kokogianakis, G. (2019). A numerical and experimental analysis of an integrated TEG–PCM power enhancement system for photovoltaic cells. *Applied Energy, 248*, 688–701.

El Kassar, R., Al Takash, A., Faraj, J., Khaled, M., and Ramadan, H. S. (2024a). Phase change materials for enhanced photovoltaic panels performance: A comprehensive review and critical analysis. *Energy and Built Environment, 6*(4), 655-675.

Foteinis, S., Savvakis, N., and Tsoutsos, T. (2023). Energy and environmental performance of photovoltaic cooling using phase change materials under the Mediterranean climate. *Energy, 265*, 126355.

Govindasamy, D., and Kumar, A. (2023). Evaluation of the impact of different composite phase change materials on reduction in temperature and enhancement of solar panel efficiency. *Journal of Energy Storage, 60*, 106631.

Homlakorn, S., Suksri, A., and Wongwuttanasatian, T. (2022). Efficiency improvement of PV module using a binary-organic eutectic phase change material in a finned container. *Energy Reports, 8*(Suppl 10), 121–128.

Karthikeyan, V., Sirisamphanwong, C., Sukchai, S., Sahoo, S. K., and Wongwuttanasatian, T. (2020). Reducing PV module temperature with radiation-based PV module incorporating composite phase change material. *Journal of Energy Storage, 29*, 101346.

Li, Z., Ma, T., Zhao, J., Song, A., and Cheng, Y. (2019). Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material. *Energy, 178*, 471–486.

Liu, L., Niu, J., and Wu, J. Y. (2023). Improving energy efficiency of photovoltaic/thermal systems by cooling with PCM nano-emulsions: An indoor experimental study. *Renewable Energy, 203*, 568–582.

Ma, T., Li, Z., and Zhao, J. (2019). Photovoltaic panel integrated with phase change materials (PV-PCM): Technology overview and materials selection. *Renewable and Sustainable Energy Reviews, 116*, 109406.

Maryanti, R., Rahayu, N. I., Muktiarni, M., Al Husaeni, D. F., Hufad, A., Sunardi, S., and Nandiyanto, A. B. D. (2022). Sustainable development goals (SDGs) in science education: Definition, literature review, and bibliometric analysis. *Journal of Engineering Science and Technology*, *17*(6), 161-181.

Mohammed, M. A., Ali, B. M., Yassin, K. F., Ali, O. M., and Alomar, O. R. (2024). Comparative study of different phase change materials on the thermal performance of photovoltaic cells in Iraq's climate conditions. *Energy Reports, 11*, 18–27.

Mubarokah, S. L., Anwar, S., Nisa, K., Miftah, H., Hastuti, A., and Nandiyanto, A. B. D. (2024). Bibliometrics study on agro-economy of biochar. *Journal of Engineering Science and Technology*, *19*, 142-152.

Nandiyanto, A. B. D., Kurniawan, T. E. G. U. H., Bilad, M. R., and Farobie, O. B. I. E. (2025). Harnessing biomass for Sustainable Development Goals (SDGs): Definition, bibliometric, application, opportunities, and challenges. *Journal of Engineering Science and Technology*, *20*(4), 1047-1068.

Nijmeh, S., Hammad, B., Al-Abed, M., and Bani-Khalid, R. (2020). A technical and economic study of a photovoltaic–phase change material (PV–PCM) system in Jordan. *Jordan Journal of Mechanical and Industrial Engineering, 14*(4), 371–379.

Rajvikram, M., Leoponraj, S., Ramkumar, S., Akshaya, H., and Dheeraj, A. (2019). Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium. *Solar Energy, 188*, 327–338.

Reji Kumar, R., Kalidasan, B., Imtiaz Ali Lagari, J. K., Siaw Paw, A. G. N. S., Sofiah, A. G. N., Suraparaju, S. K., Pandey, A. K., Samykano, M., Soudagar, M. E. M., and Khan, T. M. Y. (2024). Progress in research and technological developments of phase change materials integrated photovoltaic thermal systems: The allied problems and their mitigation strategies. *Sustainable Materials and Technologies, 40*, e00921.

Rozon, F., McGregor, C., and Owen, M. (2023). Long-term forecasting framework for renewable energy technologies' installed capacity and costs for 2050. *Energies, 16*(19), 6874.

Savvakis, N., Dialyna, E., and Tsoutsos, T. (2020). Investigation of the operational performance and efficiency of an alternative PV+PCM concept. *Solar Energy, 211*, 1283–1300.

Sharma, A., Tyagi, V. V., Chen, C. R., and Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318–345.

Soares, N., Costa, J. J., Gaspar, A. R., Matias, T., Simões, P. N., and Durães, L. (2020). Can movable PCM-filled TES units be used to improve the performance of PV panels? Overview and experimental case study. *Energy and Buildings, 210*, 109743.

Solehuddin, M., Nandiyanto, A. B. D., Muktiarni, M., Rahayu, N. I., Al Husaeni, D. N., Ragadhita, R., and Fiandini, M. (2025). Engineering research and scientific contributions at Universitas Pendidikan Indonesia: Trends, challenges, and future directions. *Journal of Engineering Science and Technology*, *20*(3), 816-836.

Sudhakar, P., Santosh, R., Asthalakshmi, B., Kumaresan, G., and Velraj, R. J. R. E. (2021). Performance augmentation of solar photovoltaic panel through PCM-integrated natural water circulation cooling technique. *Renewable Energy, 172*, 1433–1448.

Tao, M., Li, Z., and Zhao, J. (2019). Photovoltaic panel integrated with phase change materials (PV-PCM): Technology overview and materials selection. *Renewable and Sustainable Energy Reviews, 116*, 109406.