



Comparative Performance of Activated Fly Ash-Based Lauric Acid and Paraffin Wax SSPCMs for Photovoltaic Thermal Management

Nadia Melisa Fitri¹, Ahmad Zydan Alhabsyi¹, Yohandri Bow^{1,2*}, Isnandar Yunanto¹, and Erlinawati¹

¹ Department of Energy Engineering, Politeknik Negeri Sriwijaya, Palembang, 30139, Indonesia

² Applied Master of Renewable Energy Engineering Program, Politeknik Negeri Sriwijaya, Palembang, 30139, Indonesia

ARTICLE INFO

Article History:

Received: 06 August 2026

Final Revision: 14 August 2026

Accepted: 20 August 2026

Online Publication: 23 August 2026

KEYWORDS

Solar panel efficiency, shape stabilized phase change material, lauric acid, paraffin wax, activated fly ash, photovoltaic thermal management

CORRESPONDING AUTHOR

*E-mail: yohandri@polsri.ac.id

ABSTRACT

Excessive heat accumulation in photovoltaic panels increases operating temperature and reduces electrical performance, particularly in tropical regions. Shape-stabilized phase change material (SSPCM) offers a passive thermal management approach by absorbing excess heat as latent heat while maintaining dimensional stability through a supporting matrix. This study evaluates the effect of SSPCM integration on photovoltaic performance compared with a reference panel without SSPCM, and compares lauric acid- and paraffin wax-based SSPCMs using activated fly ash (AFA) as the supporting matrix. Both SSPCMs were evaluated through leakage test, Differential scanning calorimetry (DSC), and outdoor solar panel performance testing. The optimum lauric acid formulation was a 45:55 lauric acid-to-AFA ratio, with the lowest leakage rate (0.043%) and the highest latent heat (56.21 J/g). Under representative outdoor test conditions, this formulation reduced the solar panel temperature by 2.72 °C and increased efficiency by 1.76 percentage points. For the paraffin wax system, the optimum formulation was obtained at a 40:60 paraffin wax-to-AFA ratio, with a mass loss of 1.82% and a latent heat of 53.78 J/g. Under the same representative test conditions, this formulation reduced the solar panel temperature by 3.29 °C and increased efficiency by 1.88 percentage points. Across five outdoor testing sessions, LA-SSPCM and PW-SSPCM reduced the average PV temperature by 2.44 and 2.62 °C, respectively, and increased electrical efficiency by 2.53 and 1.65 percentage points, respectively. The results confirm that SSPCM integration improves photovoltaic performance. LA-SSPCM showed lower leakage rate, slightly higher latent heat, and superior electrical efficiency improvement, while PW-SSPCM provided a slightly greater average temperature reduction, although the difference in average temperature between the two SSPCMs was not statistically significant.

Contribution to Sustainable Development Goals (SDGs):

SDG 7: Affordable and Clean Energy

SDG 9: Industry, Innovation and Infrastructure

SDG 12: Responsible Consumption and Production

1. INTRODUCTION

1.1. Research Background

Solar photovoltaic (PV) technology is widely recognized as one of the most promising renewable energy systems due to its clean operation, modular configuration, and suitability for regions with high solar irradiation. Field-scale PV applications have shown potential to reduce conventional fuel consumption and CO₂

emissions [1]. However, PV performance is strongly affected by operating temperature, as excessive heat accumulation can reduce voltage output, electrical power, and conversion efficiency [2], [3]. This issue becomes more critical in tropical outdoor conditions, where high solar radiation and ambient temperature can push PV modules above their ideal operating range.



This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License

Published under licence by SAFE-Network

Therefore, effective thermal management is required to maintain PV performance under real operating conditions [4].

Researchers have developed various PV thermal management strategies, including active, passive, and hybrid cooling systems. Active cooling can enhance heat dissipation, its implementation often depends on additional energy consumption, auxiliary components, and more complex maintenance [5]. In contrast, passive cooling systems are more attractive for low-cost and small-scale PV applications because they operate without external power consumption and have simpler system configurations [4]. Among passive cooling materials, phase change materials (PCMs) have attracted interest due to their ability to store excess thermal energy as latent heat during melting and release it during solidification, thereby reducing temperature fluctuation in PV systems [6]. This thermal buffering mechanism helps reduce temperature fluctuation in PV systems, particularly when the PCM phase transition temperature is compatible with the operating temperature range of the PV module [7].

Organic PCMs, particularly fatty acid-based and paraffin-based materials, are frequently investigated for thermal energy storage and PV thermal management owing to their chemical stability, appropriate melting temperatures, and relatively high latent heat capacity [8]. Lauric acid is recognized as a bio-based fatty acid PCM with promising thermal storage characteristics [9], while paraffin wax is widely used due to its availability, low-cost, non-corrosive behavior, and stable phase change characteristics [10], [11]. Nevertheless, leakage during the solid-liquid phase transition limits the practical use of PCMs. When the PCM melts, it may flow out of the system without a supporting matrix, causing material loss and reducing long-term reliability. To overcome this issue, shape-stabilized phase change materials (SSPCMs) are fabricated by impregnating PCMs into porous matrices that retain melted PCM through capillary forces, surface tension, and interfacial interactions [12].

Fly ash, an underutilized solid waste from coal-fired power plants, offers potential as a low-cost supporting matrix for SSPCM due to its thermal stability, porous structure, and silica-alumina-based composition [13]. Fly ash-based composites have been reported as promising shape-stabilized PCM systems for thermal energy storage applications [14], [15]. However, raw fly ash may have limited pore accessibility and surface activity, which can reduce its ability to retain PCM effectively. Chemical activation using alkaline agents such as NaOH can modify the aluminosilicate structure, improve surface reactivity, and increase pore availability, making fly ash more suitable as a PCM supporting matrix [16], [17]. Despite growing studies on PCM-based PV cooling and fly ash-supported SSPCMs, direct comparison between lauric acid and paraffin wax using the same activated fly ash (AFA) matrix remains limited. Therefore, this study evaluates both SSPCM systems based on their physical stability, thermal properties, and photovoltaic performance.

1.2. Literature Review

Previous studies have reported that the performance of photovoltaic (PV) modules is governed by both environmental and operational factors, such as solar irradiance, operating temperature, wind velocity, panel surface condition, and installation angle [2]. Solar irradiance determines the available input energy, while operating temperature affects the electrical characteristics of the PV cell, particularly voltage and conversion efficiency [3]. The electrical output of a PV module is commonly

evaluated through voltage, current, power output, and efficiency parameters, which are used to assess the effectiveness of a thermal management system [18]. Under outdoor conditions, temperature fluctuation becomes more difficult to control because PV modules are continuously exposed to variations in irradiance and ambient conditions [4], [19]. Therefore, various thermal management strategies have been investigated to reduce excessive temperature rise and maintain PV performance during operation [20].

1.2.1 PCM-Based Thermal Management for Photovoltaic

Phase change materials (PCMs) are thermal energy storage materials that absorb and release heat through phase transition, commonly between solid and liquid states [8]. PCMs have been widely investigated as passive thermal management materials for PV modules because they can regulate temperature without requiring external energy input [4]. In PV systems, PCM is commonly placed on the rear side of the panel to absorb part of the heat transferred from the module during solar radiation exposure. During melting, PCM stores thermal energy as latent heat, thereby slowing the increase in panel temperature and helping maintain more stable electrical performance [6].

The overall effectiveness of PCM cooling is heavily influenced by melting temperature, latent heat capacity, thermal conductivity, PCM quantity, and the heat transfer arrangement between the PV module and PCM layer [6], [20]. A PCM with an unsuitable melting range may either melt too early and lose its buffering capacity or fail to melt sufficiently during the operating period. Therefore, the specific melting range of the PCM must be fully compatible with the actual operating temperature range of the PV module [11].

1.2.2 Lauric Acid and Paraffin Wax as Organic PCMs

Organic PCMs are widely used in thermal energy storage applications because of their excellent chemical stability, relatively high latent heat capacity, low corrosiveness, and stable phase transition behavior [21]. Lauric acid, also known as *n*-dodecanoic acid, is a fatty acid-based PCM that can be obtained from bio-based sources and has a moderate melting temperature suitable for low- to medium-temperature thermal regulation [9]. Its reliable thermal storage behavior makes it highly relevant for PV thermal management, especially under tropical outdoor conditions where panel temperatures may approach its phase transition range [22].

Paraffin wax is another commonly used organic PCM due to its widespread availability, low-cost, non-corrosive behavior, and stable melting-solidification characteristics [23]. Its thermophysical properties vary with temperature, making detailed temperature-dependent characterization important for selecting appropriate paraffin materials in various thermal energy storage applications [11]. However, both lauric acid and paraffin wax may naturally leak during the solid-liquid phase transition if directly applied without a secure supporting matrix [24]. This critical limitation requires effective shape stabilization to retain the melted PCM, reduce material loss, and improve long-term reliability during repetitive thermal cycling [25].

1.2.3 Shape-Stabilized Phase Change Materials

Shape-stabilized phase change materials (SSPCMs) are developed to overcome the leakage problem of conventional

PCMs [12]. In SSPCM systems, the PCM serves as the active latent heat storage material, while the supporting matrix maintains the composite's macroscopic shape during phase transition. The matrix retains the melted PCM through capillary forces, surface tension, adsorption, and interfacial interactions [12]. An effective SSPCM should have low leakage rate, suitable melting temperature, high latent heat capacity, good thermal stability, and compatibility between the PCM and supporting matrix [24]. Previous studies have shown that porous supporting materials such as expanded graphite, mineral-based matrices, carbon-based materials, and fly ash can improve PCM shape stability and reduce leakage [26]. For PV applications, SSPCM is more practical than conventional PCM because it can be attached to the rear side of the panel with lower risk of liquid PCM leakage during operation [20].

1.2.4 Fly Ash as a Supporting Matrix

Fly ash is a fine solid residue generated from coal combustion in coal-fired power plants. Fly ash is produced in large quantities and is often underutilized, creating potential environmental and disposal concerns [27]. Its aluminosilicate-based composition, thermal stability, and potential porous structure make it a promising low-cost supporting matrix for PCM-based composites [13]. In this study, the fly ash was obtained from PLTU Sebalang in Indonesia. Its chemical composition is dominated by SiO_2 and Al_2O_3 indicating its aluminosilicate nature of the material. This composition is important because silica–alumina-based materials are generally associated with structural stability, surface activity, and potential pore formation after activation [16]. The chemical composition of the fly ash used in this study is presented in Table 1.

Table 1. Chemical composition of fly ash from PLTU Sebalang.

Composition	wt%
SiO_2	67.23
Al_2O_3	8.21
Fe_2O_3	2.3
CaO	3.51
MgO	0.73
SO_3	0.64
Na_2O	0.35
K_2O	0.32

However, raw fly ash may have limited pore accessibility and surface activity, reducing its ability to retain melted PCM effectively [17]. Alkali activation is commonly used to improve fly ash surface and pore characteristics. Sodium hydroxide (NaOH) can interact with aluminosilicate structures, dissolve part of the amorphous silica and alumina phases, and increase surface reactivity [16]. Therefore, AFA is expected to provide better PCM impregnation and retention in lauric acid and paraffin wax-based SSPCMs [15], [26].

1.2.5 Characterization of SSPCM Performance

The performance of SSPCM is commonly evaluated through physical and thermal characterization. Leakage test is used to determine the ability of the supporting matrix to retain melted PCM during heating, where lower mass loss indicates better shape stability [26]. Thermal characterization is commonly performed using Differential Scanning Calorimetry (DSC),

which provides information on onset temperature (T_{onset}), peak temperature (T_{peak}), endset temperature (T_{endset}), and melting enthalpy (ΔH) [28]. These parameters are important because the optimum SSPCM composition should not only exhibit low leakage, but also have sufficient latent heat capacity and a phase transition range compatible with PV operating temperature [29]. Therefore, leakage and DSC characteristics are complementary indicators in evaluating the feasibility of SSPCMs as passive thermal management materials for solar panels [30].

1.3. Research Objective

This study compares lauric acid-based and paraffin wax-based shape-stabilized phase change materials (SSPCMs) incorporating AFA as the supporting matrix for passive thermal regulation of photovoltaic panels. Their performance is systematically evaluated in terms of physical stability based on leakage test, thermal properties based on DSC analysis, panel temperature reduction, and photovoltaic efficiency improvement. Through this comparison, the study evaluates the suitability of both SSPCM systems as passive thermal management materials for solar panel applications.

2. MATERIALS AND METHODS

2.1. Materials and SSPCM Preparation

The research was conducted from April to June 2026 at the Chemical Engineering Laboratory, Politeknik Negeri Sriwijaya. This specific study involved the systematic preparation and evaluation of lauric acid and paraffin wax-based SSPCMs, using AFA as the primary supporting matrix for photovoltaic passive thermal management. The overall experimental procedure consisted of four main sequential stages: initial fly ash activation, SSPCM preparation, material characterization, and final photovoltaic performance testing. Lauric acid and paraffin wax served as the organic phase change materials (PCMs), while fly ash served as the porous supporting matrix. To prepare the matrix, the fly ash was chemically activated using a 2 M NaOH solution with a strict solution-to-fly ash ratio of 5:1 (v/w). The fly ash was immersed continuously for 24 h, washed thoroughly to a near-neutral pH, and oven-dried before use.

SSPCM composites were prepared using impregnation methods tailored to each PCM's characteristics. For the lauric acid-based SSPCM, lauric acid was completely melted in a water bath at 60 °C, while the AFA was simultaneously preheated to the same temperature before mixing. The melted lauric acid and preheated AFA were then continuously stirred together in a water bath for 30 min to promote impregnation. For the paraffin wax-based SSPCM, the paraffin wax was first melted and impregnated directly into the AFA using an ultrasonication-assisted impregnation method at approximately 70 °C for 30 min. For both composite systems, the established PCM-to-AFA mass ratios were 30:70, 35:65, 40:60, 45:55, and 50:50. The resulting lauric acid samples were coded as LA-a to LA-e, while the paraffin wax samples were coded as PW-a to PW-e, as shown in Table 2.

Table 2. Composition ratios of SSPCM samples

PCM Type	Sample Code	PCM (wt%)	AFA (wt%)
Lauric Acid	LA-a	30	70
Lauric Acid	LA-b	35	65
Lauric Acid	LA-c	40	60
Lauric Acid	LA-d	45	55
Lauric Acid	LA-e	50	50
Paraffin Wax	PW-a	30	70
Paraffin Wax	PW-b	35	65
Paraffin Wax	PW-c	40	60
Paraffin Wax	PW-d	45	55
Paraffin Wax	PW-e	50	50

We evaluated the shape stability of the SSPCM samples using a leakage test. We formed each sample into a cylinder with a diameter of 6 cm and a thickness of 1 cm. We weighed the samples before and after heating to determine mass loss. Lauric acid-based samples were heated at 60 °C while paraffin wax-based samples were heated at 72 °C for 30 min. The leakage rate was determined from the percentage of mass loss using the standard evaluation method for assessing the shape stability of SSPCMs [31], as shown in Equation (1):

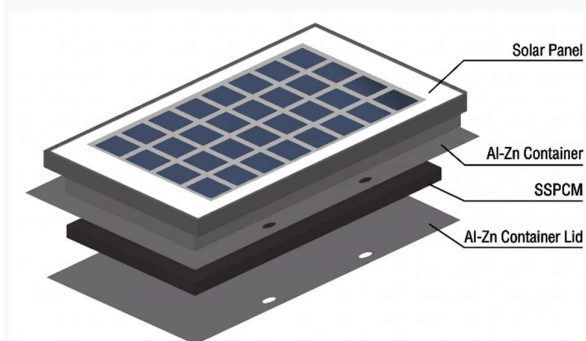
$$\varepsilon (\%) = \frac{m_i - m_f}{m_i} \times 100 \quad (1)$$

where ε is leakage rate, m_i is the initial mass before heating and m_f is the final mass after heating.

The thermal characteristics of the SSPCM composites were evaluated by differential scanning calorimetry (DSC) to determine T_{onset} , T_{peak} , T_{endset} , and melting enthalpy (ΔH). The selected formulation from each PCM system was determined based on both low leakage rate and high latent heat storage capacity.

2.2. Experimental Setup and Performance Evaluation

After material characterization, the selected SSPCM formulation from each PCM system was inserted into an aluminium-zinc container and attached to the rear of a 5 Wp monocrystalline solar panel. The container held the SSPCM layer, ensuring direct thermal contact with the panel's rear surface. We tested three identical solar panels outdoors: one reference panel without SSPCM, one with lauric acid-based SSPCM, and one with paraffin wax-based SSPCM. The reference panel served as the control, while the SSPCM-integrated panels were evaluated to assess passive thermal management effects on panel temperature and photovoltaic performance. Fig. 1 illustrates the layer configuration of the SSPCM-integrated solar panel.

**Fig. 1.** SSPCM Integrated Solar Panel Layer

We conducted outdoor performance testing over five consecutive days (10–14 June 2026) under the same measurement schedule, from 11:00 to 12:30 WIB at 5 min intervals. Because on-site meteorological sensors were not available, the ambient air temperature, relative humidity, and wind speed for each testing session were retrieved from the ERA5 reanalysis dataset through the Open-Meteo historical weather archive [32], using the geographic coordinates of the test site in Palembang (approximately 2.98° S, 104.71° E) and averaged over the same 11:00–12:30 WIB window used for the on-site measurements.

Three identical solar panels were placed side by side at a 15° tilt angle to ensure exposure to similar outdoor conditions. Light intensity was measured using a lux meter and recorded in lux during each measurement interval. The measured illuminance was converted into solar irradiance using a conversion factor of 122 lux per W/m² [33], as shown in Equation (2):

$$G = \frac{E}{122 \text{ lux} / \left(\frac{W}{m^2} \right)} \quad (2)$$

where G is the solar irradiance (W/m²) and E is the measured illuminance (lux).

Panel temperature was measured at three points on the front surface of each panel, namely the upper, middle, and lower sections, and the average value was used as the representative panel temperature. We measured the voltage and current of each solar panel directly at the panel output terminals using a digital multimeter. The electrical output power of each solar panel was calculated from the measured voltage and current [18], as shown in Equation (3):

$$P = V \times I \quad (3)$$

where P is the electrical output power (W), V is the measured voltage (V), and I is the measured current (A).

The photovoltaic efficiency was calculated as the ratio of electrical output power to incident solar power on the panel surface [18], as shown in Equation (4):

$$\eta = \frac{P}{G \times A} \times 100\% \quad (4)$$

where η denotes the photovoltaic efficiency (%), P is the electrical output power (W), G is the solar irradiance (W/m²), and A is the panel surface area (m²). We compared each SSPCM-integrated panel's performance with the reference panel based on panel temperature reduction and efficiency improvement.

For statistical analysis, we treated the five outdoor testing days as independent experimental replicates ($n = 5$). We calculated the average panel temperature and electrical efficiency for each testing day. The results are presented as mean $\pm$ standard deviation (SD). We used paired-samples t-tests to compare the reference panel with the LA-SSPCM and PW-SSPCM panels because we tested all three panels simultaneously during each outdoor session. We evaluated statistical significance at $p < 0.05$.

3. RESULT AND DISCUSSION

Material stability and latent heat storage capacity are key factors in determining the feasibility of SSPCM for photovoltaic thermal regulation. A formulation with high latent heat but poor leakage resistance may not be suitable for practical application, while a highly stable formulation with low heat storage capacity may provide limited cooling performance. For this reason, the discussion begins with leakage stability and DSC thermal properties, followed by the evaluation of panel temperature and photovoltaic efficiency under outdoor conditions.

3.1. Shape Stability Based on Leakage Test

The leakage test evaluated the AFA matrix's ability to retain melted PCM during heating. Shape stability is an important requirement for long-term SSPCM application because leakage during the solid-liquid phase transition can reduce PCM content, decrease thermal reliability, and limit practical use in solar panel thermal management [12]. In this study, we used a maximum leakage rate below 2% as the strict shape-stability criterion for feasible SSPCM compositions [14]. The leakage rates (ϵ) of lauric acid (LA) and paraffin wax (PW) based SSPCMs at different PCM-to-AFA ratios are presented in Table 3 and Fig. 2.

Table 3. Leakage rate of LA and PW SSPCM composites

Ratio PCM : AFA (wt%)	ϵ LA (%)	ϵ PW (%)
30:70	0.179	0.120
35:65	0.150	1.080
40:60	0.081	1.820
45:55	0.043	2.960
50:50	0.086	4.170

The LA-based SSPCM samples showed consistently low leakage rates of 0.043–0.179%, remaining well below the acceptable 2% criterion. In contrast, the PW-based SSPCMs showed a progressive increase in leakage rate from 0.120% at the 30:70 ratio to 4.170% at the 50:50 ratio. This difference indicates that AFA retained the molten LA more effectively than molten PW under the specific applied testing conditions. Because AFA remained the solid supporting framework during heating, the measured mass loss mainly reflected excess PCM that was not fully confined within the matrix. The retention of molten PCM in such porous supports is generally governed by capillary forces, surface tension, adsorption, and interfacial interactions between the PCM and the solid supporting matrix [9].

The LA system achieved the lowest leakage rate with LA-d at the 45:55 LA:AFA mass ratio, with an exceptionally low 0.043% leakage rate, indicating the optimum balance between PCM loading and the AFA matrix's internal retention capacity. At lower LA contents, the amount of PCM was insufficient to fully occupy the available internal pore structure, whereas excessive LA loading gradually reduced the matrix's ability to immobilize the molten PCM, resulting in a slight but measurable increase in leakage [17]. Nevertheless, all tested LA compositions remained well below the maximum allowable shape-stability criterion required for these passive thermal stabilizer applications. In contrast, leakage in the PW system increased continuously with higher paraffin content. Only the 30:70, 35:65, and 40:60 compositions met the strict 2% criterion, while leakage exceeded the acceptable limit at the 45:55 and 50:50 ratios. This finding indicates that the effective loading capacity of AFA for paraffin was approximately 40 wt%, in agreement with several previous studies on paraffin-based SSPCMs [26], [34]. Beyond this critical threshold, the capillary forces and surface adhesion within the pore network were no longer sufficient to retain the molten paraffin, allowing the excess PCM to freely migrate from the composite during the melting process [24], [25].

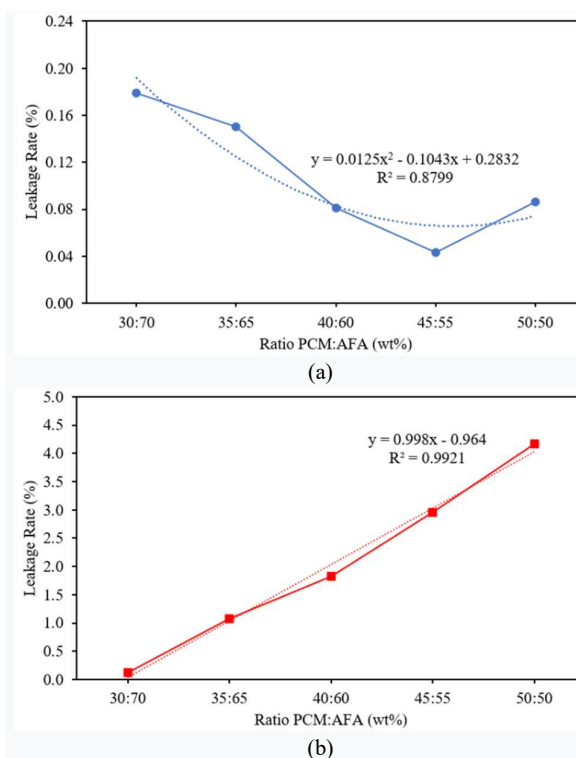


Fig. 2. Leakage rate of the (a) LA and (b) PW composites at different PCM:AFA ratios

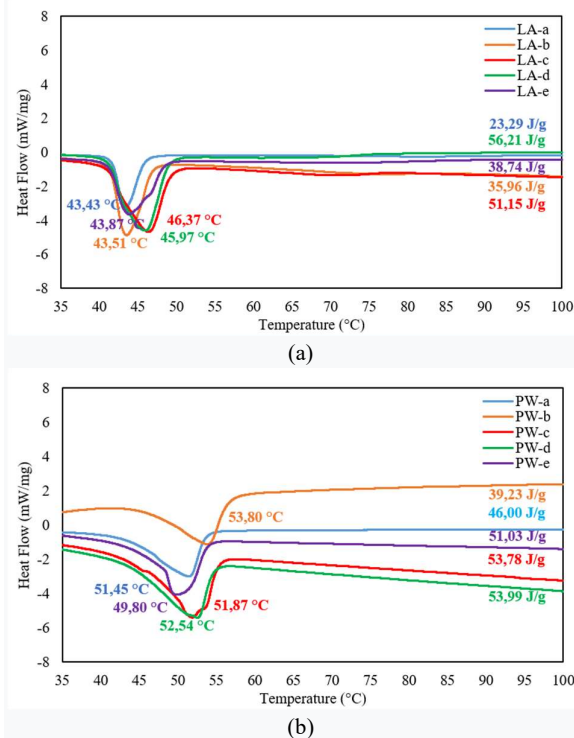
The fitted regression curves in Fig. 2 further illustrate the distinctly different leakage behaviors of the two PCM systems. The LA composites followed a second-order polynomial relationship ($y = 0.0125x^2 - 0.1043x + 0.2832$; $R^2 = 0.8799$), with a minimum near the 45:55 composition, indicating that leakage was governed by the balance between PCM loading and the retention capacity of the AFA matrix. In contrast, the PW composites showed an almost perfectly linear relationship ($y = 0.998x - 0.964$; $R^2 = 0.9921$), showing that leakage increased proportionally with increasing paraffin content. Beyond describing the experimental trends, both regression models provide a practical means of estimating leakage at intermediate compositions within the investigated range, thereby supporting composition optimization while reducing the need for additional experimental trials. Based on these results, the PW 40:60 (PW-c) composite with leakage rate 1.82% was selected as the highest loading that still satisfies the 2% criterion, while for the lauric acid the 45:55 (LA-d) composite with a leakage rate of 0.043% was selected as the optimum formulation.

3.2. Thermal Properties Based on DSC Analysis

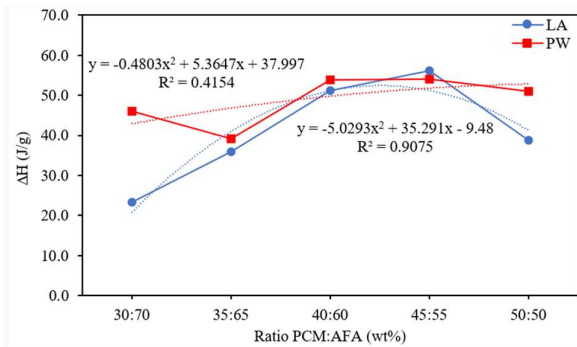
The thermal properties of all prepared composites, including the onset, peak, and endset melting temperatures and the corresponding melting enthalpy (ΔH), are clearly summarized in Table 4. The DSC thermograms of the tested composites are presented in Fig. 3, while the effect of PCM composition on the ΔH for both systems is visually compared in Fig. 4.

Table 4. DSC Analysis results of SSPCM composites

Sample	Ratio (wt%)	T _{Onset} (°C)	T _{Peak} (°C)	T _{Endset} (°C)	ΔH (J/g)
LA-a	30:70	41.80	43.43	45.48	23.29
LA-b	35:65	41.62	43.51	46.59	35.96
LA-c	40:60	41.48	46.37	49.08	51.15
LA-d	45:55	41.48	45.97	48.76	56.21
LA-e	50:50	41.51	43.87	48.22	38.74
PW-a	30:70	45.04	51.45	53.26	46.00
PW-b	35:65	47.59	53.80	56.29	39.23
PW-c	40:60	47.27	51.87	54.99	53.78
PW-d	45:55	44.47	52.54	54.27	53.99
PW-e	50:50	48.08	49.80	53.67	51.03

**Fig. 3.** DSC thermograms of the (a) LA and (b) PW composites

The DSC thermograms in Fig. 3 show a single endothermic peak for every composition in both systems, with no secondary peaks. This confirms that the melting of the lauric acid or paraffin wax is the only significant heat absorption event during heating, while the AFA acts as a thermally inert supporting matrix that does not undergo any phase transition over the tested temperature range [9]. For the LA composites, the melting peaks of all compositions are concentrated within a narrow range of about 43–46 °C, indicating that the intrinsic melting character of lauric acid is well preserved after successful impregnation into the matrix. For the PW composites, the endothermic peaks are likewise concentrated within a relatively narrow temperature band of about 50–54 °C. In both systems, the single, narrow melting peak that overlaps with the solar panel's operating temperature is a key finding because it supports effective latent heat absorption when the panel enters its high-temperature operating range.

**Fig. 4.** Melting enthalpy (ΔH) of the LA and PW composites at different PCM:AFA ratios

The LA composites melt over 41.5–49.1 °C with peaks of about 43–46 °C, whereas the PW composites melt over 44.5–56.3 °C with peak temperatures of about 50–54 °C. Both windows lie within the operating temperature range of solar panels observed in this study (up to about 57 °C), so both materials are activated as latent heat absorbers during operation; however, the LA starts melting earlier in the temperature rise, while the PW melting range coincides with the peak midday panel temperature.

The latent heat of the LA composites rises with PCM content from 23.29 J/g (30:70) to a maximum of 56.21 J/g at 45:55 and then falls to 38.74 J/g at 50:50, forming a clear optimum. This trend is well described by a downward-opening second-order polynomial ($y = -5.0294x^2 + 35.29x - 9.4772$; $R^2 = 0.9075$). The decline beyond 45:55 is attributed to the PCM content exceeding the retention capacity of the matrix, so that part of the fatty acid is weakly bound and tends to associate with its own molecules rather than acting as an effective latent heat storage phase [8], [35].

In contrast, the PW composites show non-monotonic ΔH values (46.00, 39.23, 53.78, 53.99, and 51.03 J/g) with a very low regression fit ($y = -0.4803x^2 + 5.3647x + 37.997$; $R^2 = 0.4154$). The low R^2 is itself informative. Within the 30–50 wt% loading range, composition does not systematically control the latent heat of the PW composites. This behavior is consistent with the milligram-scale DSC sample that may not fully represent the heterogeneous composite [36] and with the loss of weakly bound paraffin above the loading capacity during preparation and handling [28]. Combining shape stability and thermal capacity, LA-d (45:55, ΔH = 56.21 J/g) and PW-c (40:60, ΔH = 53.78 J/g) were selected for the panel application stage.

3.3. Effect of SSPCM on Solar Panel Surface Temperature

Lauric acid-based SSPCM (LA-SSPCM) and paraffin wax-based SSPCM (PW-SSPCM) panels were tested against the same reference panel without SSPCM under identical irradiance conditions, allowing direct comparison of the two materials' thermal responses. Five outdoor testing sessions were conducted on five consecutive days, from 10 to 14 June 2026, under naturally changing sky conditions. As a result, the solar irradiance varied between testing days. The daily average irradiance ranged from 526.69 W/m² on 14 June to 977.80 W/m² on 13 June, with an overall average of 724.99 W/m² across the five sessions. Instantaneous irradiance values varied from approximately 94 to 1539 W/m² due to intermittent cloud cover.

The reference and SSPCM panels were tested simultaneously, meaning that all three panels were exposed to the same solar irradiance at each measurement point. Therefore, differences in temperature response among the panels can be evaluated under the same solar input, whereas variations between testing sessions reflect changes in daily outdoor environmental conditions. Ambient conditions during the 11:00–12:30 WIB testing period also varied across the five sessions. The average ambient temperature was 31.4 °C, ranging from 30.4 to 32.4 °C. The average relative humidity was 61.7%, ranging from 55 to 71%, and the average wind speed was 2.8 m/s, ranging from 2.0 to 4.0 m/s. The detailed solar irradiance and specific environmental conditions for each testing session are summarized in Table 5.

Table 5. Outdoor testing conditions across the five testing sessions

Testing session	Solar irradiance (W/m ²)	Ambient temperature (°C)	Relative humidity (%)	Wind speed (m/s)
1	774.89	30.8	66	2.0
2	603.34	31.5	59	4.0
3	742.20	31.6	58	2.8
4	977.80	32.4	55	2.1
5	526.69	30.4	71	2.8
Mean	724.99	31.4	61.7	2.8

Among the five outdoor testing sessions, the first session was selected to illustrate the dynamic temperature response of the three evaluated panels. Fig. 5 shows the detailed rear surface temperature profiles of the reference, LA-SSPCM, and PW-SSPCM panels during the first test. The time axis serves only as a chronological marker of data collection, while the observed temperature changes directly reflect the thermal response of the SSPCMs and natural variations in solar irradiance.

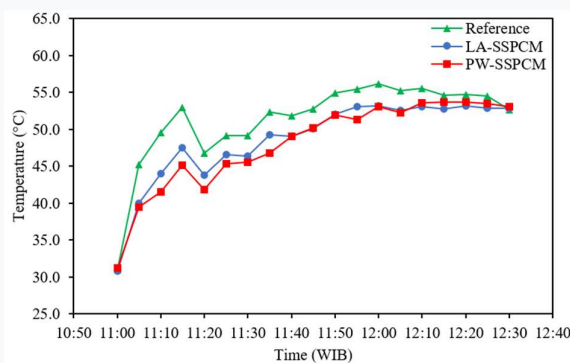


Fig. 5. Temperature profiles of the reference, LA-SSPCM, and PW-SSPCM panels during the first outdoor testing session.

The LA-SSPCM panel exhibited a lower surface temperature than the reference panel, with an average reduction of 2.72 °C and a maximum difference of 5.57 °C. This behavior indicates that the LA-based composite effectively moderated the panel temperature through the phase transition of lauric acid [30]. Owing to its lower melting range of approximately 41.48–48.76 °C, the LA-SSPCM became active earlier as the solar panel temperature increased, allowing thermal heat absorption to occur more gradually throughout the test. Although its peak cooling effect was lower than that of PW-SSPCM, the LA panel

maintained a more sustained thermal regulation and remained slightly cooler than the reference panel until 12:30 WIB, with a minimum difference of 0.17 °C.

The PW-SSPCM panel showed a higher overall average temperature reduction of 3.29 °C, with a maximum difference of 8.00 °C. This stronger suppression was associated with its higher melting range of approximately 47.27–54.99 °C, which was closer to the PV panel's peak operating temperature. As the panel temperature approached this range, the active PW composite absorbed heat more intensively, resulting in a more pronounced cooling effect during the hottest period. By the end of the test at 12:30 WIB, the temperature difference fell below 1 °C and reached −0.33 °C. This narrowing difference is better understood as a delayed thermal response of the SSPCM to the decreasing irradiance, rather than direct evidence that the PCM had completely melted [37]. When irradiance decreases, the reference panel can cool more rapidly, while the SSPCM panel tends to release the previously stored heat gradually through internal thermal heat transfer [36]. Consequently, the SSPCM panel's subsequent temperature decrease may occur more slowly than the reference panel's.

Between 11.05 and 11.50 WIB, both the integrated LA-SSPCM and PW-SSPCM panels showed fluctuating temperature profiles that closely followed the reference panel's general trend. This observed pattern reflects the complex nature of outdoor testing, where solar irradiance, wind movement, ambient temperature, and temporary shading may frequently vary within a short period [19]. The recorded fluctuations therefore do not indicate SSPCM instability, but rather its dynamic response to changing heat input. Both composites acted as flexible thermal regulators: they followed the PV panel's natural temperature changes while maintaining a lower overall temperature.

To thoroughly evaluate the comprehensive consistency of the thermal performance across different independent outdoor testing days, the average rear surface temperature obtained from each of the five distinct testing sessions was further analyzed and presented in Table 6 and Fig. 6. The control reference panel recorded an overall mean surface temperature of 49.64 ± 2.91 °C, while the LA-SSPCM and PW-SSPCM panels recorded 47.20 ± 1.68 °C and 47.02 ± 2.04 °C, respectively ($n = 5$). These quantitative values correspond to notable average temperature reductions of 2.44 °C for LA-SSPCM and 2.62 °C for PW-SSPCM relative to the reference panel. The results across the five testing sessions show that both SSPCM configurations maintained consistent thermal performance under varying outdoor conditions.

Table 6. Average temperature profiles across five outdoor testing sessions

Testing session	Reference	LA-SSPCM	PW-SSPCM
1	51.29	48.57	48.01
2	48.31	46.17	45.52
3	50.54	47.27	47.96
4	52.76	49.04	49.29
5	45.29	44.96	44.31
Mean ± SD	49.64 ± 2.91	47.20 ± 1.68	47.02 ± 2.04

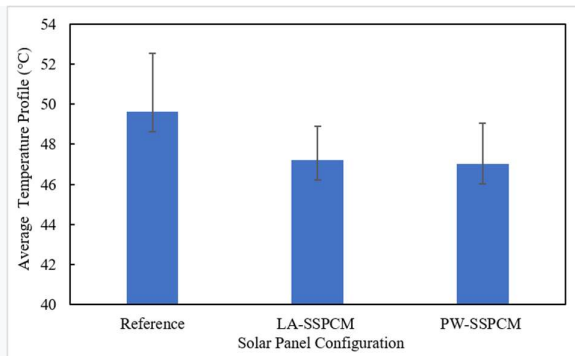


Fig. 6. Temperature profiles of the reference, LA-SSPCM, and PW-SSPCM panels across five outdoor testing sessions.

The paired-samples t-test showed that both SSPCM configurations significantly reduced the average panel temperature compared with the reference panel. The difference between the reference and LA-SSPCM panels was statistically significant ($p = 0.014$), as was the difference between the reference and PW-SSPCM panels ($p = 0.004$). In comparison, the average temperatures of LA-SSPCM and PW-SSPCM did not differ significantly ($p = 0.544$), although PW-SSPCM showed a slightly lower mean temperature.

3.4. Effect of SSPCM on Solar Panel Efficiency

Fig. 7 presents the efficiency profiles of the reference panel, LA-SSPCM panel, and PW-SSPCM panel during the first outdoor testing session from 11:00 to 12:30 WIB. Since the three panels were measured simultaneously under the same irradiance conditions, the differences in efficiency can be evaluated primarily in relation to SSPCM integration.

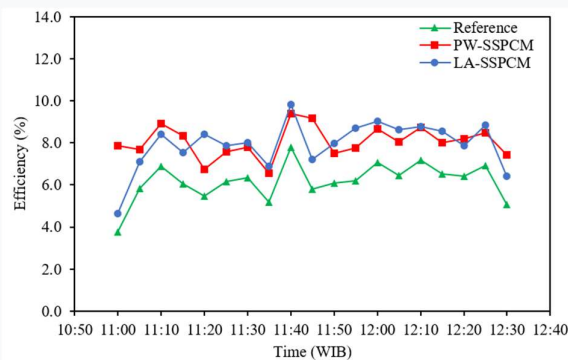


Fig. 7. Efficiency profiles of the reference, LA-SSPCM, and PW-SSPCM panels during the first outdoor testing session.

During the test, the reference panel achieved an average efficiency of 6.17%, while the LA-SSPCM panel reached 7.93%, corresponding to an improvement of 1.76 percentage points. The LA panel's efficiency remained higher than the reference panel throughout the test, indicating that the LA-based SSPCM helped maintain the PV panel's electrical performance under outdoor operating conditions. This improvement is closely related to the earlier thermal regulation provided by LA-SSPCM. As discussed in the temperature analysis, the lower melting range of LA-SSPCM, approximately 41.5–49.1 °C, allowed the composite to become active earlier during the temperature rise. By reducing the operating temperature more gradually over the measurement period, the LA panel was able to limit temperature-induced

electrical losses and sustain a higher conversion efficiency than the reference panel [6], [7].

The PW-SSPCM panel showed a slightly higher average efficiency of 8.05%, equivalent to an increase of 1.88 percentage points relative to the reference panel. This marginally higher gain is consistent with the stronger temperature suppression observed for PW-SSPCM during the higher-temperature stage of the test. The melting range of PW-SSPCM, approximately 47.27–54.99 °C, was closer to the PV panel's peak operating temperature, allowing more intensive latent heat absorption when the thermal load was highest. As a result, the PW panel achieved a more pronounced efficiency improvement during the period when temperature reduction had the greatest influence on electrical output [11], [38].

The efficiency profiles of all panels showed fluctuations, particularly during 11.05–11.45 WIB. This trend reflects the nature of outdoor testing, where variations in irradiance, cloud movement, wind conditions, and ambient temperature affect both the solar input and the panel operating temperature [19]. Such fluctuations are relevant because the optimal performance of solar panels can be affected by temperature, shading, dust, and the solar cell material itself [39]. However, the efficiency curves of the LA-SSPCM and PW-SSPCM panels remained consistently above that of the reference panel. This indicates that the efficiency improvement was not caused by differences in irradiance, since all panels received the same solar exposure, but by SSPCM's ability to reduce the thermal load on the PV cells. In silicon solar cells, elevated temperature commonly reduces the open-circuit voltage and affects the semiconductor band gap, leading to lower power output and conversion efficiency [40]. Therefore, by maintaining a lower operating temperature, both SSPCM composites helped reduce the temperature-related degradation of electrical performance.

Although the first outdoor testing session illustrates the SSPCM-integrated panels' response to changing conditions, a single session may not represent their overall performance. Therefore, five outdoor testing sessions were analyzed to assess performance consistency. The efficiency profiles summarized in Table 7 and shown in Fig. 8.

Table 7. Average efficiency profiles across five outdoor testing sessions

Testing session	Reference	LA-SSPCM	PW-SSPCM
1	6.17	7.93	8.05
2	6.45	8.91	8.15
3	5.20	7.85	6.68
4	4.69	7.82	6.33
5	5.38	8.04	6.96
Mean ± SD	5.58 ± 0.72	8.11 ± 0.46	7.23 ± 0.82

Across the five outdoor testing sessions, the reference panel achieved an average electrical efficiency of $5.58 \pm 0.72\%$, while the LA-SSPCM and PW-SSPCM panels achieved $8.11 \pm 0.46\%$ and $7.23 \pm 0.82\%$, respectively ($n = 5$). Relative to the reference panel, average efficiency improved by 2.53 percentage points for LA-SSPCM and 1.65 percentage points for PW-SSPCM. The paired-samples t-test indicated statistically significant improvements in electrical efficiency for both SSPCM configurations compared with the reference panel, with $p = 0.00034$ for LA-SSPCM and $p = 0.000017$ for PW-SSPCM. The

LA-SSPCM also showed a higher average efficiency than the PW-SSPCM, and this difference was statistically significant ($p = 0.033$).

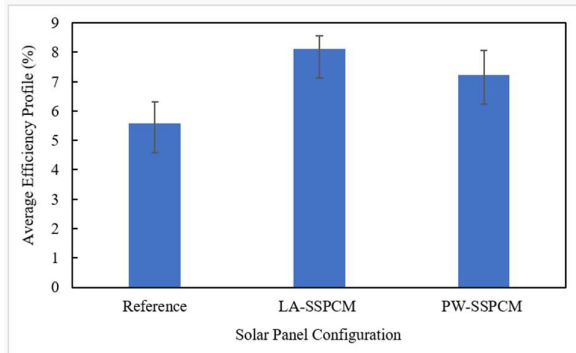


Fig. 8. Efficiency profiles of the reference, LA-SSPCM, and PW-SSPCM panels across five outdoor testing sessions.

Overall, both LA-SSPCM and PW-SSPCM improved PV panel efficiency through passive thermal regulation, although their effects differed slightly. Across the five testing sessions, LA-SSPCM exhibited a higher average electrical efficiency than PW-SSPCM, although the first-session profile showed a slightly higher efficiency for PW-SSPCM. These results confirm that waste-based SSPCMs can effectively improve PV performance by stabilizing the thermal condition of the panel under real outdoor operation.

3.5. Long-Term Stability and Thermal Cycling Considerations

The outdoor evaluation was conducted over five consecutive days under real operating conditions. During the testing period, both SSPCM-integrated panels were repeatedly heated and cooled as solar irradiance and ambient conditions changed. The performance of each SSPCM panel was compared with the reference panel during the same testing session. Across the five testing sessions, the efficiency improvement remained relatively stable. The LA-SSPCM showed an average improvement of 2.53 percentage points, while the PW-SSPCM showed an average improvement of 1.65 percentage points compared with the reference panel. No clear decrease in efficiency improvement was observed across the five testing sessions. The temperature reduction was also relatively consistent during the first four sessions. The fifth session showed a lower temperature reduction for both SSPCM panels, when daily irradiance was at its lowest. This suggests that the variation was more likely related to the outdoor conditions than to material degradation.

The AFA matrix mainly supports the composites' shape stability. The matrix remained as the supporting phase during PCM melting and helped retain the molten PCM within the composite. The LA composites showed leakage rates of 0.043–0.179%, while the selected PW-c composite showed a leakage rate of 1.82%. These low leakage values indicate that most of the PCM remained within the supporting matrix during the leakage test. The relatively consistent thermal performance across the five outdoor testing sessions did not show an apparent progressive decline in thermal regulation during the test period. However, the increase in leakage observed at higher paraffin loadings indicates that leakage may become a limitation when the PCM content exceeds the retention capacity of the AFA matrix.

Long-term aging effects were not evaluated in this study. Repeated phase transitions over a longer period may affect the latent heat capacity, PCM retention, and microstructure of the composites. Previous studies have reported that form-stable paraffin- and fatty-acid-based PCMs can maintain their thermal properties after repeated thermal cycling [24], [25], [26]. These findings support the potential stability of the SSPCM systems, but they cannot be directly used to establish the long-term durability of the composites investigated in this study. Therefore, longer thermal cycling tests are required to evaluate the aging behavior of both SSPCM systems. Accelerated melting–solidification cycles combined with periodic DSC analysis and leakage measurements could be used to assess changes in latent heat capacity, phase transition characteristics, and shape stability during prolonged operation.

3.6. Practical Applicability and Scalability

The results obtained from the 5 Wp PV modules demonstrate the potential of AFA-based SSPCMs for practical thermal management of photovoltaic panels. The use of AFA as the supporting matrix also provides an additional benefit by utilizing coal combustion waste as a functional material. For larger PV modules or arrays, the SSPCM layer could be adapted by adjusting the material quantity and coverage area according to the module dimensions. However, the optimum SSPCM thickness, thermal contact, and heat transfer characteristics may differ with module size and configuration [41]. Therefore, further testing at larger module scales is needed to determine the appropriate material loading and configuration for effective thermal management.

In terms of installation, the SSPCM configuration used in this study was placed on the rear side of the PV module using an aluminium-zinc container, so that the front surface remained exposed to solar radiation. This configuration is consistent with previous studies that applied PCM-based cooling at the rear side of PV modules under tropical conditions [42]. For practical application, the containment system should maintain adequate sealing to minimize PCM leakage during repeated thermal cycling. Sufficient thermal contact between the SSPCM layer and the rear surface of the PV module is also required to facilitate heat transfer. In larger PV installations, the additional mass of the SSPCM and its container should be considered in the design of the mounting structure.

The use of AFA may also provide an economic benefit because an industrial waste material is utilized as the supporting matrix. However, the economic feasibility of the proposed SSPCM system depends on the cost of PCM, AFA activation, containment materials, fabrication, installation, and maintenance. These costs should be considered alongside the additional electrical energy gained from improved PV performance. Previous techno-economic studies have shown that PCM integration can improve PV thermal performance, while the economic benefit depends on the balance between additional system costs and the resulting energy gain [41], [42]. Therefore, a detailed techno-economic analysis is required to evaluate the economic feasibility of the proposed SSPCM system for larger-scale PV applications.

4. CONCLUSION

This study evaluated and compared lauric acid (LA) and paraffin wax (PW)-based shape-stabilized phase change materials (SSPCMs) using activated fly ash (AFA) as the supporting matrix for passive thermal management of photovoltaic panels. The LA composites showed better shape stability, with leakage values of 0.043–0.179%, and the optimum composition was LA-d (45:55) with the lowest leakage of 0.043%. In comparison, PW leakage increased with increasing PCM content, and PW-c (40:60) had the highest leakage at 1.82%. DSC analysis showed melting enthalpies of 56.21 J/g for LA-d and 53.78 J/g for PW-c, with melting ranges suitable for the PV panel's operating temperature.

Outdoor testing showed that both SSPCM configurations improved PV thermal and electrical performance compared with the reference panel. In the representative outdoor test, LA-SSPCM reduced the panel temperature by 2.72 °C and increased the efficiency by 1.76 percentage points, while PW-SSPCM produced a larger temperature reduction of 3.29 °C and increased the efficiency by 1.88 percentage points. Across five outdoor testing sessions, LA-SSPCM and PW-SSPCM reduced the average PV temperature by 2.44 and 2.62 °C, respectively, while increasing the average electrical efficiency by 2.53 and 1.65 percentage points, respectively. These results indicate that LA-SSPCM provided the higher average electrical efficiency improvement, whereas PW-SSPCM provided slightly greater average temperature reduction.

Overall, both AFA-based SSPCMs demonstrated potential for passive photovoltaic thermal management. The LA-based composite showed better leakage resistance, slightly higher latent heat capacity, and greater average efficiency improvement, while the PW-based composite provided greater temperature reduction under the tested outdoor conditions. The use of AFA as the supporting matrix also provides a potential pathway for utilizing coal combustion waste in thermal management applications. However, this study did not evaluate long-term thermal-cycling durability or large-scale application. Further research should therefore focus on extended thermal cycling, long-term leakage and aging behavior, and techno-economic assessment at larger PV module or array scales.

REFERENCE

- [1] A. E. Putra, A. Hasan, and Y. Bow, "Performance Evaluation of 119.88 Kwp Iot Based on-Grid Solar System At Admin Building Grissik," *EKSAKTA J. Sci. Data Anal.*, vol. 6, no. 2, pp. 124–134, 2025, doi: 10.20885/eksakta.vol6.iss2.art8.
- [2] O. Bamisile, C. Acen, D. Cai, Q. Huang, and I. Staffell, "The environmental factors affecting solar photovoltaic output," *Renew. Sustain. Energy Rev.*, vol. 208, no. November 2024, p. 115073, 2025, doi: 10.1016/j.rser.2024.115073.
- [3] V.-S. Hudișteanu, N.-C. Cherecheș, F.-E. Țurcanu, I. Hudișteanu, and C. Romila, "Impact of Temperature on the Efficiency of Monocrystalline and Polycrystalline Photovoltaic Panels: A Comprehensive Experimental Analysis for Sustainable Energy Solutions," *Sustainability*, vol. 16, no. 23, pp. 10566, 2024, doi: 10.3390/su162310566.
- [4] M. R. Elavarasan, R. Pugazhendhi, S. Shafiq, S. Gangatharan, M. Nadarajah, and G. M. Shafiullah, "Efficiency enhancement of PV panels with passive thermal management using PCM : An exhaustive review on materials , designs and effective techniques," *Appl.*

- Energy*, vol. 382, no. December 2024, p. 125217, 2025, doi: 10.1016/j.apenergy.2024.125217.
- [5] S. M. Shalaby, M. K. Elfakharany, B. M. Moharram, and H. F. Abosheisha, "Experimental study on the performance of PV with water cooling," *Energy Reports*, vol. 8, pp. 957–961, 2022, doi: 10.1016/j.egy.2021.11.155.
- [6] Z. Xu, Q. Kong, H. Qu, and C. Wang, "Cooling characteristics of solar photovoltaic panels based on phase change materials," *Case Stud. Therm. Eng.*, vol. 41, no. December 2022, p. 102667, 2023, doi: 10.1016/j.csite.2022.102667.
- [7] A. Yusuf, S. Dhiya, U. Agoes, S. Surjamanto, W. Inge, and M. Sutjahja, "Determining the phase change characteristics of lauric acid to realise its optimum performance in latent thermal energy storage," *J. King Saud Univ. – Eng. Sci.*, no. 10, 2025, doi: 10.1007/s44444-025-00004-y.
- [8] S. Kahwaji and M. A. White, "Organic Phase Change Materials for Thermal Energy Storage: Influence of Molecular Structure on Properties," *Molecules*, vol. 26, no. 21, pp. 6635, 2021, doi: 10.3390/molecules26216635.
- [9] R. Naresh, R. Parameshwaran, and V. Vinayaka, "Study on thermal energy storage properties of bio-based n-dodecanoic acid / fly ash as a novel shape-stabilized phase change material," *Case Stud. Therm. Eng.*, vol. 30, no. December 2021, p. 101707, 2022, doi: 10.1016/j.csite.2021.101707.
- [10] C. V. Podara, I. A. Kartsonakis, and C. A. Charitidis, "Towards Phase Change Materials for Thermal Energy Storage: Classification, Improvements and Applications in the Building Sector," *Applied Sciences*, vol. 11, no. 4, pp. 1490, 2021, doi: 10.3390/app11041490.
- [11] M. Kraiem, M. Karkri, M. Fois, and P. Sobolciak, "Thermophysical Characterization of Paraffins versus Temperature for Thermal Energy Storage," *Buildings*, vol. 13, no. 4, 2023, doi: 10.3390/buildings13040877.
- [12] S. Zhang et al., "A review of phase change heat transfer in shape-stabilized phase change materials (ss-PCMs) based on porous supports for thermal energy storage," *Renew. Sustain. Energy Rev.*, vol. 135, no. July 2020, p. 110127, 2021, doi: 10.1016/j.rser.2020.110127.
- [13] J. Huang, H. Chen, J. Yang, T. Zhou, and H. Zhang, "Effects of particle size on microstructure and mechanical strength of a fly ash based ceramic membrane," *Ceram. Int.*, vol. 49, no. 10, pp. 15655–15664, 2023, doi: 10.1016/j.ceramint.2023.01.157.
- [14] L. Liu, B. Peng, C. Yue, M. Guo, and M. Zhang, "Low-Cost, Shape-Stabilized Fly Ash Composite Phase Change Material Synthesized By Using A Facile Process For Building Energy Efficiency," *Mater. Chem. Phys.*, vol. 222, pp. 87–95, 2019, doi: 10.1016/j.matchemphys.2018.09.072.
- [15] P. Liu, X. Cui, Y. Wang, Z. Zhang, J. Rao, S. Jiang, and X. Gu, "Preparation and Characterization of Lauric Acid/Modified Fly Ash/Graphene Composite as Low-Cost and Eco-Friendly Phase Change Materials for Thermal Energy Storage," *Energies*, vol. 16, no. 15, pp. 5666, 2023, doi: 10.3390/en16155666.
- [16] A. K. Murmu, L. Parida, and P. K. Senapati, "Desilication of High-Silica Indian Coal Fly Ash by Alkali Leaching With KOH and NaOH: A Comparative Study," *Int. J. Coal Prep. Util.*, vol. 44, no. 7, pp. 866–881, Jul. 2024, doi: 10.1080/19392699.2023.2228708.
- [17] C. Li, Q. Yu, Y. Deng, Q. Su, T. Xiao, and Y. Sun, "Preparation and Properties of Phase Change Energy Storage Composites Based on Modified Fly Ash," *Materials*, vol. 18, no. 9, pp. 2153, 2025, doi: 10.3390/ma18092153.

- [18] A. Taqwa, T. Dewi, A. A. Sasmanto, and Y. Bow, "Feasibility Study and Design of IoT-based Monitoring for Remote PV System," *Technol. Rep. Kansai Univ.*, vol. 63, no. 1, pp. 6933–6944, 2021.
- [19] A. Agüera-Pérez, M. J. Espinosa-Gavira, J. C. Palomares-Salas, J. J. González-de-la-Rosa, J. M. Sierra-Fernández, and O. Florencias-Oliveros, "Meteorological contexts in the analysis of cloud-induced photovoltaic transients: A review," *Renew. Sustain. Energy Rev.*, vol. 202, no. December 2022, 2024, doi: 10.1016/j.rser.2024.114689.
- [20] S. Nishad, Z. Ahmad, and I. Krupa, "Enhancement of photovoltaic module performance by thermal management using shape-stabilized PCM composites," *Sol. Energy Mater. Sol. Cells*, vol. 273, no. January, p. 112948, 2024, doi: 10.1016/j.solmat.2024.112948.
- [21] K. Alassaad, J. Minto, and P. De Wilde, "Enhancing Building Thermal Performance: A Review of Phase Change Material Integration," *Appl. Therm. Eng.*, vol. 268, pp. 1–43, 2025, doi: 10.1016/j.applthermaleng.2025.125849.
- [22] H. Zainuddin, M. M. M. Hanifah, M. Z. Hussin, and N. Muhammad, "Cell Temperature Determination based on IEC61215: Solar Photovoltaic Experimental Study of Tropical Malaysia," *J. Renew. Energy Smart Grid Technol.*, vol. 19, no. 2, pp. 1–6, 2024, doi: 10.69650/rast.2024.258005.
- [23] Q. Al-Yasiri and M. Szabó, "Paraffin As a Phase Change Material to Improve Building Performance: An Overview of Applications and Thermal Conductivity Enhancement Techniques," *Renew. Energy Environ. Sustain.*, vol. 6, p. 38, 2021, doi: 10.1051/rees/2021040.
- [24] D. Das, R. Crosby, and M. C. Paul, "A comprehensive review on the form stable phase change materials for storing renewable heat preparation, characterization and application," *J. Energy Storage*, vol. 110, no. November 2024, p. 115284, 2025, doi: 10.1016/j.est.2024.115284.
- [25] A. Wadee, P. Walker, N. McCullen, and V. Ferrandiz-Mas, "The effect of thermal cycling on the thermal and chemical stability of paraffin phase change materials (PCMs) composites," *Mater. Struct. Constr.*, vol. 58, no. 1, pp. 1–14, 2025, doi: 10.1617/s11527-024-02556-y.
- [26] G. Hekimoglu *et al.*, "Thermal management performance and mechanical properties of a novel cementitious composite containing fly ash/lauric acid-myristic acid as form-stable phase change material," *Constr. Build. Mater.*, vol. 274, 2021, doi: 10.1016/j.conbuildmat.2020.122105.
- [27] L. Sawunyama, O. C. Olatunde, O. A. Oyewo, M. F. Bopape, and D. C. Onwudiwe, "Application of coal fly ash based ceramic membranes in wastewater treatment: A sustainable alternative to commercial materials," *Heliyon*, vol. 10, no. 2, p. e24344, 2024, doi: 10.1016/j.heliyon.2024.e24344.
- [28] M. Gao, S. Zhao, H. Yang, X. Wu, and Y. Xiao, "An Analysis of the Influence of DSC Parameters on the Measurement of the Thermal Properties of Phase-Change Material," *Materials*, vol. 17, no. 23, pp. 5689, 2024, doi: 10.3390/ma17235689.
- [29] S. Çetin and Ü. Nazlı, "The Calculation of Experimental Mass Fractions of Phase Change Material in a Latent Heat Thermal Energy Storage Unit by Means of a Novel Thermal Analysis Method," *J. Therm. Anal. Calorim.*, vol. 150, no. 14, pp. 11035–11048, 2025, doi: 10.1007/s10973-025-14425-z.
- [30] A. A. Miaari, K. O. Mohasein, A. Al-Ahmed, and M. A. Hafiz, "Experimental investigation on thermal management and performance enhancement of photovoltaic panel cooled by a sustainable shape stabilized phase change material," *Case Stud. Therm. Eng.*, vol. 67, no. July 2024, p. 105763, 2025, doi: 10.1016/j.csite.2025.105763.
- [31] Y. Li, Y. Gao, X. Cao, X. Rong, and B. Chen, "Phase Change Materials Based on Cobalt/Nitrogen Double-Doped ZIF-67 Derived Carbon," *RSC Adv.*, vol. 13, no. 38, pp. 26907–26917, 2023, doi: 10.1039/d3ra04002j.
- [32] H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, *et al.*, "The ERA5 global reanalysis," *Q. J. R. Meteorol. Soc.*, vol. 146, no. 730, pp. 1999–2049, 2020, doi: 10.1002/qj.3803.
- [33] P. R. Michael, D. E. Johnston, and W. Moreno, "A conversion guide: solar irradiance and lux illuminance," *J. Meas. Eng.*, vol. 8, no. 4, pp. 153–166, 2020, doi: 10.21595/jme.2020.21667.
- [34] D. K. Yadav, P. K. S. Rathore, R. K. Singh, A. K. Gupta, and B. S. Sikarwar, "Experimental Study on Paraffin Wax and Soya Wax Supported by High-Density Polyethylene and Loaded with Nano-Additives for Thermal Energy Storage," *Energies*, vol. 17, no. 11, pp. 2461, 2024, doi: 10.3390/en17112461.
- [35] J. A. Noël *et al.*, "Clusters in Liquid Fatty Acids: Structure and Role in Nucleation," *J. Phys. Chem. B*, vol. 123, no. 32, pp. 7043–7054, 2019, doi: 10.1021/acs.jpcc.9b05017.
- [36] S. S. Bhakre, P. D. Sawarkar, and V. R. Kalamkar, "Numerical study on photovoltaic thermal phase change material system in hot climatic conditions," *Applied Thermal Engineering*, vol. 227, pp. 120423, 2023, doi: 10.1016/j.applthermaleng.2023.120423.
- [37] M. Han, K. Jiao, L. Lu, Z. Jin, T. Ma, and Q. Wang, "PEG-based solid-solid phase change materials for passive cooling of solar photovoltaic panels," *Applied Energy*, vol. 394, pp. 126190, 2025, doi: 10.1016/j.apenergy.2025.126190.
- [38] H. M. Maghrabie, A. S. A. Mohamed, A. M. Fahmy, and A. A. Abdel, "Performance enhancement of PV panels using phase change material (PCM): An experimental implementation," *Case Stud. Therm. Eng.*, vol. 42, no. October 2022, p. 102741, 2023, doi: 10.1016/j.csite.2023.102741.
- [39] M. Zulfahmi, R. Kusumanto, and Y. Bow, "Automatic Cleaning System Design to Increase PV Panel Output Power," *Int. J. Res. Vocat. Stud.*, vol. 1, no. 2, pp. 59–66, 2021, doi: 10.53893/ijrvocas.v1i2.48.
- [40] A. S. Al-Ezzi and M. N. M. Ansari, "Photovoltaic Solar Cells: A Review," *Applied System Innovation*, vol. 5, no. 4, pp. 67, 2022, doi: 10.3390/asi5040067.
- [41] T. Ibrahim, J. Faraj, H. El Hage, R. Taher, S. Ali, and M. Khaled, "Parametric enviro-economic analysis of cooling photovoltaic panels with phase change materials," *Int. J. Thermofluids*, vol. 27, no. March 2025, 2025, doi: 10.1016/j.ijft.2025.101151.
- [42] F. Puspongoro, A. M. Fathoni, D. Agustina, T. M. I. Mahlia, and N. Putra, "Thermal performance and techno-economic analysis of passive cooling for photovoltaic panel using Phase Change Material (PCM) in the tropics," *Results Eng.*, vol. 28, no. October, p. 107547, 2025, doi: 10.1016/j.rineng.2025.107547.