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Photovoltaic-thermal system using shea butter as a phase change material for power generation in Nigeria, Sub-Saharan Africa

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Electricity demand in Sub-Saharan Africa is rising, and in Nigeria, over 40% lack access to electricity. A photovoltaic-thermal (PV-T) system was simulated in TRNSYS, using shea butter for active cooling of photovoltaic (PV) modules. Its performance was compared with that of conventional paraffin wax, and the effects of system design parameters were examined. Efficiency gains from using shea butter and paraffin wax were 0.18% and 0.03%, respectively, during peak solar hours. Notably, shea butter reduced cell temperatures by 1.75 °C during peak sunlight compared with paraffin wax. Peak electrical power and efficiency reached 130.53 W and 11.35%, versus 109.78 W and 9.10% for conventional PV. The optimal flow rate was identified as 2.0 LPM, with a shea butter layer thickness of 0.04 m to optimise thermal capacity and heat transfer. Environmentally, shea butter is renewable and biodegradable, with a lower carbon footprint of 2.20 kg CO₂/kg compared with 3.78 kg CO₂/kg for paraffin wax, according to CarbonCloud data. As a bio-based energy storage medium, shea butter not only reduces global warming potential but also supports the SDGs, including affordable energy, climate action, and responsible consumption.

KEYWORDS

organic PCMs, paraffin wax, phase change material, photovoltaic-thermal, shea butter, sub-Saharan africa

1 Introduction

The world's growing population significantly increases demand for energy to meet human needs. Scientists are investigating alternatives to non-renewable energy sources, such as fossil fuels, which cause environmental problems and are finite. Global warming has become one of the most serious life-threatening challenges on Earth (Agbo et al., 2021). According to the Global Energy Perspective 2025, electricity demand will continue to increase globally, driven by buildings, industry, and transport, particularly in Europe, the United States of America, and China.

Electricity demand in Sub-Saharan Africa is projected to increase significantly in the coming years. In 2023, Nigeria's population was nearly 224 million, requiring substantial energy to support economic development and sustainability (Sasu, 2024). Nigeria relies primarily on fossil fuels for energy, but these resources are finite, unlike renewable options such as solar power. More than 40% of Nigerians lack access to electricity due to inadequate infrastructure, financial constraints, and poor electricity generation (Sawadogo et al., 2020).

Solar energy has attracted attention in energy generation because it offers a promising option for both electrical and thermal power to meet Nigeria's clean energy needs. Solar energy is an inexhaustible renewable resource with significant potential in countries located closer to the equator. When properly managed, it can provide a considerable share of the world's energy from the sun, approximately equal to 1.8 MW annually (Fahmi et al., 2014).

The photovoltaic (PV) cells are made from semiconductors that convert sunlight into electricity (Oko et al., 2012). The PV cells are assembled into modules and connected in series and parallel to form a panel. Other accessories, such as the battery bank (storage), voltage regulator, inverter (DC/AC converter), and loads, are connected to the PV panel.

The PV panel converts solar radiation into electrical and thermal power. However, PV cells have limited absorption of the solar spectrum; they absorb high-energy radiation above the band gap to generate electron-hole pairs, while lower-energy radiation is reflected (Awai et al., 2024). The limited efficiency of PV cells in converting incident radiation into electricity results in heat accumulation within the cells (Adun et al., 2022).

Sub-Saharan Africa is known for high, prolonged solar radiation, which can raise PV cell temperatures. According to the World Sunshine Map, Africa receives more annual hours of sunshine than any other continent. Prolonged sunlight on the PV panel increases the surface temperature of the PV cells. This temperature rise reduces the panels' electrical efficiency: a 10 °C increase causes approximately a 5% decrease in PV system performance (Sarafraz et al., 2019).

Cooling PV systems in sub-Saharan Africa is vital for improving their efficiency and prolonging their lifespan. Various approaches have been examined in the literature to improve the efficiency of PV panels through active cooling, such as heat exchangers using fluids (e.g., water and nanoparticle-infused water), known as photovoltaic-thermal (PV-T) systems. Kuefouet Alexis et al. (2022) compared the cooling of a hybrid solar PV-T system using monocrystalline, polycrystalline, and amorphous silicon solar panels. The PV-T system made of polycrystalline silicon achieved the highest electrical output, followed by monocrystalline and amorphous silicon. The PV-T integrated with phase change material uniformly regulates PV cell temperature to an optimal operating condition. Likewise, passive cooling strategies, such as applying photovoltaic-phase change materials (PV-PCM) without circulating fluids or heat exchangers, have also been explored. A combined aluminium heat sink, mounted at the rear of the PV panel alongside surface water cooling, was employed to maintain the module surface temperature at 20 °C, resulting in a power increase of 20.96 W and a 3% boost in electrical efficiency (Idoko et al., 2018).

The PCM's charging and discharging behaviour, which provides storage capability, helps regulate the temperature of the PV cells during phase change. A combined passive and active cooling method, employing RT55 paraffin wax and a thermoelectric generator (TEG), was used to cool the PV panel. This approach increased the maximum energy conversion efficiency from 30% to 35.2% and reduced the maximum temperature from 85 °C to 71 °C with the PCM-integrated system (Gürbüz et al., 2023). When PV cells operate at different temperatures, they incur ohmic losses that are minimal when connected in series. Parthiban et al. (2020)

developed a three-dimensional thermal model of a PVT system to analyse the temperature distribution in the panel using both a serpentine and a harp-type (parallel-pipe) configuration. The harp-type heat exchanger cools and distributes the PV panel's cell temperature more evenly compared to the serpentine type. Similarly, Tarabsheb et al. (2013) investigated the non-uniform cooling of PV cells' operating temperature observed under PV-T systems. They installed cooling pipes beneath each PV string to improve the electrical efficiency of the PV panels.

Vaziri Rad et al. (2024) investigated cooling methods for a flat plate and a concentrated PV-T system. The water-based CPV/T system, combined with paraffin wax and copper fins, performed best, achieving electrical, thermal, and exergy efficiencies of 15.5%, 37.4%, and 16.7%, respectively, while reducing the PV cell temperature by 20 °C. Additionally, a PV-T system integrated with nano-paraffin and nanofluid reduced the PV cell temperature by 19 °C and increased electrical efficiency by 106% and 56% relative to a conventional PV panel and a water-cooled system, respectively (Al-Ghezi et al., 2022; Dayer et al., 2023) modelled a fan-shaped finned tube to enhance the thermal conductivity of PCM. Heat storage and energy efficiency improved by 13.4% and 10.2%, respectively, while the PCM melting time decreased by 36.2%. Ali Bhutto et al. (2024) combined water and phase-change materials for cooling are installed at the rear of the PV panel, achieving a cell temperature of 59 °C. Water cooling alone reduces the cell temperature to 49 °C, whereas water and PCM further reduce it to 36 °C. Similarly, Li et al. (2023) presented a water-based solar PV-T system embedded with PCM, showing reductions of 12.54 °C and 42.28 °C in cell temperature relative to PV-T and PV systems, respectively.

Waqas et al. (2019) inserted phase change material in tubes evenly and attached to the back of the PV module, reducing the peak cell temperature by 6 °C–9 °C. Hassan et al. (2020) introduced a PV-T/PCM system with nanofluid, alongside PV/PCM and traditional PV, using RT-35HC with graphene nanoparticles ranging from 0.005% to 0.15%. The lowest temperature drops observed were 23 °C, 16.1 °C, and 11.9 °C for nanofluid-based PV-T/PCM, water-based PV-T/PCM, and PV/PCM, respectively. Similarly, Kumar et al. (2020) compared three PV setups: a standalone PV, a PV with PCM in an aluminium container, and a PV with PCM in an aluminium container with fins. The finned PV reduced the cell temperature by 22.3 °C, whereas the non-finned version reduced it to 12 °C.

Charcoal with and without metal flakes to prevent PCM (Lauric acid) leaks was used to enhance heat transfer in the PV-T system at an optimal flow rate of 0.2 L/min, decreasing PV cell temperature by 24.82 °C in the combined PCM and metal flakes system (Maneechot et al., 2025). Similarly, a half-cycled tube thermal collector was developed to improve the thermal and electrical efficiencies of PV-T systems integrated with paraffin wax as a PCM. The PV-T/PCM system achieved electrical and thermal efficiencies of 12.23% and 68.38%, respectively, exceeding those of the PV-T system (12.16% and 50.9%) (Maseer et al., 2025).

Azimi and Sharifzadeh (2025) highlighted the significance of meticulous selection of phase change materials, considering their melting points and interactions with nanoparticles, for optimal thermal management in solar energy systems. They integrated a phase change material (PCM) with a melting point of 39.47 °C,

TABLE 1 Recent studies on the PVT-PCM system using paraffin wax as the PCM.

Authors	PCM applied	Working fluid
Maneechot et al. (2025)	Lauric acid	Water
Vaziri Rad et al. (2024)	Paraffin wax	Water
Ali Bhutto et al. (2024)	Paraffin wax	Water
Li et al. (2023)	Paraffin wax	Water
Bouzelmad et al. (2023)	Paraffin	Water
Colarossi and Principi (2022)	Paraffin	Water
Kong et al. (2022)	Paraffin	Water
Yousef et al. (2022)	Paraffin wax	Water
Naghdibishi et al. (2020)	Paraffin wax	Water and, EG 50%
Hassan et al. (2020)	RT-35HC	Graphene nanoparticles
Hossain et al. (2019)	Lauric acid	Water
Maatallah et al. (2019)	Paraffin wax	Water
Hosseinzadeh et al. (2018)	Paraffin wax	ZnO/water nanofluid
Kazemian et al. (2018)	Paraffin wax	Water
Mousavi et al. (2018)	Paraffin C15, C18, C22	Water

which demonstrated superior heat absorption and storage, thereby contributing to the cooling of the photovoltaic (PV) panel.

Sharifzadeh et al. (2024) developed a phase change material (PCM)-based cooling system augmented with hierarchical zinc oxide (ZnO) and expanded graphite (EG) nanofillers to enhance the thermal conductivity of PCMs and increase photovoltaic (PV) panel efficiency. Their experimental procedure involved integrating a PV module with various PCMs, including paraffin, beeswax, and a bio-PCM composed of oleic acid and beeswax, and subsequently comparing their performance under simulated solar radiation. The results demonstrated a reduction in PV temperature from 64.23 °C (without cooling) to 54.11 °C with paraffin, 57.15 °C with beeswax.

Economically, Yousef et al. (2022) studied PV, PV-PCM, and PV-PCM/aluminium foam (AF) systems. During summer, the electrical efficiency rose by 9% for PV-PCM and 14% for PV-PCM/AF. The electricity costs were \$0.1165 and \$0.1145 per kWh for PV-PCM and PV-PCM/AF, respectively, compared to \$0.1162 per kWh for a standard PV system. Evaluating energy costs and LCOE helps assess the costs of PV-T systems when integrated with PCM. Therefore, the design of a PV-T/PCM system must ensure high energy efficiency. Overall, the total cost of a PV-T/PCM system could be 15%–20% lower, resulting in a payback period that is about 6 years shorter than that of a PV-T system (Cui et al., 2022). Table 1 presents some recent studies on PV-T/PCM using paraffin wax as PCM and water as the working fluid.

The literature discusses various cooling techniques for PV panels. One method involves arranging serpentine channels at the rear, which results in non-uniform cooling of the PV cells and can create hot spots, leading to ohmic losses. To address the limitations of PVT systems, the hybrid PVT/PCM approach was introduced. However, PCMs have low thermal capacity, prompting the addition of nanoparticles and fins to

TABLE 2 Types used in the TRNSYS simulation.

Type	Model
15-3	Energy + weather (EPW)
590d	PV-T/PCM
65d	Online printer without a file
65c	Online printer with a file
25a	Printer
14h	Forcing function
24	Integrator
57	Unit converter
47d	Battery
165	Controller
48c	Inverter
41	Load profile sequencer
60d	Thermal storage tank
3d	Pump
1260_v2a	Mixing valve
1258_v2a	Diverging valve

enhance heat transfer. Economically, PVT/PCM systems require a higher initial investment than traditional PV systems. Nonetheless, the payback period is relatively short if the dual output is fully utilised, particularly in regions with abundant solar radiation and long hours of sunlight, such as sub-Saharan Africa.

Many studies, both experimental and numerical, have been conducted to minimise the rise in cell temperature of PV panels, given that sub-Saharan Africa receives more solar radiation hours than other regions. However, gaps remain, including the lack of studies on this system in sub-Saharan Africa and the limited use of bio-based PCMs in the literature.

This study addresses gaps in existing research, emphasising the limited number of studies on PV-T-PCM in Sub-Saharan Africa. In this region, photovoltaic cells are exposed to high temperatures, and diverse climate conditions require tailored evaluations of PVT-PCM systems. While paraffin PCMs are well documented, research on bio-based PCMs suitable for African environments remains limited. A bio-based PCM, specifically shea butter, has not yet been examined in PVT/PCM systems and is introduced. Although paraffin wax, derived from hydrocarbons and fossil fuels, offers high latent heat and benefits long-term energy storage, it is neither environmentally sustainable nor eco-friendly compared to shea butter.

2 Methodological setup

2.1 Physical and computational model

The PV-T/PCM system was modelled in TRNSYS software to utilise solar energy for electricity and thermal energy collection. It

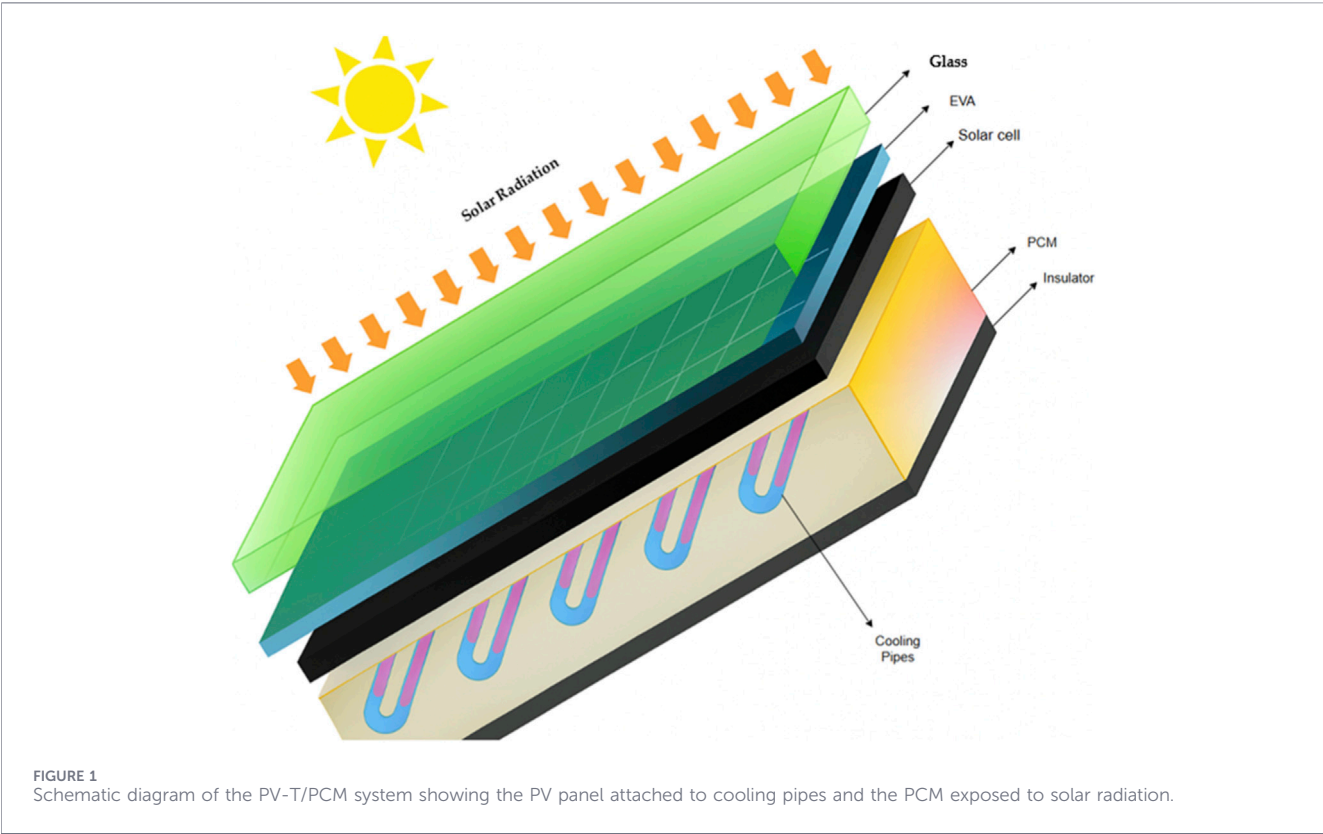


FIGURE 1
Schematic diagram of the PV-T/PCM system showing the PV panel attached to cooling pipes and the PCM exposed to solar radiation.

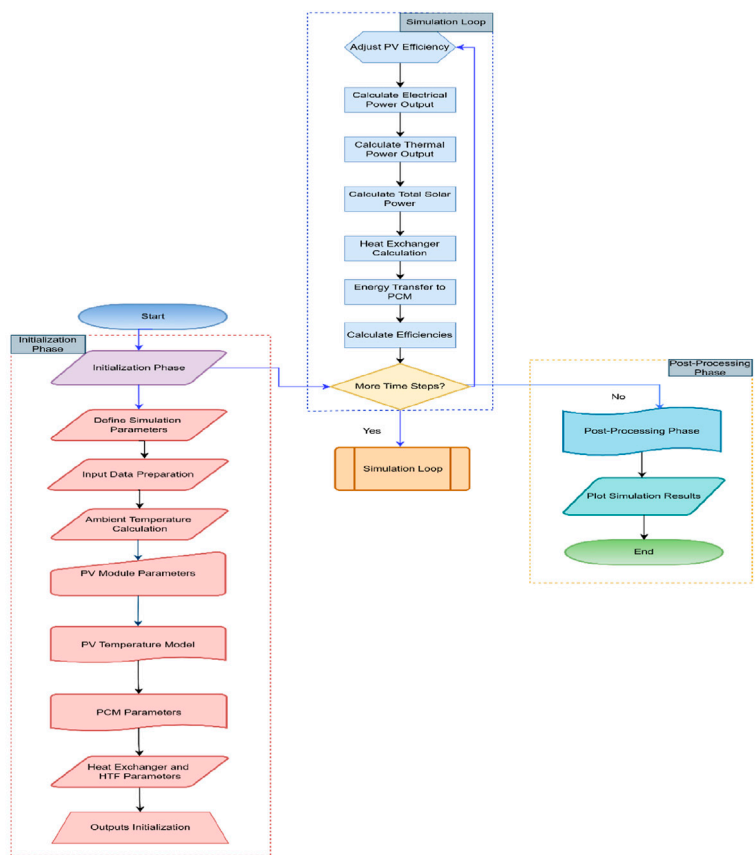
combined photovoltaic panels with copper thermal absorbers to capture excess heat. Shea butter and paraffin wax were introduced into the system as PCM to regulate the PV cell temperature. PCM absorbs and releases heat during phase changes (e.g., solid-to-liquid and *vice versa*), helping maintain an optimal PV surface temperature and enhancing efficiency. The working fluid flows through the tubes in contact with the PCM, transferring heat by conduction and convection. A regulated pump restores the PCM to its initial temperature. The pump operates in an OFF-ON-OFF cycle, turning on when the PCM's temperature approaches its melting point and off when it is near the fluid inlet temperature. The OFF and ON controllers were connected, with a 10 °C temperature difference and a monitoring inlet temperature of 20 °C; the high-limit cut-out temperature was 100 °C. The working-fluid flow was assumed to be laminar at a rate of 0.028 kg/s. The simulation time step was set to 30 min to monitor all transient behaviour.

Computational models developed using TRNSYS software were used to simulate the electrical and thermal performance of the hybrid PV-T/PCM system. TRNSYS uses “Type” models, which do not exchange information directly but can communicate *via* declared variables and Type Equations, where calculations are performed, and results are sent to other Types as inputs. Table 2 presents the Types used in this work. The model analyses heat-transfer mechanisms and evaluates the influence of PCM on system efficiency. Simulation tools incorporated local climate data from Maiduguri, northeastern Nigeria—covering solar radiation, ambient temperature, and wind speed—to estimate energy production. The weather data was obtained from the EnergyPlus Weather (EPW) dataset.

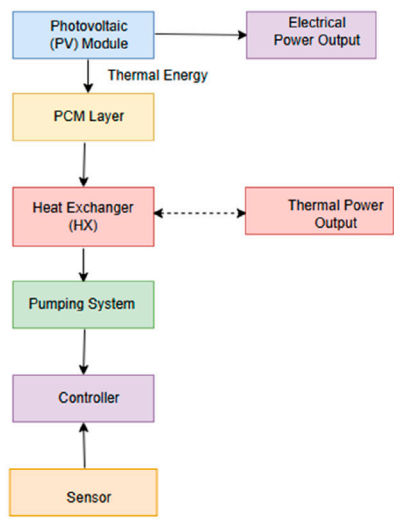
TABLE 3 Parameters of the PVT system used in the model (Su et al., 2017).

Parameter	Symbol	Value
Length of the PV module	L	1.8 m
Width of the PV module	W	1 m
Packing factor	F	0.83
Reference values	η_{ref} β_{ref} T_{ref}	12%, 0.0045K ⁻¹ , and 293 K
Emissivity	τ	0.9
Absorptance	α	0.9
Tubes diameter	D	0.025 m
Absorber thickness	δ	0.005 m

The PV-T/PCM layers depicted in Figure 1 consist of ethylene-vinyl acetate (EVA), Tedlar, and a glass cover. The thermal collector features a flat-plate absorber and copper tubes welded to the collector plate. Sunlight follows a specific path, passing through the glass to reach the EVA layer and subsequently the solar cells. Energy transfer within the PV cell depends on the transmissivity and absorptivity of the PV layers, as outlined in Table 3. Part of the incident solar energy is converted into electricity, while the remaining heat is conducted to the absorber plate. The phase change material (PCM) absorbs heat from the absorber *via* conduction and undergoes a phase change. When fully charged, the PCM discharges by circulating a working fluid through pipes to absorb the heat, which can then be used for low-temperature household applications.



a) Flowchart of the simulation process.



b) technical route diagram of the PV-T/PCM system.

FIGURE 2 (a,b) The flowchart of the simulation process and the technical route diagram of the PV-T/PCM system, illustrating the stages and path of the simulation.

2.2 Mathematical modelling equations

The following assumptions were made under the mathematical model:

- The ohmic losses are considered negligible. This assumption enables the model to focus on heat-transfer processes and the phase-change effects of the PCM within the system, while neglecting the negligible electrical resistance of the solar cells, wiring, and contacts.
- The sky is an opaque body. This reduces the complex radiative transfer calculations for a semi-transparent atmosphere to simple surface-to-surface radiation heat exchange.
- The thermal-physical properties of the thermal collector and PV layers remain constant and independent of the temperature. The model focuses primarily on heat transfer (conduction into the PCM, convection to the fluid, and radiative losses) and the PCM's latent heat.
- The contact resistance is negligible with solid components. Assuming perfect contact simplifies the energy balance equations, since the thermal resistance associated with these solid-solid contacts is negligible relative to the conductive, convective, and radiative heat losses.
- The PCM melting temperature and thermal conductivity are constant in the numerical simulation. A single constant melting point makes it easier to track the transition from solid to liquid.
- The PCM is homogeneous and isotropic in both phases. The PCM properties are uniform throughout its volume and the same in all directions (x, y, and z).
- The working fluid flows in one direction. This indicates the absence of turbulence, reducing the governing equations to a one-dimensional heat-transfer problem.

The research pathway and simulation process of the PV-T/PCM system are illustrated in the flowchart diagram and technical route diagram in [Figures 2a,b](#).

The energy equations for the individual PV-T/PCM layers, which account for heat-transfer processes, are presented in the preceding sections.

2.2.1 Glass cover layer

Convective and radiative heat transfer take place between the glass and the atmosphere. While radiant heat transfer occurs within the PV panel, convective heat transfer occurs between the air layer and the PV panel. [Equation 1](#) through (6) ([Bouzelmad et al., 2023](#)) illustrate these heat-transfer processes in the glass cover layer.

$$G\alpha_g = h_{r,g-s}(T_g - T_s) + h_{c,g-e}(T_g - T_e) + (h_{r,g-pv} + h_{c,g-pv}) \times (T_g - T_{pv}) \quad (1)$$

The radiative heat transfer coefficient between the glass cover and the atmosphere is given by [Equation 2](#)

$$h_{r,g-s} = \frac{\epsilon_g \sigma (T_g^4 - T_s^4)}{(T_g - T_s)} \quad (2)$$

where T_s is the effective sky temperature and is given in [Equation 3](#) and T_e is the environmental temperature.

$$T_s = 0.0552T_e^{1.5} \quad (3)$$

The convective heat transfer between the glass cover and the environment, as a function of wind speed, is described by [Equation 4](#).

$$h_{c,g-e} = 3v_{wind} \quad (4)$$

The radiative heat-transfer coefficient for the glass cover and the PV panel layers is given in [Equation 5](#).

$$h_{r,g-pv} = \frac{\sigma(T_g^2 + T_{pv}^2)(T_g + T_{pv})}{\left(\frac{1}{\epsilon_g} + \frac{1}{\epsilon_{pv}} - 1\right)} \quad (5)$$

The convective heat-transfer coefficient for the air layer impinging on the glass cover and the PV panel is given in [Equation 6](#).

$$h_{c,g-pv} = \frac{Nu_a k_a}{\delta_a} \quad (6)$$

2.2.2 The PV cell layer

The PV panel captures solar radiation incident on the glass cover, converting some of it into electricity, while the rest is lost through radiative heat transfer to the cover. Convection occurs between the interlayer air and conductive heat transfer to the absorbing plate. The energy balance for this process is described in [Equation 7](#).

$$G\tau_g \alpha_{pv}(1 - \eta_{pv}) = (h_{r,g-pv} + h_{c,g-pv})(T_{pv} - T_g) + \frac{T_{pv} - T_{ab}}{R_{pv,ab}} \quad (7)$$

The electrical efficiency of the PV system is presented in [Equation 8](#)

$$\eta_{pv} = \eta_r [1 - \beta_r (T_{pv} - 293.15)] \quad (8)$$

The thermal resistance between the PV panel and the absorbing plate is given by [Equation 9](#).

$$R_{pv,ab} = \frac{\delta_{pv}}{\lambda_{pv}} + \frac{\delta_{ab}}{\lambda_{ab}} \quad (9)$$

2.2.3 Heat absorbing plate layer

Conductive heat transfer occurs between the heat absorber plate, the PV panels with the PCM, and the working fluid in the pipes. [Equation 10](#) illustrates the energy conversion process within this layer.

$$\frac{(T_{pv} - T_{ab})}{R_{pv,ab}} = \frac{(T_{ab} - T_t)}{R_{ab,t}} + \frac{(T_{ab} - T_{pcm})}{R_{pcm,ab}} \quad (10)$$

2.2.4 The pipes

Conductive heat transfer occurs between the absorber plate, the PCM, and the pipes, and convective heat transfer within the working fluid in the pipes, as illustrated in [Equation 11](#).

$$h_{ab,t} A_{ab,t} (T_{ab} - T_t) = h_{t,w} A_{t,w} (T_t - T_w) + h_{pcm,t} A_{pcm,t} (T_{pcm} - T_t) \quad (11)$$

Equation 12 provides the convective heat transfer coefficient between the working fluid inside the pipes and the pipe wall.

$$h_{w,t} = Nu_w \frac{\lambda_w}{D_t} \quad (12)$$

The heat transfer coefficient between the pipes, absorber plate, and PCM is defined by Equations 13,14.

$$h_{ab,t} = \frac{8\lambda_{ab}}{l - D_t} \frac{\delta_{ab}}{W} \quad (13)$$

$$h_{pcm,t} = \frac{2\lambda_{pcm}}{\delta_{pcm}} \left(\frac{\pi}{2} + 1 \right) \frac{D_t}{W} \quad (14)$$

Equation 15 presents the convective heat transfer coefficient between the working fluid and the tube walls.

$$h_{t,w} A_{t,w} (T_t - T_w) = c_p \dot{m} (T_{out} - T_{in}) \quad (15)$$

The energy equation for the cooling pipes is solved concurrently with the PCM enthalpy formulation to capture both sensible and latent heat during melting and solidification.

The PCM encompasses both sensible and latent heat storage, so the overall enthalpy can be expressed as:

$$\rho \frac{\partial H}{\partial t} = \nabla \cdot (k \nabla T) + S \quad (16)$$

Where:

$$H = c_p (T - T_{ref}) + \beta L$$

and

$$\beta = \begin{cases} 0 & T < T_s \\ \frac{T - T_s}{T_l - T_s} & T_s \leq T \leq T_l \\ 1 & T > T_l \end{cases}$$

Where:

H = total enthalpy

L = latent heat

β = liquid fraction

T_s, T_l = solidus and liquidus temperatures

Coupling between pipes and PCM, the heat flux term linking the two equations is:

$$q_{pcm} = h_{pcm,t} A_{pcm,t} (T_{pcm} - T_t) \quad (17)$$

2.2.5 PCM layer

According to Ahmad et al. (2021a), Shea butter has a transition temperature range of 31.26 °C–40.16 °C with a latent heat of 50.36 kJ/kg. The convective heat transfer is negligible; therefore, it is disregarded in the solid-liquid process. The quantity of heat absorbed by the PCM to charge fully, as well as the mass,

momentum, and energy of the PCM, are given in Equations 18–21 (Li et al., 2023).

$$\delta Q_{pcm} = WL \left[\frac{(T_{ab} - T_{pcm})}{R_{ab,pcm}} + h_{pcm,t} (T_t - T_{pcm}) - (T_t - T_{pcm}) - (T_{pcm} - T_i) / R_{pcm,i} \right] \delta t \quad (18)$$

If $Q_{pcm} < Q_{sol}$,

$$T_{pcm} = T_{mt} - \frac{Q_{sol} - Q_{pcm}}{c_{pcm,sol}}, \lambda_{pcm} = \lambda_{pcm,sol} \quad (19)$$

If $Q_{sol} < Q_{pcm} < Q_{liq}$,

$$T_{pcm} = T_{mt}, \lambda_{pcm} = \lambda_{pcm,sol} \frac{Q_{liq} - Q_{pcm}}{Q_{liq} - Q_{sol}} + \lambda_{pcm,liq} \frac{Q_{pcm} - Q_{sol}}{Q_{liq} - Q_{sol}} \quad (20)$$

If $Q_{liq} < Q_{pcm}$,

$$T_{pcm} = T_{mt} - \frac{Q_{pcm} - Q_{liq}}{c_{pcm,liq}}, \lambda_{pcm} = \lambda_{pcm,liq} \quad (21)$$

where Q_{pcm} : quantity of heat in the PCM layer; Q_{sol} , Q_{liq} : quantity of heat inside the PCM at the solid and liquid states, respectively; T_{pcm} : PCM layer temperature; T_{mt} : PCM melting temperature; T_i : insulation layer temperature.

The instantaneous and cumulative heat stored and released by the PCM is described in Equations 22, 23 (Surya et al., 2024).

$$Q_{PCM,cha} = m_{PCM} \times [C_{p,s} (T_{PCM,2} - T_{PCM,1}) + (L_m) + C_{p,l} (T_{PCM,2} - T_{PCM,1})] \quad (22)$$

$$Q_{PCM,dis} = m_{PCM} \times [C_{p,l} (T_{PCM,1} - T_{PCM,2}) + (L_m) + C_{p,s} (T_{PCM,1} - T_{PCM,2})] \quad (23)$$

$Q_{PCM,cha}$ and $Q_{PCM,dis}$ are the quantities of heat of charge and discharge of the PCM, respectively, m_{PCM} is the mass of the PCM, $C_{p,s}$ and $C_{p,l}$ are the heat capacities of the solid and liquid state of PCM, respectively; $T_{PCM,1}$ and $T_{PCM,2}$ are the initial temperature and final temperature of the PCM, respectively, and L_m is the latent heat of PCM.

2.2.6 Insulation layer

The energy equation for insulation is given in Equation 24.

$$\frac{(T_i - T_{pcm})}{R_{pcm,i}} = h_{i,e} (T_i - T_e) \quad (24)$$

2.2.7 Thermal and electrical power gain

The heat gained by the collector equals the sum of the heat gained by the water through the pipes and the heat gained by the PCM, as given in Equation 25.

$$Q_h = c_p \dot{m} (T_{out} - T_{in}) + Q_{pcm} \quad (25)$$

The electrical power of the PV module is given in Equation 26.

$$Q_{ele} = G \cdot A \cdot \tau_g \alpha_{pv} \cdot p_a \cdot \eta_{pv} \quad (26)$$

Electrical, thermal, and total efficiencies are used to assess the performance of PV solar systems, as shown in Equations 27–29.

$$\eta_{ele} = \frac{Q_{ele}}{GA} \quad (27)$$

$$\eta_{th} = \frac{Q_{th}}{GA} \quad (28)$$

$$\eta_{to} = \eta_{th} + \frac{\eta_{ele}}{\eta_{power}} \quad (29)$$

2.2.8 Thermal contact resistance

The current model assumes perfect thermal contact among the PV panel, heat exchanger, and PCM layer. However, in real-world scenarios, interfacial thermal contact resistance arises from surface roughness, imperfect bonding, air gaps, and encapsulation materials. Microencapsulated PCM further adds resistance from its polymer shell and inter-particle voids, reducing effective thermal conductivity and heat transfer rates. As a result, the model may overestimate heat extraction efficiency and temperature uniformity (Incropera et al., 2007; Bahrami et al., 2006).

In an actual system, the PV-T/PCM setup is integrated as follows:

PV panel → adhesive/interface (absorber plate) → heat exchanger → PCM container → PCM (microencapsulated).

Each interface contributes a resistance to a sum:

$$R_{total} = R_{PV-HX} + R_{HX-PCM} + R_{PCM} \quad (30)$$

$$R_c = \frac{1}{h_c A}$$

Where:

R_c = contact resistance (K/W)

h_c = thermal contact conductance (W/m²·K)

A = contact area (m²)

Then, the heat flux is:

$$q = \frac{T_1 - T_2}{R_c} \quad (31)$$

Therefore, the boundary condition is:

$$-k \frac{\partial T}{\partial x} = \frac{T_{PV} - T_{HX}}{R_c} \quad (32)$$

This introduces a temperature discontinuity at the interface, which is physically realistic.

2.2.9 Variability in shea butter properties and its impact on PVT/PCM system performance

Shea butter exhibits significant variability in its thermophysical properties due to differences in fatty acid composition, geographic origin, and processing methods. Studies show that its melting onset usually occurs between 31 °C and 40 °C, with a latent heat of around 50 J/g, though these values vary across samples and processes (Salisu et al., 2022). The fatty acid profile, especially the ratio of stearic to oleic acids, varies by region and method, affecting melting point, viscosity, and texture (Honfo et al., 2013; Tchobo et al., 2018). Traditional extraction methods can increase free fatty acids and impurities, impacting melting behaviour and oxidative stability

(Honfo et al., 2013). Additionally, genetic and environmental factors influence composition, leading to observable differences in thermal properties (Moharram et al., 2006).

Synthetic phase change materials (PCMs), such as paraffin wax, demonstrate relatively stable phase transitions, in contrast to shea butter, which comprises triacylglycerols (approximately 77.7%–92.4%) and diacylglycerols (approximately 7.6%–22.6%) (Goumbri et al., 2024). The proportions of these components fluctuate in response to biochemical and environmental factors. Such variability has a direct impact on PVT/PCM systems, wherein the phase change material (PCM) must melt within the operating temperature range of photovoltaic (PV) modules.

Differences in properties are mainly due to variations in fatty acid composition. Higher saturated fat content increases the melting point and viscosity, while unsaturated fat content decreases the transition temperature and enhances fluidity. This regional botanical diversity causes noticeable differences in thermal behaviour, as demonstrated by comparative studies of shea butter from different locations (Goumbri et al., 2024). Moreover, processing techniques such as roasting, filtration, and refining affect crystalline and impurity content, leading to variations in thermal responses across batches. Additionally, alterations in viscosity affect natural convection and heat distribution within the PCM, which in turn influences temperature uniformity across the PV surface.

At the system level, thermophysical variability impacts the effectiveness of PCM in temperature regulation. The timing of melting signals the onset of latent heat absorption. If melting is delayed, PV cell temperatures rise, reducing electrical efficiency. Conversely, earlier melting shortens the cooling period during peak sunlight hours. Changes in latent heat capacity also influence storage: lower values lead to faster saturation and shorter cooling times, while higher values enable extended thermal buffering. If the melting temperature of shea butter is too low, its cooling ability diminishes, increasing the risk of PV overheating. On the other hand, too high a melting temperature may prevent melting altogether. Suitable for PV cooling, shea butter with a melting temperature between 31 °C and 40 °C aligns with the operating temperature of typical PV cells.

Long-term reliability is of paramount importance. Repetitive thermal cycling may induce oxidation, polymorphic transitions, or phase segregation, potentially diminishing performance. Encapsulation methodologies are instrumental in safeguarding the PCM from oxygen and moisture, thereby improving resistance to degradation caused by cyclic thermal processes (Salisu et al., 2022). Ensuring stability throughout repeated thermal cycling is especially critical for large-scale applications, where sustained performance over extended periods is imperative.

The current study does not include direct experimental thermal-cycling measurements of the shea butter PCM. Instead, it employs a numerical model that assumes constant thermophysical properties and a fixed melting temperature, as in existing literature (Ahmad et al., 2021a; Salisu et al., 2022). Degradation behaviour was evaluated using a theoretical first-order decay model commonly applied to latent-heat storage materials as presented in Equation 33 (Incropera et al., 2007).

$$P(N) = P_0 e^{-kN} \quad (33)$$

Where:

- $P(N)$ = thermophysical property after N cycles
- P_0 = initial value
- k = degradation constant
- N = number of thermal cycles

Exponential decay models are commonly used in heat transfer and reliability analysis to describe cumulative property degradation (Incropera et al., 2007). System feasibility was evaluated based on stability under repeated thermal cycling, a key criterion for PCM use in thermal energy storage (Farid et al., 2004). Therefore, conservative thresholds were set, with performance deemed acceptable if property degradation remains below 10% over 1 year of daily cycles (365 cycles). The decay equation solution suggests an upper-bound degradation constant of about:

$$k \leq 3 \times 10^{-4} \text{ per cycle}$$

Based on this value, the predicted cycle number at 20% degradation is approximately 770 cycles, equivalent to roughly 2.1 years. Given that operating temperatures remain near the melting point yet below the thermal decomposition thresholds, it is probable that the actual degradation constant is considerably lower. Furthermore, encapsulation techniques can be employed to mitigate degradation by effectively preventing exposure to oxygen and moisture (Salisu et al., 2022).

Overall, although shea butter is bio-derived and exhibits a low environmental impact, its inherent natural variability may introduce uncertainties in thermal performance and long-term consistency. To ensure stable operation in PVT/PCM applications, it is essential to implement mitigation strategies, including enhanced extraction controls, compositional analyses (including DSC and fatty-acid profiling), and techniques such as blending or fractionation.

2.2.10 The differential scanning calorimetry (DSC) of shea butter

DSC is a thermal analysis technique used to measure the heat flow difference in a specimen to a reference as a function of temperature/time, subjecting both the specimen and reference to the same controlled temperature in a specified atmosphere using the same measurement system (Islam et al., 2022). The shea butter is mainly composed of triacylglycerols (TAG) and diacylglycerols (DAG) with 77.7%–92.4% and 7.6%–22.6%, respectively (Goumbri et al., 2024).

Figure 3 displays the DSC thermogram of shea butter. The graph reveals two main dips: one indicating a solid-solid phase transition and the other representing melting. The solid-solid transition occurs between about 28 °C and 31 °C, while the melting, or “mushy zone,” starts dipping around 32.5 °C, peaks at 37.5 °C, and concludes by 40 °C. A summary of the thermophysical properties of shea butter is presented in Table 4.

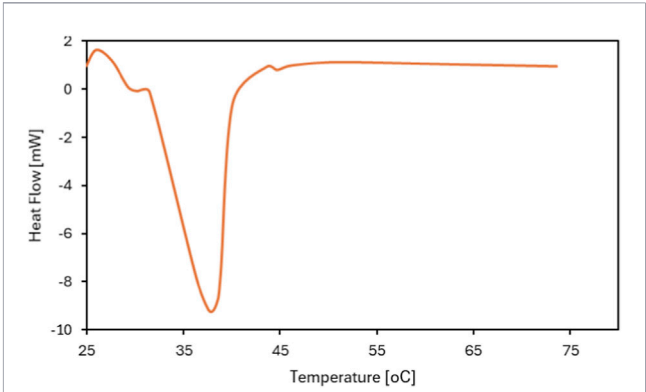


FIGURE 3 Differential scanning calorimetry (DSC) thermogram of shea butter showing the heat flow and phase change process in shea butter. (Salisu et al., 2022) [Reprinted with permission].

TABLE 4 Thermophysical properties of shea butter (Ahmad et al., 2021b) and paraffin wax (Yousef et al., 2022).

Thermal properties	Shea butter	Paraffin wax
Melting point	32 °C	42 °C
Latent heat	50.36 kJ/kg	165 kJ/kg
Density	910 kg/m3	880 kg/m3
Specific heat capacity (solid)	3.19 kJ/kg °C	2.0 kJ/kg °C
Specific heat capacity (liquid)	3.32 kJ/kg °C	2.0 kJ/kg °C
Thermal conductivity	0.26 W/m. K	0.2 W/m. K
PCM thickness	0.03 m	0.03 m

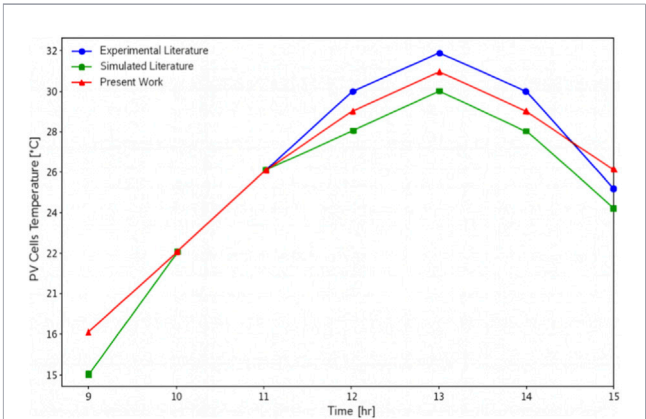
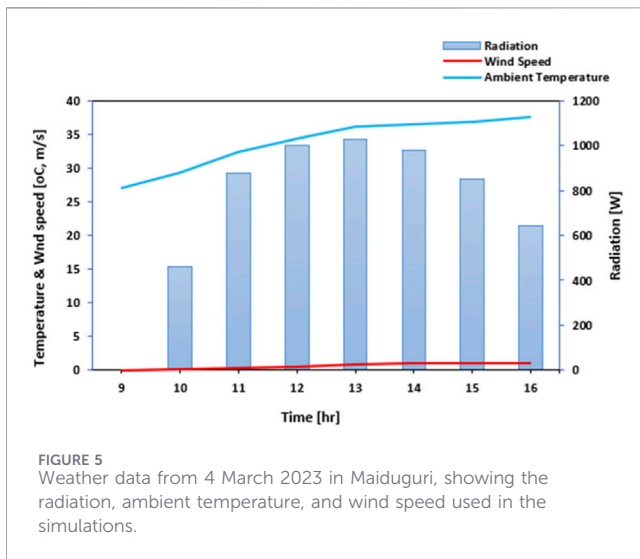


FIGURE 4 Comparison of PV cell temperatures in the present work with those reported in the literature, showing the temperatures after applying the cooling mechanism.



3 Results and discussions

3.1 Validation of the model

This study was validated with experimental and simulation results in the literature. The details of the experimental parameters, including PCM thermo-physical properties and PV optical properties, can be obtained from (Li et al., 2023).

Figure 4 compares the PV cell temperature between the experimental and simulation results reported in literature and in the present work.

The Root Mean Square Error (RMSE) between the present work and the experimental literature and simulation datasets, respectively, was calculated using Equation 34.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2} \quad (34)$$

Where P_i is the present value and O_i is the literature value.

Therefore, the RMSE between the present work and the experimental and simulation literature is 1.069 °C and 1.254 °C, respectively. A lower RMSE (<2 °C) indicates strong agreement between the present and literature datasets. The lower RMSE of 1.069 °C suggests that the present work aligns more closely with experimental literature than with simulation literature. In practice, deviations of approximately 1 °C are typically acceptable and may result from environmental or sensor variability.

The Mean Absolute Error (MAE) was also calculated using Equation 35 and measures the average absolute difference between predicted values and actual observations.

$$MAE = \frac{1}{n} \sum_{i=1}^n |P_i - O_i| \quad (35)$$

Therefore, the MAE is 0.86 °C and 1.00 °C against experimental and simulation literature, respectively, signifying the present work's deviation from experimental data by < 1 °C on average, and slightly more from the simulation data.

In conclusion, RMSE and MAE on experimental data were lower, indicating that the present work more closely matches

real-world measurements than simulations. This validation constitutes experimental evidence for the model presented in this work, given the absence of real-world measurements.

The present simulations used weather data from the month with the highest solar radiation in the region. TRNSYS software facilitated the modelling for the period from 9:00 a.m. to 4:00 p.m. on 4 March 2023. The weather data applied in the simulation is shown in Figure 5. The PV-T/PCM model components in TRNSYS were connected via FORTRAN code that simulates the physical behaviour of the model, including energy transfer and phase change processes described by Equations 1–32. Convective and radiative heat transfer occurred between the glass top and the environment, whereas heat transfer between the insulation layer and the environment was neglected because of negligible temperature differences. The inlet temperature was set at 20 °C. Incident solar irradiance on the PV cell was partially converted into electricity; the remainder was converted into heat, which was transferred to the PCM and then to the working fluid in the pipes. Throughout the simulation, the PCM energy (phase change), PV cell temperature, and outlet fluid temperature were monitored.

3.2 Comparison of paraffin wax and shea butter application as PCM in PV-T systems

Figure 5 shows the changes in solar radiation, ambient temperature, and wind speed on a typical day, 4 March 2023, in Maiduguri. The simulation shows a maximum solar radiation of 1,024.48 W/m² at 13:00, with the ambient temperature rising to 37.45 °C at 16:00. Wind speed gradually increased throughout the day, peaking at 1.10 m/s.

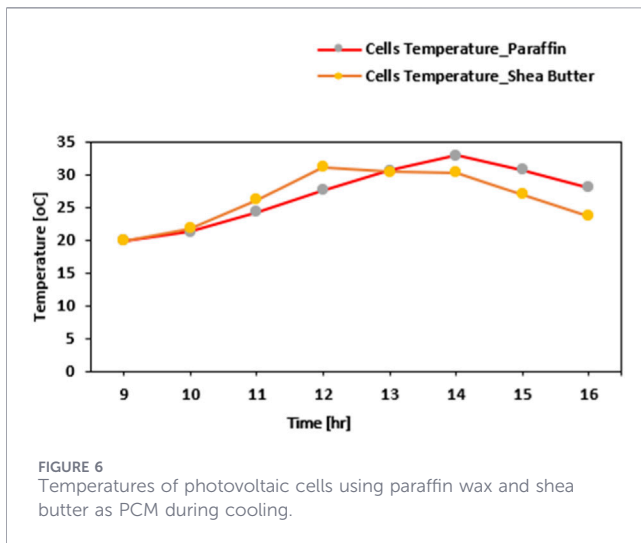
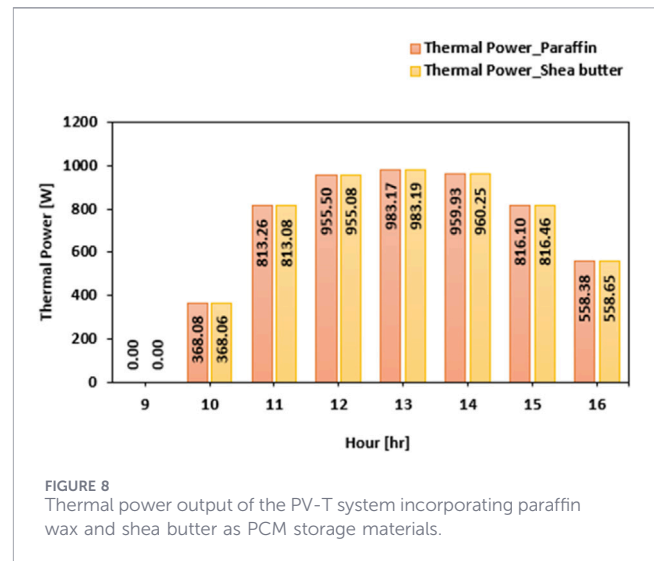
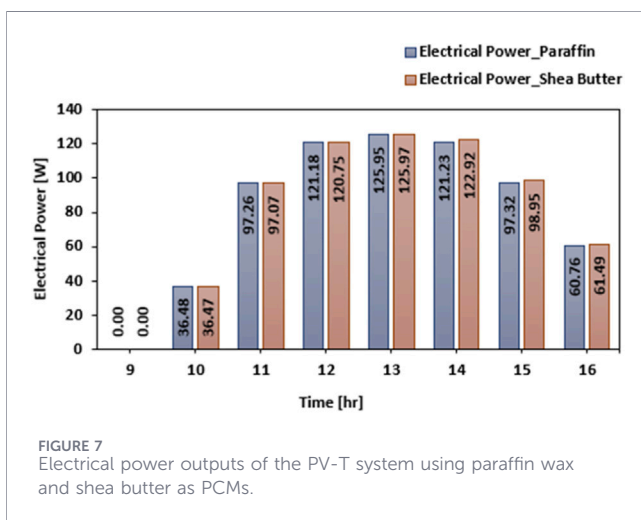
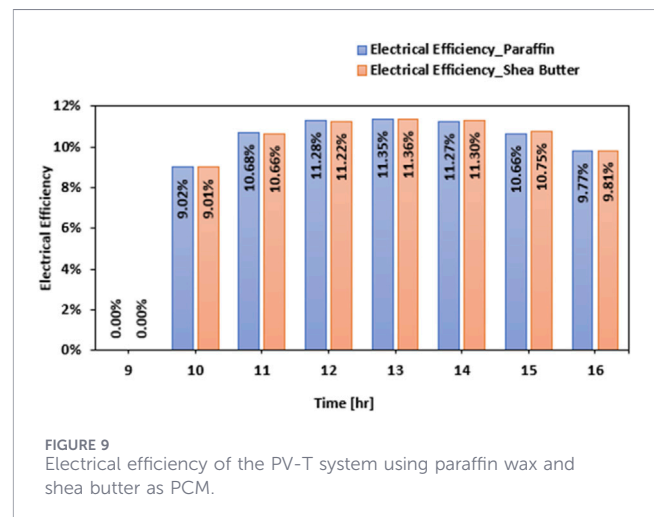
The study compared the effects of using paraffin wax and shea butter for photovoltaic cooling, focusing on PV cell temperature, electrical and thermal power outputs, and electrical and thermal efficiency.

3.2.1 photovoltaic cells temperature

The PV cells cooled by paraffin wax and shea butter reach their peak temperatures of 32.96 °C at 14:00 °C and 31.21 °C at noon, respectively. Their different melting points and latent heats play a vital role in their variations in cooling times. Shea butter melts at 32 °C with a latent heat of 50.34 J/g and cools faster than paraffin wax, which melts at 42 °C with a latent heat of 165 J/g. These differences in phase-change timing triggered the pump at different times; it was activated at noon, when shea butter was nearly fully charged, whereas paraffin wax was still charging. Shea butter kept the PV panel cooler, maintaining a temperature difference of 1.75 °C compared to paraffin wax (Figure 6). The lower latent heat and melting temperature of shea butter are advantageous during phase change, particularly at lower temperatures, thereby reducing the PV cell temperature more effectively than paraffin wax.

3.2.2 Electrical power

Both shea butter and paraffin wax achieved maximum electrical power output at 13:00, coinciding with peak solar radiation, with shea butter exceeding paraffin wax slightly. During the peak hours of



12:00–14:00, the difference in power output between shea butter and paraffin wax was 1.23 W. Although this 1.28 W difference is relatively small considering the system's size. This is because shea butter significantly enhances the pumping system during peak sunlight, thereby cooling the PV cells more effectively than paraffin wax at that time, as shown in Figure 7.

3.2.3 Thermal power

Paraffin wax's thermal outputs marginally exceeded those of shea butter, as shown in Figure 8. Its higher latent heat of 165 kJ/kg conferred an advantage in thermal storage compared with shea butter, which has a latent heat of 50.36 kJ/kg. However, from 13:00, shea butter begins to dissipate heat, exhibiting slightly higher thermal power due to pump activation, whereas paraffin wax remained in the charging mode. The thermal power difference during peak solar radiation hours (12:00–14:00) was only 0.08 W, favouring paraffin wax, a difference negligible in practical terms.

3.2.4 Electrical efficiency

The electrical efficiency of paraffin and shea butter PCMs correlates with the PV cell temperature gradient for both types. Efficiency peaked at 13:00, coinciding with the highest solar radiation. The system performs optimally during this peak, provided that the PV cell temperatures remain within the recommended range. The efficiency difference between the two PCMs was only 0.03% under peak sunlight conditions. However, shea butter shows a slight performance edge during peak hours when the pump is active, as shown in Figure 9.

3.2.5 Thermal efficiency

From noon until the end of the simulation, paraffin wax exhibits slightly lower thermal efficiency than shea butter. The rapid heating of shea butter, owing to its lower melting point and

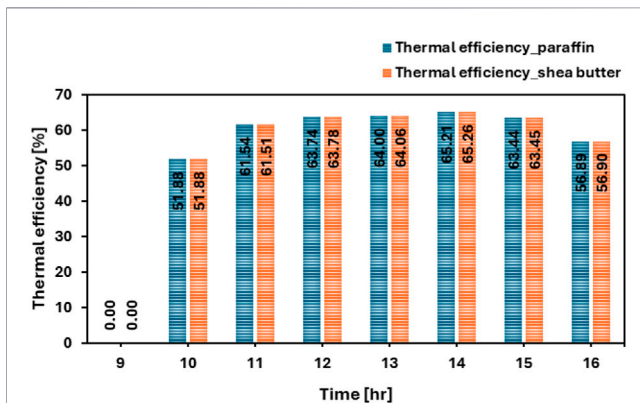


FIGURE 10
Thermal efficiency of the PV-T system using paraffin wax and shea butter as PCM storage media.

latent heat, triggers the pump to circulate the heat-transfer fluid (HTF). Thermal efficiency is determined by the heat absorbed and released by the HTF. As shown in Figure 10, shea butter outperforms paraffin wax in thermal efficiency by 0.03% during peak solar radiation.

In conclusion, shea butter's low latent heat limits its storage capacity, thereby accelerating pump activation during peak sunlight to cool the PV cells, compared with traditional wax (paraffin). This resulted in a 1.75 °C reduction in PV cell temperature relative to paraffin wax during peak hours, although the performance differences were minimal. Variations in power output and efficiency are proportional to the temperature gradient across the PV cell. For larger systems, these minor differences can significantly affect system performance or economic outcomes.

3.3 Comparison of the new hybrid PV-T/PCM system integrated with shea butter and a traditional PV panel

The hybrid photovoltaic-thermal (PV-T) system integrated with a phase change material (PCM) aims to tackle the rising temperature gradient in traditional PV cells. Unlike conventional PV panels, which generate only electrical energy, the PV-T/PCM system delivers both electrical and thermal energy. Simulations were performed to evaluate and compare the temperature, electrical power output, and efficiency of the PV-T/PCM system with conventional PV systems.

3.3.1 The temperature of the PV cells in the PV-T/PCM an PV system

The traditional PV panel's cell temperature reaches a maximum of approximately 71.09 °C at 1:00 p.m., whereas the PVT/PCM system's cell temperature peaks at 31.21 °C at noon. Both start at 20 °C at 9 a.m. and gradually increase with solar radiation, peaking around midday (12 PM–2 PM) before decreasing later. The uncooled PV panel consistently shows higher cell temperatures than the cooled PV-T/PCM system, as shown in Figure 11.

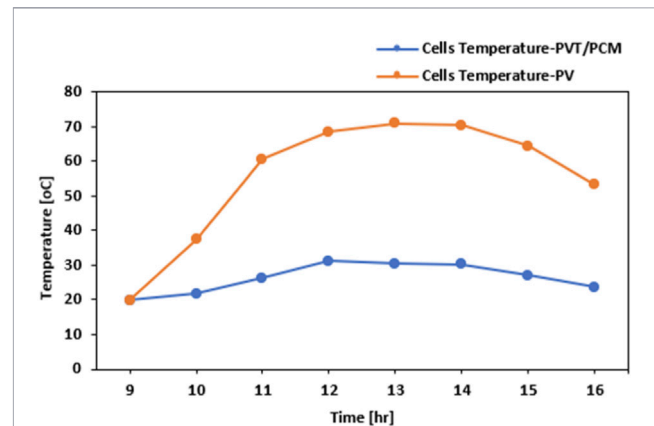


FIGURE 11
Comparing the temperature of the PV cells in the hybrid PV-T/PCM system and the uncooled PV panel.

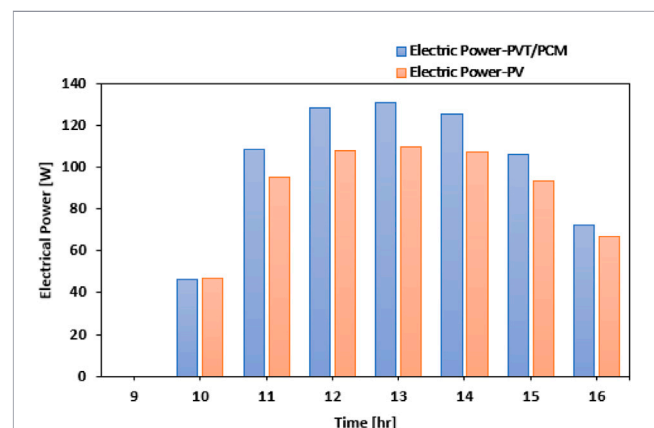


FIGURE 12
Electrical power output of the PV-T/PCM and PV systems.

Significantly, the hybrid system lowers PV cell temperatures by nearly 39.88 °C during peak hours compared to the traditional PV system. This reduction in temperature boosts both power output and the system's lifespan.

3.3.2 Electrical power output of the PVT/PCM system and PV panel

The hybrid PVT/PCM system consistently produces more electrical power than the traditional PV panel from 10:00 a.m. to 4:00 p.m. Its power peaks from 12:00 to 2:00 p.m., reaching a maximum of 130.53 W at 13:00, while the PV system peaks at 109.78 W at the same time. Both systems' power increases from 10:00 a.m., peaks midday, and then decreases towards 4:00 p.m., as shown in Figure 12. Higher midday values are due to increased solar radiation, and the PVT/PCM system consistently outperforms the PV system during this period. The cooled PVT/PCM system achieves a 17.27% improvement in power output during peak sunlight hours compared with the uncooled PV system.

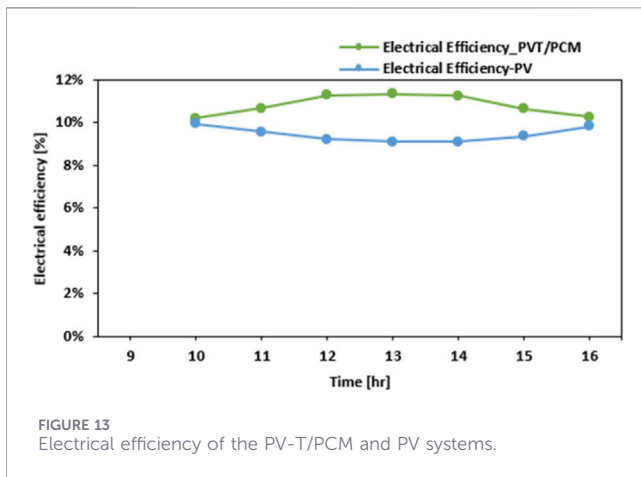


FIGURE 13
Electrical efficiency of the PV-T/PCM and PV systems.

3.3.3 Electrical efficiency of the PV-T/PCM and PV systems

The electrical efficiency of the hybrid PV-T/PCM system started at 10.22% and peaked at 11.35% around 1:00 p.m. Meanwhile, the traditional PV system's efficiency remained lower, ranging from 9.96% to 9.10% during peak sunlight hours. The cooled PV-T/PCM system consistently outperformed the uncooled PV system by an electrical efficiency improvement of 22% at peak times. This efficiency gap remains stable throughout the observed period. Figure 13 displays the electrical efficiencies of both the PV-T/PCM and PV systems.

In summary, the hybrid PV-T/PCM system outperforms traditional PV systems by lowering cell temperature by 39.88 °C, increasing electrical power output by 17.27%, and improving efficiency by 22%. These benefits are particularly apparent around midday when solar exposure is maximised. The findings indicate that integrating a PCM cooling mechanism into photovoltaic systems can substantially improve their performance, particularly under high solar irradiance, thereby increasing efficiency and effectiveness in high-insolation areas.

3.4 Parametric sensitivity analysis of the PV-T/PCM system

Adjusting parameters such as flow rate and PCM thickness can enhance the performance of the PV-T/PCM system. The system's sensitivity was examined using variables including cell and outlet water temperatures, electrical and thermal power outputs, and overall efficiency.

3.4.1 Effects of flow rate on the performance of the PV-T/PCM system

The study selected a flow-rate range of 0.5–3.5 LPM to assess its impact on the PVT/PCM system's performance. The analysis was conducted under the following conditions.

3.4.1.1 Cell and outlet water temperature

As the flow rate increases from 0.5 LPM to 1.5 LPM, both outlet and cell temperatures decrease. Beyond 1.5 LPM, temperatures

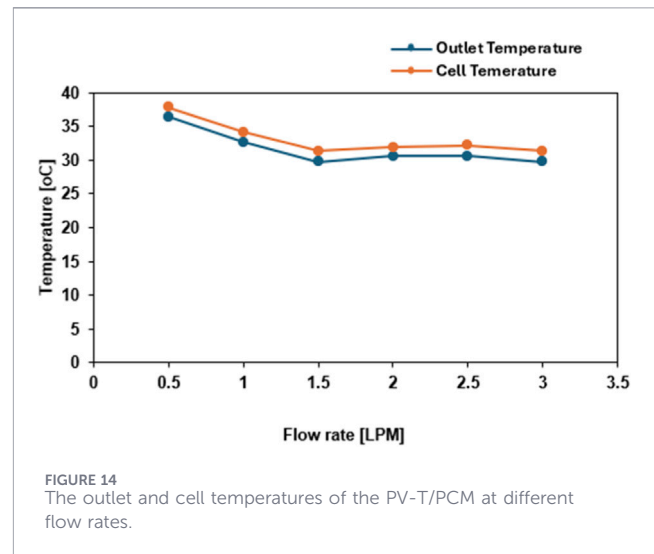


FIGURE 14
The outlet and cell temperatures of the PV-T/PCM at different flow rates.

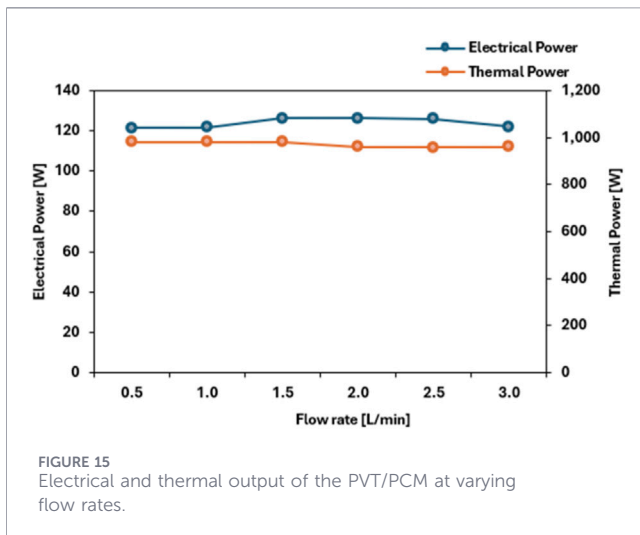
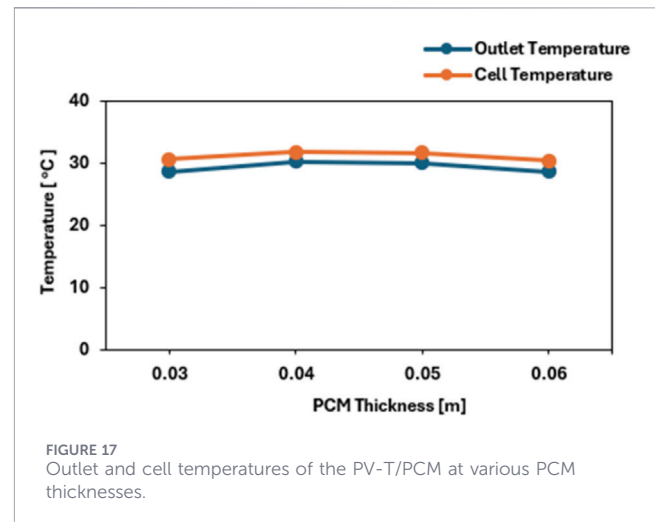
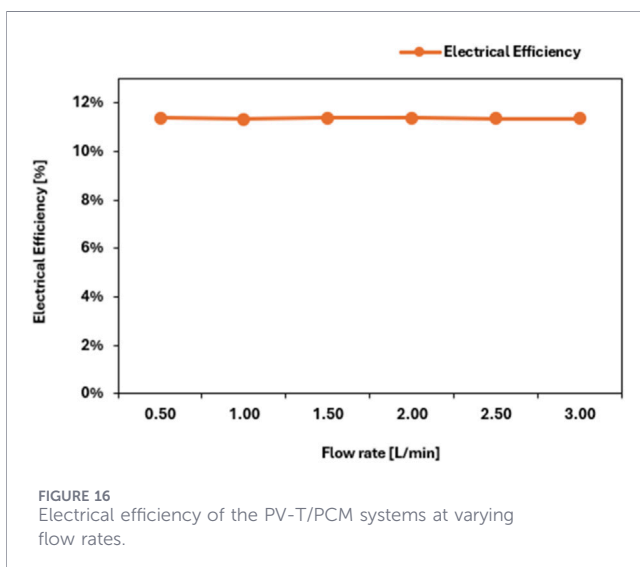
stabilise slightly but continue a minor downward trend. The outlet temperature consistently remains lower than the PV cell temperature across all flow rates. Raising the flow rate improves the phase transition of PCM by enhancing heat transfer between the water and PCM. Moreover, higher flow rates increase heat conduction in the fluid, resulting in an 18.84% reduction in the PV cell and outlet temperatures. At low flow rates, increased thermal resistance reduces convective heat transfer, making PCM properties dominant. Higher flow rates decrease thermal resistance, thereby enhancing convective cooling and reducing the PCM's influence. Temperatures stabilise between 1.5 and 3 LPM, with slight decreases in both outlet and cell temperatures, indicating an optimal flow rate of approximately 2 LPM, as shown by Hossain et al. (2019) and Surya et al. (2024). Figure 14 illustrates the outlet water and cell temperatures of PV-T/PCM under various flow conditions.

3.4.1.2 Electrical and thermal energy

Electrical power increases from 121.48 to 126.21 W, as the flow rate rises from 0.5 to 2.5 LPM, peaking at 2.0 LPM before stabilising at 2.5 LPM. Similarly, thermal power increases slightly from 982.69 to 983.12 W, as the flow rate increases from 0.5 to 1.5 LPM, then remains approximately constant at 960.68 W up to 3.0 LPM. Both electrical and thermal powers exhibit stable patterns for a modest increase from 0.5 to 2.5 LPM, as shown in Figure 15. Higher flow rates facilitate greater heat removal, consistent with the increase in power. For thermal power, increasing the flow rate briefly boosts power output, then causes a slight decline. The steady electrical and thermal power levels between 1.5 and 2.5 LPM indicate the system's optimal flow rates of 2 LPM for electrical power and 1.5 LPM for thermal power, supported by Surya et al. (2024) and (Hossain et al., 2023).

3.4.1.3 Electrical efficiency

Electrical efficiency remains consistent across flow rates from 0.5 to 3.0 LPM, with minimal fluctuations, indicating that flow-rate variations have a limited impact on efficiency within this range. The electrical efficiency of PV-T/PCM slightly rises with increasing water flow rate, from 11.39% to a peak of 11.40% at



2 LPM. After reaching this optimal point, the efficiency plateaus, as shown in Figure 16.

In summary, as the flow rate increases from 0.5 to 1.5 LPM, both the outlet and cell temperatures decrease by 20% and 18.84%, respectively, with slight stabilisation beyond 1.5 LPM. The outlet temperature consistently remains lower than the cell temperature due to enhanced heat transfer across the water-PCM interface, resulting in more effective cooling of the PV cells. Electrical power peaks at 2.0 LPM and then declines slightly. Meanwhile, thermal power rises slightly to 1.5 LPM before stabilising. Both electrical and thermal power levels are off by approximately 1.5–2.5 LPM, indicating that this range is the optimal flow rate for the system. Electrical efficiency remains mostly unchanged, with a small peak at 2 LPM, suggesting that variations in flow rate have minimal impact on efficiency within this range. Therefore, 2 LPM is the optimal flow rate for electrical power and efficiency under these conditions. These results are consistent with those of (Fayaz et al., 2019; Hossain et al., 2019; Surya et al., 2024; Rao et al., 2022; Alsaqoor et al., 2023).

3.4.2 Effect of shea butter (PCM) thickness on the performance of the PV-T/PCM system

A PCM thickness range of 0.03–0.06 m was used to evaluate the sensitivity of the PV-T/PCM system's performance. The system analysis was performed under the following conditions.

3.4.2.1 Cell and outlet temperature

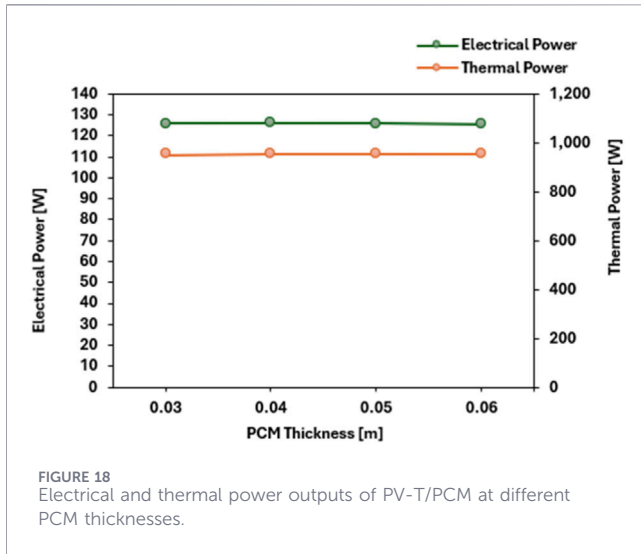
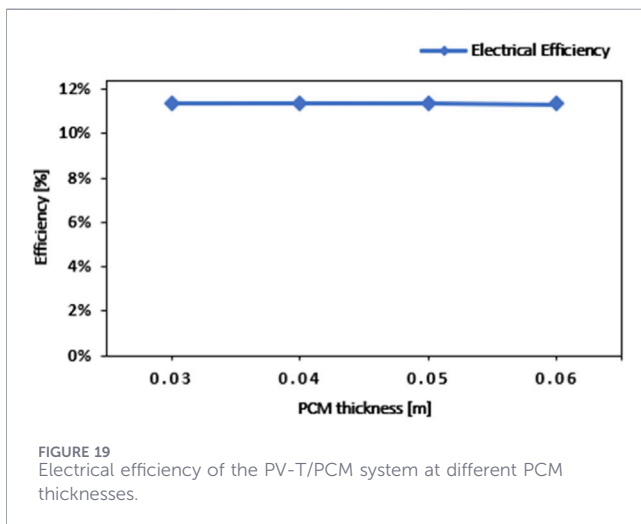
The outlet and cell temperatures exhibit similar trends across different PCM thicknesses. Both rise by 9.93% for PV cells and 5.89% for outlet temperatures as the thickness increases from 0.03 to 0.04 m. After reaching a peak at 0.04 m, these temperatures decline and stabilise. The cell temperature remains consistently higher than the outlet temperature for all PCM thicknesses. Increasing PCM thickness improves heat transfer across the PCM-PV cell interface, but the heat-transfer coefficient to the working fluid decreases because the heat must travel a greater distance. While greater PCM thickness reduces thermal resistance and boosts energy storage, this benefit only holds up to an optimal point. Beyond that point, however, heat transfer efficiency and system performance decline. Figure 17 shows the outlet and cell temperatures as a function of shea butter thickness.

3.4.2.2 Electrical and thermal power outputs

Electrical and thermal power remain relatively constant as PCM thickness increases from 0.03 to 0.06 m. Electrical power increases slightly from 125.97 to 126.37 W, and thermal power rises slightly from 955.06 to 955.55 W. The parallel lines indicate proportional changes in power output as PCM thickness varies. Therefore, increasing the PCM thickness has little effect on power, as both electrical and thermal powers remain nearly constant over this range. Figure 18 shows the electrical and thermal power outputs at different PCM thicknesses.

3.4.2.3 Electrical efficiency

Electrical efficiency remains stable, with a small rise from 11.36% to 11.41% between 0.03 and 0.04 m. Changes in PCM thickness within this range have little effect on efficiency. The PCM layer's thickness is linked to its thermal capacity, whereas the heat-transfer coefficient between the working fluid and the PCM



layer remains low. Figure 19 shows electrical efficiency as a function of PCM thickness.

In summary, increasing the shea butter (PCM) layer enhances its thermal capacity, enabling it to store more heat. However, thicker layers can reduce heat transfer between the working fluid and the PCM, increasing the thermal resistance and hindering heat flow. This is a critical factor in the design of PCM-based thermal systems. Striking a balance between thermal capacity and efficient heat transfer is essential for optimal performance. Consequently, a 0.04 m shea butter (PCM) layer provides the highest electrical power and efficiency, making it the best choice. This aligns with Su et al. (Su et al., 2017), who recommend PCM thicknesses of 0.03 and 0.036 m.

3.5 The combined electrical and thermal efficiency, and overall exergy efficiency of the system

Based on the peak performance results from Sections 3.2, 3.3, the overall energy and exergy efficiencies of the hybrid PV-T/

PCM system (utilising shea butter) and the standard photovoltaic system were evaluated under maximum-solar-radiation conditions ($1,024.48 \text{ W/m}^2$ at 13:00 h). With a collector area of 1.8 m^2 , the total incident solar energy amounted to 1844.06 W . During peak conditions, the PV-T/PCM system attained an electrical output of 130.53 W , corresponding to an electrical efficiency of 11.35% , while the conventional photovoltaic system produced 109.78 W with an efficiency of 9.10% . The combined energy and exergy efficiencies of the PV-T/PCM and PV systems is presented in Figure 20.

The combined energy efficiency of the PV-T/PCM system was determined as follows through Equation 36 (Hossain et al., 2019).

$$\eta_{\text{total}} = \frac{P_{\text{elec}} + Q_{\text{thermal}}}{GA} \quad (36)$$

Utilising a peak thermal output of approximately 982.69 W (Section 3.4.1), the aggregate useful energy gain amounted to $1,113.22 \text{ W}$, culminating in a combined electrical-thermal efficiency of 60.4% . Conversely, the traditional photovoltaic (PV) system, which generates electricity only, achieved a total efficiency of 9.10% . This significant increase exemplifies the efficacy of thermal energy recovery in hybrid PV-T systems, consistent with prior PV-T research (Hossain et al., 2019; Hosseinzadeh et al., 2018).

In exergy analysis, electrical power was treated as pure exergy, whereas thermal exergy was calculated using the standard availability relation, incorporating the Petela model for solar exergy and the classical thermal exergy formulation in Equation 37 (Hossain et al., 2019; Kazemian et al., 2018):

$$Ex_{\text{thermal}} = Q_{\text{thermal}} \left(1 - \frac{T_a}{T_{\text{out}}} \right) \quad (37)$$

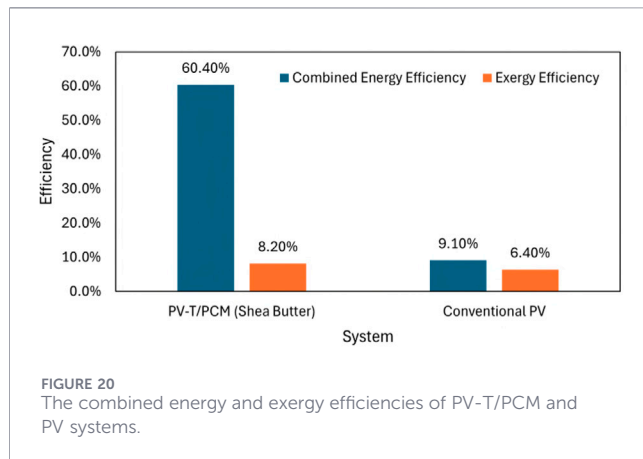
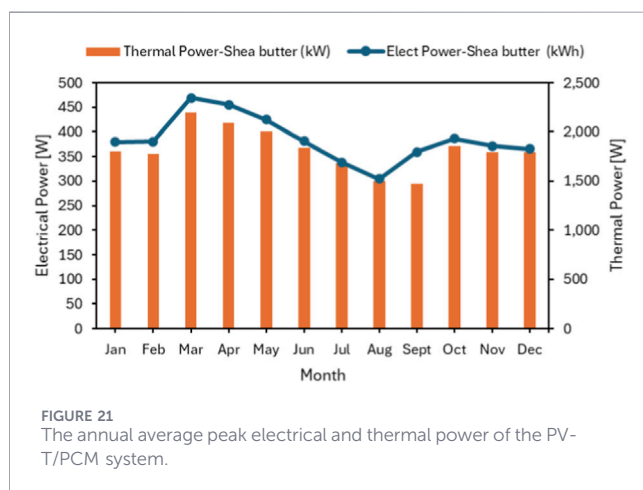
From Sections 3.2, 3.4.1, with an ambient temperature of 310 K and an outlet temperature around 313 K during peak operation, the thermal exergy contribution was about 9.43 W . The total useful exergy output of the PV-T/PCM system reached 139.96 W . The solar exergy input was estimated at 0.93 GA using Petela's formulation (Kazemian et al., 2018), which equals 1714.97 W . As a result, the overall exergy efficiency of the PV-T/PCM system was calculated as 8.2% .

Regarding the traditional photovoltaic (PV) system, as electrical energy constitutes pure exergy, the exergy efficiency was determined as follows by Equation 38 (Hossain et al., 2019):

$$\eta_{\text{ex,PV}} = \frac{P_{\text{elec}}}{Ex_{\text{solar}}} \quad (38)$$

yielding 6.4% .

These results indicate that, while the hybrid PV-T/PCM system significantly enhances overall energy efficiency from 9.10% to 60.4% , the increase in exergy efficiency remains relatively modest, progressing from 6.4% to 8.2% . This outcome is anticipated, given that low-temperature thermal energy has limited capacity for work potential, despite its substantial contribution to overall energy utilisation. Similar findings have been documented in previous studies on PV-T/PCM exergy performance (Hossain et al., 2019; Maatallah et al., 2019).



3.6 Sensitivity analysis of diurnal temperature fluctuations, humidity, and seasonal solar radiation on the PV-T/PCM system

Figure 21 illustrates the monthly variations in the electrical and thermal outputs of the PV-T/PCM system, which employs shea butter as the phase-change material. The electrical output typically ranges from approximately 300–470 W, whereas the thermal output fluctuates between 1.45 and 2.2 kW throughout the year. These variations are attributable to seasonal changes in solar irradiance, fluctuations in ambient temperature, and atmospheric conditions.

3.6.1 Sensitivity to seasonal solar irradiance

Seasonal variations in solar irradiance constitute the primary factor affecting both electrical and thermal outputs. As illustrated in Figure 1, March shows peak electrical and thermal powers of 469.14 W and 2.19 kW, respectively. Conversely, August shows the lowest output, with electrical power at 304.24 W and thermal power at 1.49 kW.

Electrical and thermal outputs exhibit annual fluctuations of approximately 32%–35%, indicating a high sensitivity to variations in solar irradiance. The optimal performance is generally observed

during the dry months of March and April, when solar radiation is at its peak, whereas the lowest output is typically recorded during the rainy months of July and August due to cloud cover and reduced solar flux.

3.6.2 Sensitivity to daily temperature fluctuations

Sub-Saharan climates experience daily temperature fluctuations of 15 °C–20 °C. These variations influence the operating temperature of photovoltaic (PV) cells, the melting and solidification cycle of phase change materials (PCM), and heat transfer between the absorber and PCM.

Higher daytime temperatures increase PV cell temperature, which typically reduces electrical efficiency according to the PV temperature coefficient and is presented in Equation 39 (Awai et al., 2024):

$$\eta_e = \eta_{ref} [1 - \beta(T_c - T_{ref})] \quad (39)$$

Where

$$\beta \approx 0.0045 \text{ K}^{-1}$$

If the cell temperature rises by 10 °C, electrical efficiency decreases by approximately:

$$\Delta\eta = 0.0045 \times 10 = 4.5\%$$

The PCM layer mitigates this effect by absorbing surplus heat during peak periods. This study shows that the PV-T/PCM system maintains the cell temperature approximately 39.88 °C lower than that of conventional solar panels, thereby aiding in stabilising electrical output under hot conditions. Consequently, daily temperature fluctuations primarily influence the charging and discharging cycles of the PCM, rather than inducing significant declines in overall system power.

3.6.3 Sensitivity to humidity and cloud cover

Relative humidity exhibits a significant correlation with cloud formation throughout the wet season. As illustrated in Figure 21, the minimum system output is observed in August, aligning with the period of peak humidity and cloud cover within the region. This decline is primarily attributable to solar attenuation due to atmospheric moisture and cloud cover, rather than to temperature effects. Additionally, humidity modestly diminishes radiative cooling by elevating the effective sky temperature; however, this effect remains relatively minor compared to variations in irradiance.

In conclusion, variability in solar irradiance is the primary factor affecting system performance, resulting in approximately a 33.5% seasonal variation in power output. Diurnal temperature fluctuations influence phase change material (PCM) charge-discharge cycles; however, these effects are alleviated by latent heat storage. Elevated humidity levels and cloud cover diminish solar radiation, consequently reducing output during the rainy season months. Despite these climatic fluctuations, the photovoltaic-thermal (PV-T)/PCM system demonstrates considerable stability, thereby affirming its suitability for regions characterised by significant seasonal variations.

4 Resource availability and scalability of shea butter PCM

Shea butter is extracted from the nuts of the *Vitellaria paradoxa* tree, which occurs naturally throughout the West African “shea belt,” a region spanning more than twenty countries. West Africa is responsible for most of the global production, with approximately 800,000 tonnes of shea kernels collected annually, thereby supporting extensive food and cosmetic industries and sustaining the livelihoods of millions of rural households (Global Shea Alliance, 2023; FAO, 2023). Nigeria alone accounts for approximately 35%–40% of the world’s shea nut production, thereby establishing itself as one of the leading producers within the region (UNDP SDG Investor Platform, 2024; Naangmenyele, 2023).

Based on the collector configuration employed in this investigation, a standard PV-T/PCM module with a collector surface area of 1.8 m² and a PCM thickness of 0.04 m necessitates approximately 60–70 kg of shea butter per unit. For small-scale household PV-T systems or rural microgrid initiatives, the required PCM quantities are comparatively modest. For example, a community installation supporting 100 households would require approximately 6–7 tonnes of PCM, which constitutes a negligible portion of the region’s annual shea production. Consequently, the deployment of decentralised PV-T systems is unlikely to influence existing food or cosmetic markets (Naangmenyele, 2023; CBI, 2026).

However, large utility-scale PV-T systems may require significantly more PCM. A solar installation with several thousand PV-T collectors could need hundreds of tonnes, while a large solar farm might require tens of thousands of tonnes. Such demand could impact existing shea butter markets, which are primarily driven by the food and cosmetic industries (Turreira-García, 2025; Global Shea Alliance, 2023). To prevent market disruptions, large energy projects should prioritise sustainable harvesting, expand shea agroforestry, and enhance processing efficiency, ensuring PCM use does not compete with traditional markets.

5 Conclusion

A photovoltaic-thermal (PV-T) system incorporating a phase change material (PCM) was modelled in TRNSYS, with shea butter as the PCM. Its performance was compared to that of traditional paraffin wax, and the sensitivity of different system design parameters was analysed. The key findings are:

- The PV-T system, combined with shea butter, successfully cooled PV cells by 1.75 °C during peak sunlight, compared to paraffin wax. During the simulation’s sunniest hours, shea butter produced 1.28 W more power than paraffin wax. Although paraffin’s high latent heat gave it superior thermal performance, shea butter yielded a slight 0.03% advantage in electrical and thermal efficiency.
- The hybrid PV-T/PCM system maintains lower PV cell temperatures than conventional PV systems, particularly between 12 noon and 2 p.m. by 39.88 °C. At peak times, the

system generated 130.53 W of electrical power with an efficiency of 11.35%, compared to 109.78 W and 9.10% for traditional PV.

- Increasing the water flow rate from 0.5 to 1.5 LPM lowers PV cell and outlet temperatures by 18.84% and 20%. The electrical power increases from 121.48 to 126.21 W, peaking at approximately 2.0 LPM. Thermal power and electrical efficiency stay steady between 1.5 and 2.5 LPM. Consequently, 2.0 LPM was determined to be the optimal flow rate for maximising both electrical power output and efficiency.
- A thicker layer of shea butter increases thermal capacity but reduces heat-transfer efficiency because of increased thermal resistance. Research shows that the highest electrical power and efficiency occur at a thickness of 0.04 m. Beyond this point, increasing PCM thickness stalls both electrical and thermal power, and electrical efficiency remains relatively constant across PCM thicknesses.
- According to Carbon Cloud data, shea butter, a bio-based phase change material (PCM), offers considerable environmental and sustainability advantages over paraffin wax. Its carbon footprint is recorded at 2.20 kg CO₂ per kilogram, compared with 3.75 kg CO₂ per kilogram for paraffin wax. Moreover, shea butter contributes to achieving Sustainable Development Goals (SDGs) 13 and 5. Economically, the payback period for the PV-T/PCM system is approximately half that of the PV system when installed in regions with high solar radiation, such as sub-Saharan Africa, assuming the thermal output is effectively utilised, as documented in the literature.
- Although this study concentrates on shea butter as a bio-based phase change material (PCM), the proposed PV-T/PCM system configuration is not restricted to a single material. The modelling framework developed herein can be adapted to a broad spectrum of bio-based PCMs possessing appropriate thermophysical properties. A paramount design criterion for PCM integration in photovoltaic-thermal systems is that the phase-transition temperature matches the optimal operating temperature range for photovoltaic cells, typically between 30°C and 45 °C. Shea butter was selected for this study due to its melting temperature (approximately 32 °C), which resides within this optimal temperature range.
- Additionally, its latent heat storage capacity enables it to effectively absorb excess thermal energy from the photovoltaic (PV) module. Nevertheless, numerous other bio-based phase change materials (PCMs) possess comparable properties and may also be considered for integration into the photovoltaic-thermal (PV-T) system architecture. Among these materials, fatty acids obtained from vegetable oils are particularly advantageous owing to their high latent heat capacity, relatively stable thermal cycling behaviour, and renewable sources. Moreover, numerous such materials can be locally procured in tropical and subtropical regions, thereby potentially decreasing transportation emissions and enhancing the sustainability of the supply chain.

This study extends beyond a simple laboratory experiment, especially in regions with abundant solar radiation, such as sub-Saharan Africa. Many rural regions in sub-Saharan Africa lack reliable electricity, underscoring the importance of this research

for off-grid rural electrification and cooling solutions. In the context of sustainable development and the circular economy, shea butter, a byproduct of agroforestry in West Africa, can be utilised in PV-T systems to enhance the value of local agricultural supply chains. The bio-based energy storage derived from shea butter supports multiple SDGs, including affordable energy, climate action, and responsible consumption.

6 Limitations of the study

Although the current study demonstrates promising thermal regulation performance by employing shea butter as a bio-based phase change material (PCM) within the PV-T system, it is imperative to recognise practical limitations related to the material's long-term stability. The existing numerical model presumes homogeneous and consistent thermophysical properties of the PCM throughout the operational period. Nonetheless, in actual installations, bulk organic PCMs are susceptible to degradation phenomena during multiple melting–solidification cycles.

An important limitation pertains to the potential leakage of PCM during the phase transition. When the PCM melts, volumetric expansion and increased fluid mobility may lead to leakage in the absence of perfectly sealed containment structures. Such leakage can diminish effective PCM mass and consequently reduce the system's latent heat storage capacity. Similar challenges have been documented in PV-T/PCM systems that utilise paraffin and other organic PCMs, where issues of leakage and containment reliability are critical to the design process (Hosseinzadeh et al., 2018; Hossain et al., 2019).

A second challenge involves oil separation and phase segregation. Organic PCMs like shea butter consist of triglyceride mixtures with varying melting points. Repeated thermal cycling can cause these components to fractionate or segregate, thereby shifting the effective melting range and reducing latent heat storage capacity over time. Phase segregation may also result in uneven melting behaviour and higher thermal resistance within the PCM layer. Similar stability issues have been observed in PCM-enhanced PV-T systems and thermal energy storage materials undergoing long-term cycling (Maatallah et al., 2019; Kazemian et al., 2018).

Furthermore, prolonged thermal cycling may induce degradation, particularly in bio-based Phase Change Materials (PCMs) that are exposed to oxygen or moisture. Over time, such processes can gradually affect the PCM's thermal conductivity, latent heat capacity, and phase-transition characteristics.

To address these risks in practical use, various engineering approaches can be employed, such as enhancing containment design, adding porous support matrices, such as metal foam or graphite structures, and applying stabilising additives. Microencapsulation, in which PCM particles are encapsulated in polymer shells, is also commonly used to prevent leakage, minimise phase segregation, and improve long-term cycling stability. However, this method might increase thermal resistance (Cui et al., 2022; Hossain et al., 2019).

Thirdly, the analysis predominantly relies on numerical simulations conducted utilising TRNSYS software, with the assessment of system performance based on meteorological data

characteristic of Maiduguri, Nigeria. Although the model has been validated against experimental results reported in the literature, the system itself has not yet been tested under actual outdoor operating conditions.

The lack of field-scale experimental validation constitutes a significant limitation, especially for systems intended for deployment in Sub-Saharan Africa. Real operational environments may introduce additional factors that are challenging to represent comprehensively in numerical models. These factors include:

- Dust buildup on PV surfaces
- Extreme ambient temperature fluctuations
- Variable wind conditions
- Long-term thermal cycling of the PCM
- Material degradation or leakage during repeated melting and solidification

7 Suggestion for further research

This research was conducted at the level of the PV panel and demonstrates promising potential. However, scaling up to larger PV farms depends on the availability and stability of shea butter under repeated thermal cycles, as well as the risk of quality degradation. Shea butter, derived from West African shea nuts, must be sustainably harvested to avoid deforestation while enabling scalability. Establishing a supply chain—such as collaborating with shea cooperatives and adopting mechanised shea butter production—is crucial for maintaining ethical standards.

Future research should focus on evaluating durability by conducting extended thermal cycling tests and examining encapsulated or composite PCM configurations to improve the long-term reliability of PV-T/PCM systems in real-world settings.

An outdoor experiment in sub-Saharan Africa should be performed to validate the numerical analysis presented here. The system could also be scaled for practical use in households or commercial settings such as schools or hospitals to meet energy requirements. Furthermore, a thorough economic and environmental assessment of the hybrid PVT system combined with shea butter, based on primary data, should be conducted to provide a viable alternative to existing PCM integration methods for decision-makers (Mahbuba et al., 2022).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. PK: Supervision, Writing – review and editing. KP: Supervision, Writing – review and editing.

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The author(s) declared that generative AI was not used in the creation of this manuscript.

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Glossary

G	Solar radiation intensity (W/m^2)
τ	Transmission coefficient
ε	Emissivity
α	Absorption coefficient
m	Mass flow rate (kg/s)
T	Temperature (K)
η_{pv}	PV efficiency (%)
β_r	Efficiency at references
$.v_{wind}$	Wind speed (m/s)
λ	Thermal conductivity (W/m.K)
D	Diameter (m)
W	Width (m)
R	Thermal resistance
Nu	Nusselt number
δ	Thickness (m)
c_p	Heat capacity ($\text{kJ/kg} \cdot \text{K}$)
h_c	Convective heat transfer coefficient ($\text{W/m}^2.\text{K}$)
h_r	Radiative heat transfer coefficient ($\text{W/m}^2.\text{K}$)
Pa	Encapsulation factor
Q_h	Quantity of heat
Q_{ele}	Quantity of electricity
η_{th}	Thermal efficiency
η_{ele}	Electrical efficiency
η_{to}	Total efficiency
Td	Tedler
e	Environment
s	Sky
g	Glass cover
pv	Photovoltaic
i	Insulation layer
w	Water
ab	Absorber plate
a	Air layer
t	Tube
sol	Solid
liq	Liquid
mt	Melting temperature
pcm	Phase change material
th	Thermal
ele	Electrical
to	Total



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