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Experimental Study of the Thermal Performance of an Air Solar Collector with Latent Heat Storage Based on Beeswax

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ABSTRACT: The mismatch between the availability of solar radiation during the day and heat demand in the evening is one of the challenges of solar energy. Energy storage is a solution that can improve the efficiency of solar thermal applications. In this article, we focused on the experimental study of the thermal performance of an air-based solar collector using beeswax as a phase change material (PCM). A container filled with beeswax, which has a melting point of 60°C, is placed beneath the absorber of the collector with storage. Solar thermal collectors are designed and tested under the climatic conditions of the city of Thiès, Senegal. The effect of storage on the outlet air temperature and the efficiency over four days is discussed. The performance of the thermal collector with storage is compared to that of a conventional air collector. Experimental results indicate that it is possible to obtain an air temperature difference of 5.4°C at the outlets of the two collectors for one hour after sunset. Based on the results obtained in this study, it is demonstrated that the use of beeswax improves the outlet air temperature after sunset.

KEYWORDS: Air solar collector; phase change material (PCM); beeswax; thermal energy storage; instant efficiency; air outlet temperature; daily efficiency

1 Introduction

Because it is so abundant, solar energy is the most promising of all renewable energy sources [1]. The drying of agricultural and fishery products is one of the main applications of solar energy in sub-Saharan Africa, a region with considerable solar potential. Traditional drying methods have been practiced in sub-Saharan Africa since ancient times. However, these methods are inadequate due to dust and the presence of insects. Solar dryers can serve as an alternative to improve traditional drying, as they are simple to build and use. In a solar dryer, solar radiation is converted into heat by the collector. The collector then transfers this heat to the air, which, in turn, heats the product to reduce its moisture content. The intermittent nature of solar energy is one of the main limitations of solar dryers. This problem can be mitigated by storing excess energy during periods of intense sunlight for use during periods of low sunlight. Temporary storage of thermal energy can be an important mechanism for compensating for this imbalance between supply and demand [2]. Thermal energy can be stored as sensible heat, latent heat, or chemical energy. Latent heat storage is one of the most efficient techniques due to its compactness, high energy density, and ability to store heat at a constant temperature [2,3]. Numerous experimental studies have been conducted on the integration of PCMs into the air collectors of solar dryers.

Kabeel et al. [3] compare a conventional air-type solar collector with a corrugated-plate collector using paraffin wax as a PCM. The results show that the air temperature at the outlet of the corrugated-plate collector is 1.5°C to 7.2°C higher than the ambient temperature for 3.5 h after sunset. The study also shows that the air temperature at the outlet of the conventional collector is 1°C to 5.5°C higher than the ambient temperature for 2.5 h after sunset at a flow rate of 0.062 kg/s. The study also shows that thermal storage improves the daily efficiency of the corrugated-plate collector by 12% compared to that of a corrugated-plate collector without PCM. Singh et al. [4] are testing an air-based solar collector that uses paraffin which has a melting point of 54°C as a storage material. Air circulates outside the cylinders filled with paraffin. The results show a maximum temperature difference of 2°C to 9°C between the air temperature at the collector outlet and the ambient temperature. Dosapati and Mandapati [5] compare a flat-plate air solar collector with a corrugated-plate air solar collector. Both collectors use paraffin as a storage medium to produce hot air at night. They observed a drop in air temperature of 7°C to 8°C during paraffin charging and an increase of 4°C to 5°C during discharge. The results also show that the daily efficiency of the corrugated-plate collector is 22% higher than that of the flat-plate collector during charging and 6% higher during discharge. Esakkimuthu et al. [6] conducted experiments on an air-based solar collector using inorganic salt as a PCM (HS58). They observed a temperature difference of 5°C to 11°C between the air exiting the collector and the ambient environment after sunset. Agarwal and Sarviya [7] use a shell-and-tube heat exchanger with paraffin as the storage medium for a solar dryer. The results show that this system is effective for drying food products during hours without sunlight. They observed an increase in the outlet air temperature from 5°C to 17°C over a 10-h period during PCM discharge. Agyenim and Hewitt [8] use a concentric tube equipped with fins and containing 98 kg of RT58 (PCM) as a storage system. The results indicate that an increase in the fluid inlet temperature from 60.9°C to 65.98°C improves the heat transfer coefficient by up to 70% during the charging process and by 11.3% during the discharging process. Fath [9] uses copper cylinders filled with paraffin wax as the solar collector absorber. The study shows a temperature difference of 5°C between the outlet air and the ambient environment for 4 h after sunset, and a daily efficiency of 63.35%. Tyagi et al. [10] conducted experiments on a solar air heating system that uses paraffin as a PCM. The air temperature reaches its maximum at noon in the system without storage and at 4:30 p.m. in the system with storage. Benli and Durmuş [11] use $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ -which has a melting point of 29°C-as a Phase Change Material (PCM) for greenhouse heating. Compared to a conventional system, this system meets approximately 18% to 23% of the greenhouse's daily thermal energy needs over a period of 3 to 4 h. El Khadraoui et al. [12] compared two air-type solar collectors, each with an area of 2 m². The air temperature at the outlet of the collector with a 6-cm-thick paraffin layer beneath its absorber is 3°C to 7°C higher than that of the collector without storage after sunset. Bhale et al. [13] compared a sensible heat storage system and a combination of sensible and latent heat storage are compared in a concentrated solar power system. Stearic acid is used as the PCM. The results show that the system combining both storage modes performs better. Tadele Embiale and Gudeta Gunjo [14] conducted experiments with a solar dryer that uses paraffin as a PCM. The study found that thermal storage mitigates temperature fluctuations and increases the drying time by three hours per day. Enibe [15] examines the performance of an air-based solar collector that uses paraffin as a PCM. The experiment was conducted in Nigeria at ambient temperatures ranging from 19°C to 41°C and under daily solar radiation ranging from 4.9 to 19.9 MJ/m². The results show that this system is effective for drying crops. Hussein and Taqi Al-Najjar [16] tested two solar water heaters equipped with paraffin having melting points of 38°C and 50°C, respectively. The results indicate that the water temperature at the outlet of the water heater using the (PCM50) is 9.3°C higher than the ambient temperature at a flow rate of 0.1 L/min. Jeong et al. [17] investigate paraffin microcapsules as a heat transfer fluid in a solar collector. The study shows that this fluid improves thermal efficiency by 33.6% compared to water. Fu et al. [18] are studying the effect of convection type on air-cooled solar collectors using RT-35 as a PCM. The results show that the combination

of forced convection and nighttime insulation improves the average internal temperature by 1.4°C. Agrebi et al. [19] compare experimental and numerical studies of a heat exchanger using polyethylene glycol 600 as a PCM. The results show that varying the flow rate from 0.03 to 0.07 kg/s significantly reduces the material's charging and discharging times. An average discrepancy of less than 4% between the two models indicates good agreement. Bhaisare et al. [20] are conducting research on solar technologies equipped with latent heat storage. The study reveals that the low thermal conductivity (0.1 to 0.7 W/m·K) of PCMs limits their performance. They also show that adding 3% nanographene, a carbon-based nanoparticle, improves thermal conductivity by 146.3%. Sathyamurthy et al. [21] are studying the thermal efficiency of a solar still. They use cans filled with beeswax as a storage system. They are comparing this system to another in which the cans are filled with beeswax and coated with iron oxide nanoparticles. The study shows that the latter configuration is the most efficient, with an efficiency of 60%. Medjahed et al. [22] investigate the effect of varying the mass fraction of a mixture of paraffin and beeswax on plaster used as an insulating material. The results show a decrease in thermal conductivity as the mass fraction of the mixture increases. Medjahed et al. [23] conducted experiments on a heat exchanger using beeswax as a PCM. The results show that temperature variation has a greater effect on charging time than on flow rate. They also indicate that the discharging time is longer than the charging time due to the gradual formation of a solid layer of PCM around the outer surface of the heat exchanger. Dong et al. [24] mixed coffee waste and beeswax to produce a fully bio-based PCM composite. This composite material showed encouraging results, with a charge capacity of 78.8% and a phase-change enthalpy of 135.3 J/g after 48.7 cycles. Over 500 thermal cycles at 70°C for 4 h, no leakage was detected, and the material retained 98.2% of its capacity. Ben Belgacem et al. [25] have developed a new material composed of beeswax, graphite, and carbon nanotubes to overcome the low thermal conductivity of beeswax. The addition of 10% by mass of graphite improves thermal conductivity and results in a high latent heat of 131.1 J/g.

Most research on the integration of PCMs into thermal collectors has focused on paraffins and hydrated salts. Unlike these two materials, beeswax is bio-based and therefore not harmful to the environment. Paraffin waxes are expensive, flammable, and derived from petroleum. Their low thermal conductivity is considered their main drawback [3,25]. Melted salts are corrosive. An alternative to paraffin and hydrated salts is the use of natural phase-change materials. Among natural PCMs, beeswax shows great potential. It is abundant and requires little processing. It has the advantage of being readily available and is more affordable than paraffin or hydrated salts. The integration of natural PCMs into thermal collectors has not been the subject of many studies. This work focuses on the experimental study of the performance of a flat-plate air-side thermal collector using beeswax. An analysis of the integration of beeswax is conducted by comparing a conventional thermal collector with a beeswax-based thermal collector. [Section 1](#) of this article presents the background and relevance of the study. The experimental methods and equipment are explained in [Section 2](#). [Section 3](#) contains the thermal analysis equations, and the experimental results are discussed in [Section 4](#). [Section 5](#) presents the conclusions drawn from the results of this experimental study.

2 Experimental Procedure

2.1 Experimental Setup

The experimental setup includes a conventional air-type thermal collector, a thermal collector with latent heat storage, iButton temperature sensors, a solarimeter, an anemometer, and a power supply. The thermal collector consists of a single pane of glass, a steel absorber plate, and insulation. A box containing beeswax is placed beneath the absorber of the storage collector. The box is made of iron, measures 2.5 cm in height, and has a surface area of 0.35 m². All sides of the thermal collectors are insulated. Air inlet and outlet ducts with a cross-sectional area of 0.02 m² are used. [Fig. 1a–e](#) shows the equipment used for

experimentation. The dimensions of the solar collector and the thermophysical and optical properties of the various collector components are presented in [Tables 1](#) and [2](#), respectively.

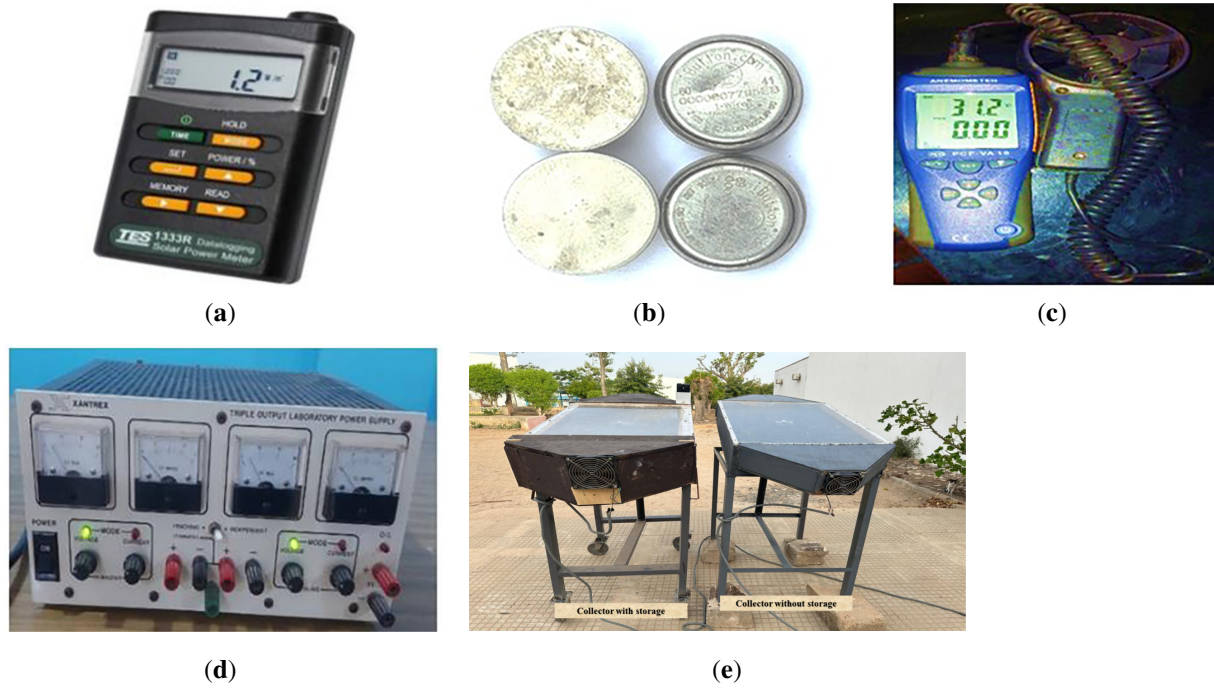


Figure 1: The instruments used in the experiment: (a) solarimeter; (b) iButton temperature sensors; (c) anemometer; (d) power supply; (e) collector with and without storage.

Table 1: Dimensions of the solar collector.

Dimension	Value (m)
Collector width	0.5
Collector length	0.70
Phase change material box height	0.025
Glass thickness	0.003
Thickness of wooden frame	0.02
Absorber thickness	0.015
Air channel height	0.04

Table 2: Thermo-physical and optical properties of the different collector components [\[26\]](#).

	ρ (kg/m ³)	C_p (J/kg·K)	λ (W/m·K)	μ (kg/m·s)	τ	A
Air	1.177	1006	0.0262	1.85×10^{-5}	0.85	/
Glass	2530	720	1.2	/	/	0.92
Steel	7800	486	51.9	/	/	/
Wood	700	2093	0.16	/	/	/

Note: μ : dynamic viscosity; τ : transmittance; A: absorption coefficient. For the rest, see [Section 3](#).

To ensure that the beeswax fills the entire volume of the box perfectly, we put it through the various stages shown in Fig. 2a–d. Fig. 2a shows 7 kg of solid beeswax; we then scrape it (Fig. 2b) to facilitate heating, as shown in Fig. 2c. Finally, we cool it (Fig. 2d) before filling the container.

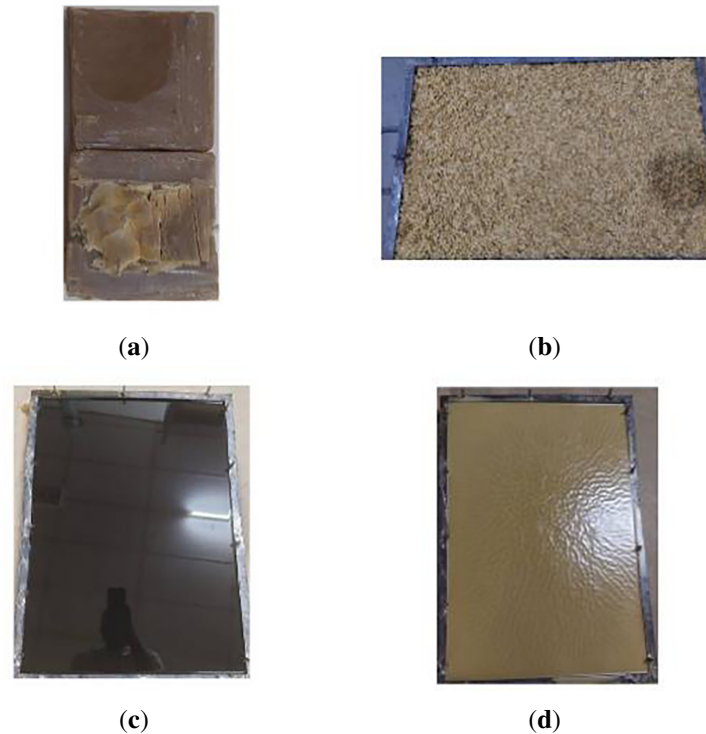


Figure 2: Processing of beeswax: (a) solid beeswax; (b) grated beeswax; (c) heated beeswax; (d) cooled beeswax.

Fig. 3 shows a schematic diagram of the air-based thermal collector with thermal storage. Beeswax, which has a melting point between 58°C and 62°C , is used as the storage material. The thermophysical properties of beeswax are listed in Table 3.

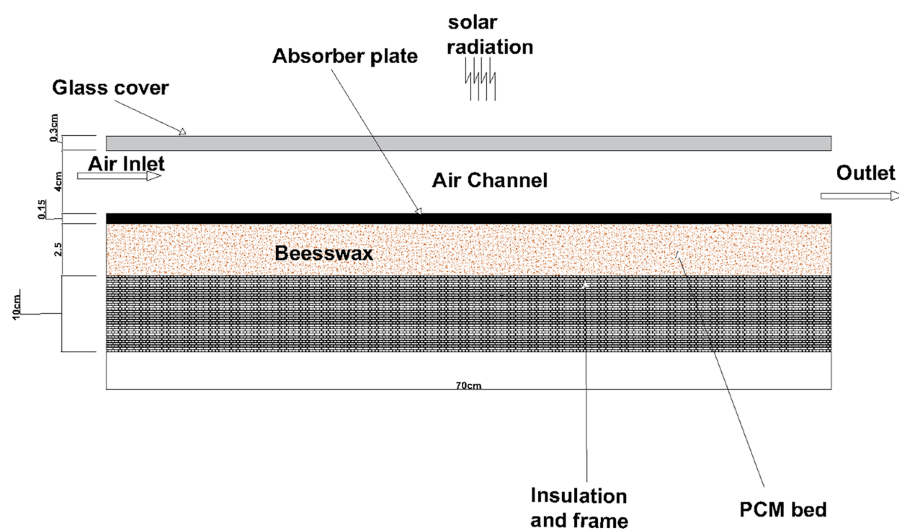


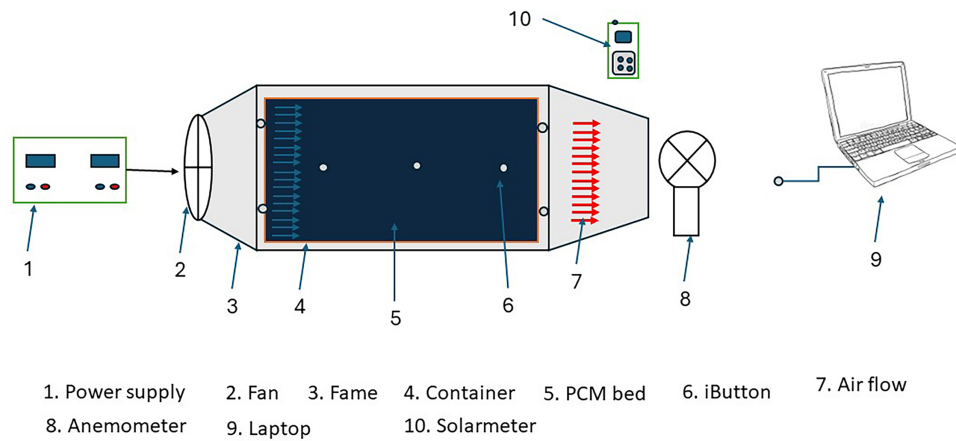
Figure 3: Cross-section view of the solar collector and the PCM box.

Table 3: Thermo-physical properties of beeswax.

Phase Change Material	Melting Temperature (°C)	Thermal Conductivity [W/m·K]	Volumetric Capacity [J/m ³ ·K]
Beeswax	58–62	0.52591	7,850,259.996

2.2 Measurement and Experimental Procedures

The tests were conducted simultaneously on the thermal collector without storage and on the thermal collector with latent heat storage using beeswax under the weather conditions of the Thies region in Senegal. Parameter measurements began between 8:00 a.m. and 8:30 a.m. and ended between 8:00 p.m. and 9:00 p.m. during the month of July 2024, and between 6:00 p.m. and 7:00 p.m. during the months of January and February 2026. The air-based thermal collector without storage serves as a reference for studying the effect of storage on the outlet air temperature. A power supply (XANTREX) is used to operate the fan responsible for circulating air through the collector. An iButton temperature sensor, with an operating range of -40°C to 85°C and an accuracy of $\pm 0.5^{\circ}\text{C}$, is used to measure the temperature of the air, the absorber, the ambient air, and the PCM. Air velocity is measured using a PCE.VA.10 anemometer, with a measurement range of 0.3 to 45 m/s and an accuracy of $\pm 3\% + 1$, allowing for the measurement of air velocity at the outlet. Solar radiation is measured using a Mod.SORM solarimeter, with an accuracy of $\pm 10 \text{ W/m}^2$. The data stored in the iButton sensors and the solarimeter are exported to a computer for processing. Fig. 4 illustrates the measurements and the experimental procedure.

**Figure 4:** Top view of the schematic representation of the experimental procedure and the instrument.

3 Thermal Performance Parameters

The purpose of the solar collector is to produce hot air. The thermal power absorbed by the air allows us to evaluate the collector's performance. We also need to know the percentage of heat absorbed by the air relative to the solar radiation received by the collector, which gives us the efficiency. In this section, the equations governing the thermal performance parameters of the air solar collector are evaluated as follows.

$$Q_u = mc_p \Delta T_c \quad (1)$$

$$\varepsilon = \frac{Q_u}{IA} \quad (2)$$

$$E_j = \frac{\sum Q_u}{\sum I \times A} \quad (3)$$

Q_u (W) heat transfer rate received by the air; m (kg/s) the air flow rate in the collector; C_p (J/kg.K) Specific heat capacity; ΔT_c (K) air temperature difference across the collector; ε (%) Instantaneous thermal efficiency; I (W/m²) Solar radiation; A (m²) the collector surfaces; E_j (%) daily efficiency; λ (W/m.K) Thermal conductivity; ρ (kg/m³) density.

4 Results and Discussion

The experimental study involves measuring the temperature of the absorbers, the beeswax, the heat transfer fluid (air), the ambient air, and the daily solar radiation at the site, and then determining the efficiency. We conducted these experiments in July 2024 (the rainy season) and in January and February 2026 (the dry season) in Thiès, Senegal. Fig. 5 shows the temperature trends for the PCM, the absorber of the PCM-equipped collector, and solar radiation on 06 July 2024. We observe that the intensity of the solar radiation increases between 8 a.m. and 12 p.m., at which point it reaches its peak, and then decreases. Fig. 5 shows that the absorber temperature is higher than that of the PCM from 8:21 a.m. to 4:40 p.m., followed by a temperature reversal observed until 9:00 p.m. The temperature difference observed up to the inversion suggests that the absorber transfers heat to the PCM and that, subsequently, the PCM transfers heat to the absorber. Between 8:21 a.m. and 3:30 p.m., the PCM temperature rises from 30°C to 60.44°C, corresponding to the period during which it receives sensible heat. From 3:30 p.m. to 5:26 p.m., we have the PCM melting phase. This phase is characterized by a very slow change in temperature (60.44°C–60.93°C). During this phase, the PCM temperature averaged 60.68°C for two hours, while the absorber temperature decreased, resulting in the inversion observed between the two temperatures at 4:40 p.m. We can conclude that starting at 4:40 p.m., the PCM becomes the heat source for the collector. From 8:21 a.m. to 5:26 p.m., the PCM receives heat (charging phase), and from that point on, the PCM temperature changes from 60.93°C to 49°C, corresponding to the discharging phase. We also note that, starting at 4:40 p.m., the absorber receives heat from the PCM, but its temperature continues to drop because the upper part of the collector is not insulated. This drop in temperature can also be explained by the low heat flux received by the absorber due to the insulating layer that forms at the top of the PCM during its discharge [23].

Fig. 6a–d shows the temperature variations of the collector absorbers with and without storage and solar radiation for the four days. We observe the same variations in these parameters over these four days. We note that solar radiation is more stable in January and February. The measured daily average values for solar radiation are 598, 463.4, 743.5, and 716.5 W/m² for 06 July 2024, 09 July 2024, 31 January 2026, and 03 February 2026, respectively. These average radiation values indicate that 31 January 2026, is the sunniest day. We can see from this graph that the absorber temperature of the thermal collector without PCM is higher than that of the collector with PCM from the start until 5:36 p.m., 6:24 p.m., 5:41 p.m., and 5:32 p.m., respectively, for 06 July 2024, 09 July 2024, 31 January 2026, and 03 February 2026; thereafter, we observe a reversal of temperatures for the remainder of the day. From the start until the reversal occurs, the absorber with the PCM transfers heat to the material, which then releases it. We also note that storage helps smooth out temperature fluctuations in the absorber by increasing the system's overall thermal inertia, and that the absorber temperature in the collector without storage is higher for most of the day. These curves also confirm the drop in absorber temperature after the inversion due to heat loss.

Fig. 7a–d shows the changes in air temperature at the outlet of the collector without storage, the collector with storage, and the ambient temperature for the four days. The curves indicate that the air temperatures at the outlet of the thermal collectors are, on average, always higher than the ambient temperature, with

maximum deviations of 17.4°C and 14°C , respectively, for the collector without storage and the collector with storage on 06 July 2024. The observation regarding the temperature trends of the two absorbers (Fig. 6a–d) also applies to the outlet air temperatures. We observed an outlet air temperature difference of 2.9°C , 2.6°C , 4.8°C , and 5.4°C between the two collectors, respectively, on 06 July 2024, 09 July 2024, 31 January 2026, and 03 February 2026, after sunset, due to the discharge of the PCM. The greatest temperature difference is observed during the dry season, due to high solar radiation. The results show that the outlet air temperature depends heavily on solar radiation.

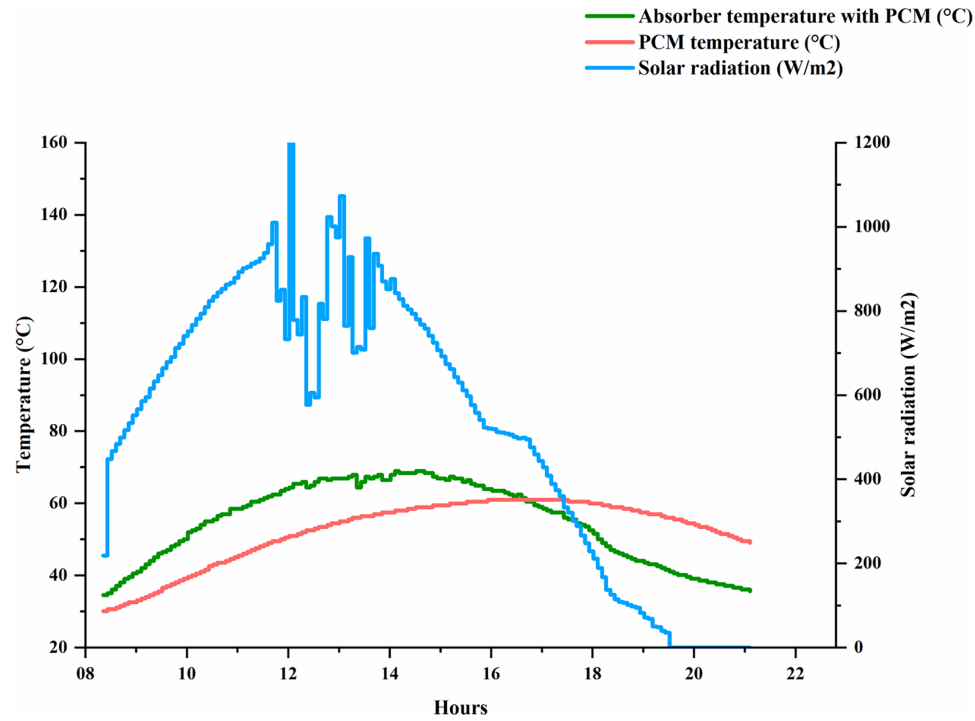


Figure 5: Absorber temperatures with storage, PCM temperature and solar radiation on 06 July 2024.

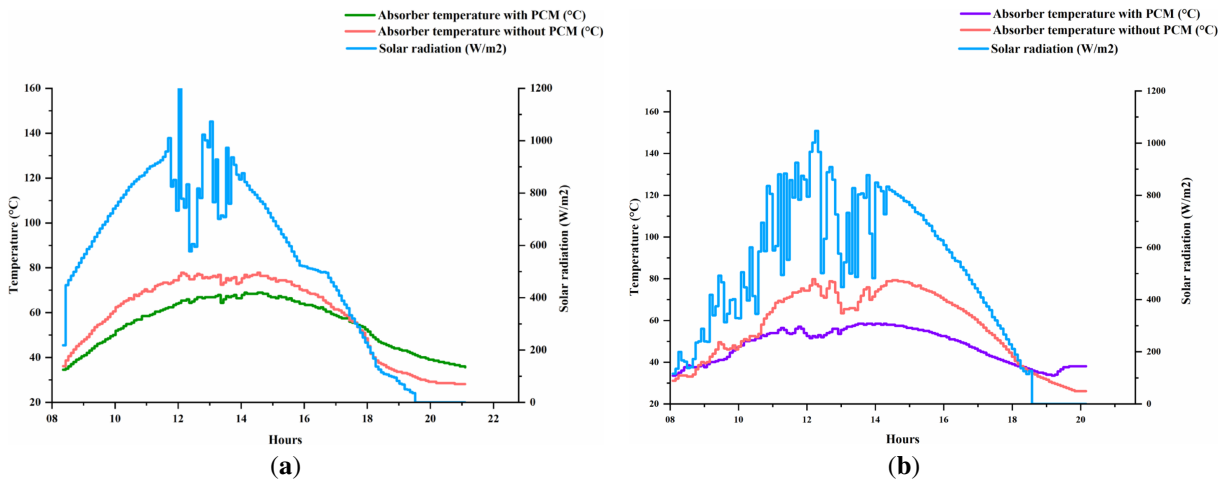


Figure 6: (Continued)

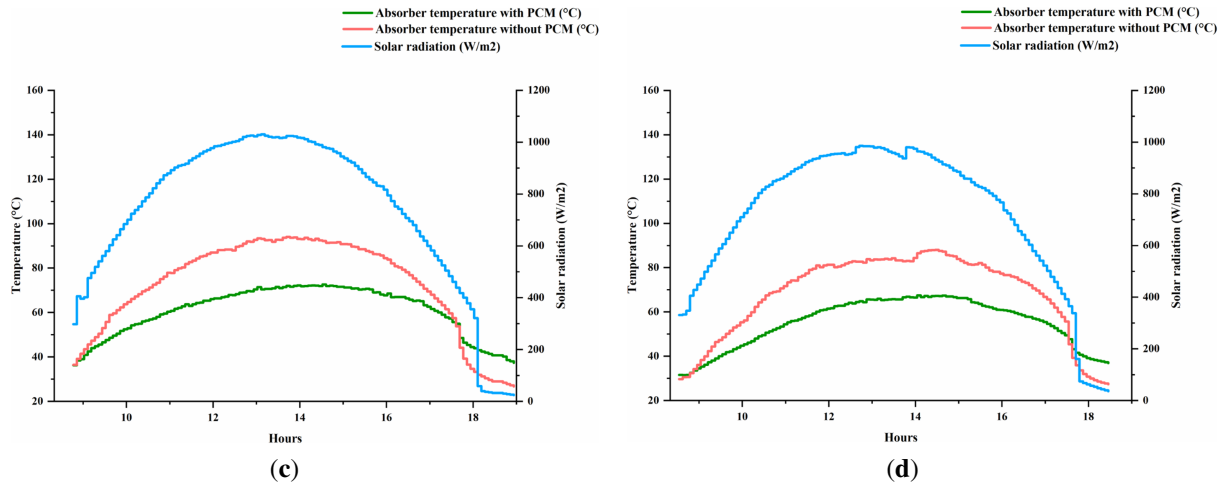


Figure 6: Absorber temperatures with and without PCM and solar radiation of: (a) 06 July 2024; (b) 09 July 2024; (c): 31 January 2026; (d) 03 February 2026.

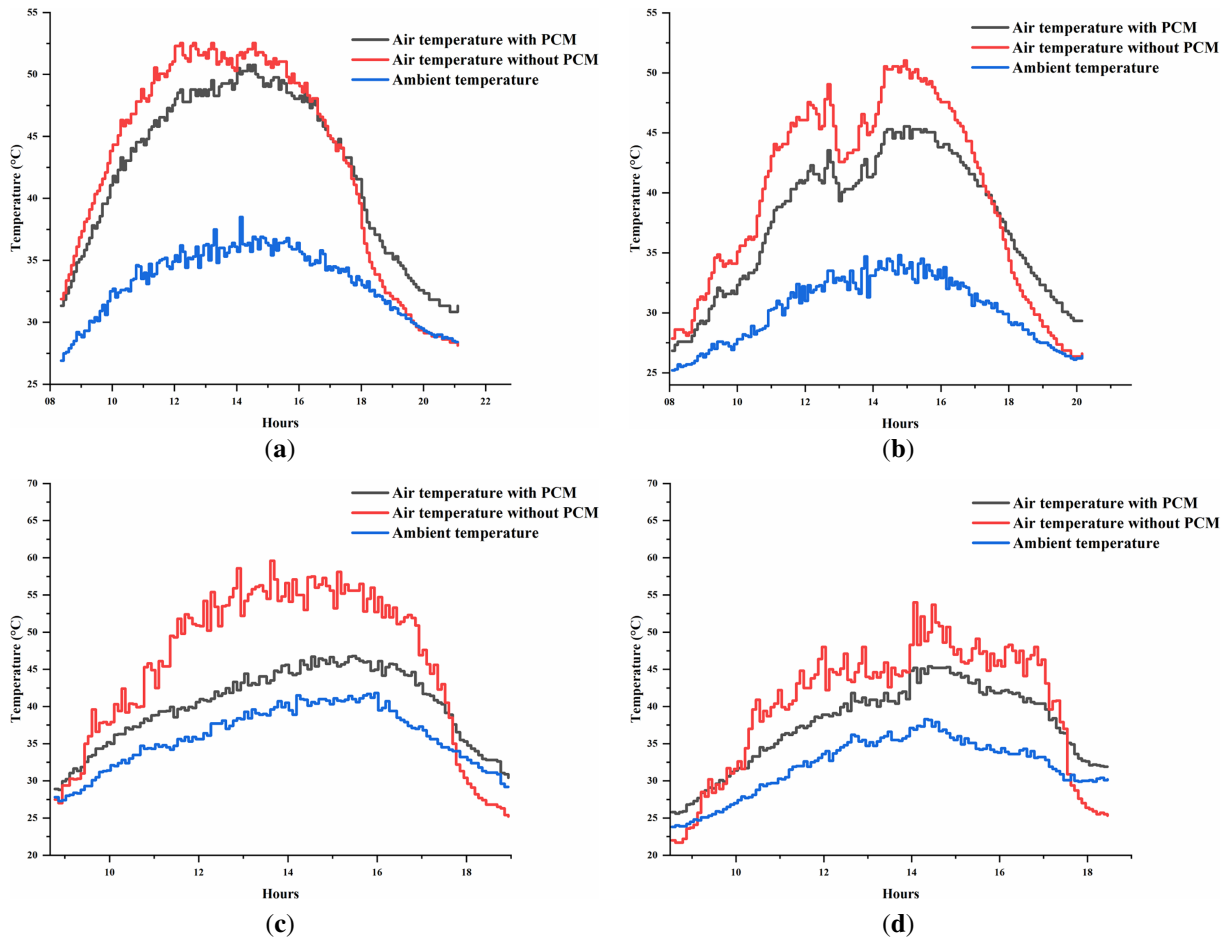


Figure 7: Air outlet temperatures of the two collectors (with and without PCM) and the ambient temperature: (a) 06 July 2024; (b) 09 July 2024; (c) 31 January 2026; (d) 03 February 2026.

Fig. 8a–d illustrates the variation in daily solar radiation and the heat flux absorbed by the air in the solar collectors over the same four days. The curves show that solar radiation follows a typical pattern, peaking at noon before gradually decreasing toward the end of the day. The heat flux absorbed by the air is higher in the solar collector without PCM than in the one equipped with PCM during the day; this trend reverses at sunset for the same reasons as before. It should be noted that the storage system allows the air to recover heat after sunset. We observe that on 03 February 2026, the air in the solar collector with storage absorbed more heat, 59.22 W, due to strong sunlight. This absorbed heat explains why the greatest difference in outlet air temperature between the two collectors was recorded on that day.

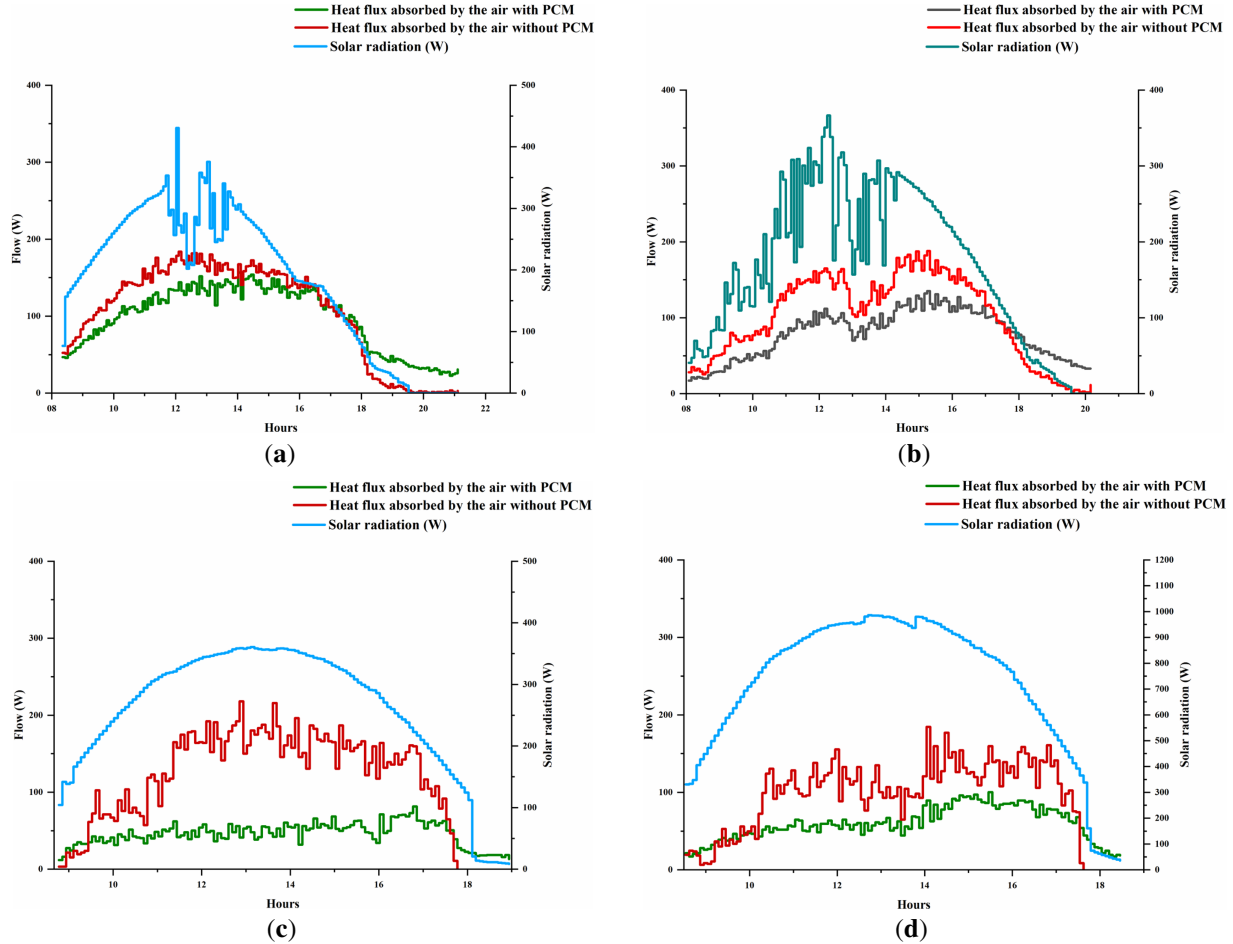


Figure 8: Thermal flux absorbed by the air of the collector without PCM, the collector with PCM and of the solar radiation: (a) 06 July 2024; (b) 09 July 2024; (c) 31 January 2026; (d) 03 February 2026.

Fig. 9a–d shows the instantaneous thermal efficiency profiles of the two thermal collectors for the following dates: 06 July 2024; 09 July 2024; 31 January 2026; and 03 February 2026. These figures indicate that the instantaneous thermal efficiency of the collector without PCM is generally higher than that of the collector with PCM for most of the day. The thermal efficiency of the collector with PCM remains lower than that of the collector without PCM throughout the four days of measurement up until sunset. From that point on, the performance of the collector with PCM increases due to the discharge of the material at the end of the day. For example, on 31 January 2026, the daily efficiency of the collectors with and without storage was

17% and 45%, respectively. It can be observed that the PCM reduces the collector's daily efficiency but allows heat to be recovered when sunlight is no longer available.

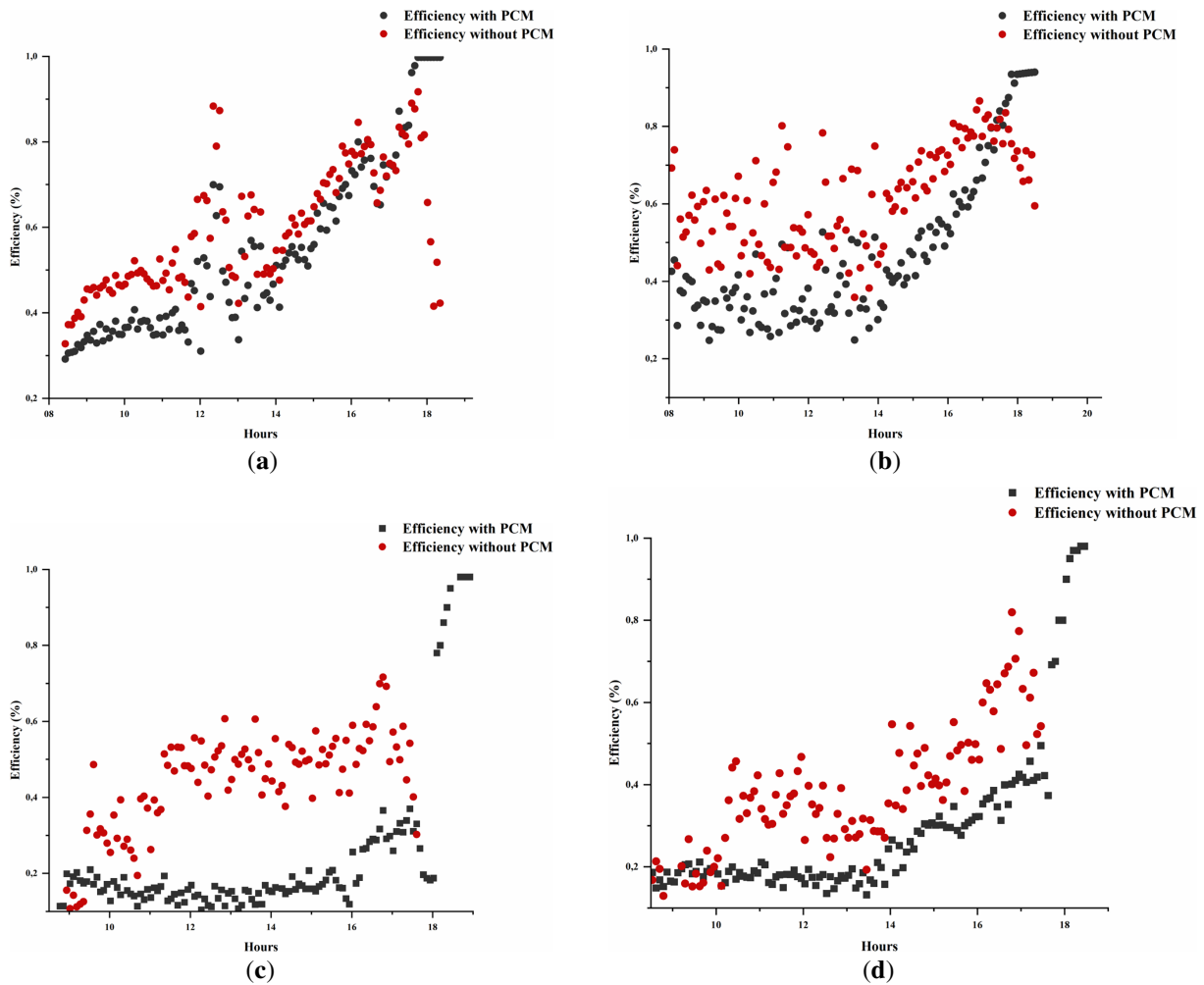


Figure 9: Instantaneous thermal efficiencies of the collector without PCM and the collector with PCM: (a) 06 July 2024; (b) 09 July 2024; (c) 31 January 2026; (d) 03 February 2026.

Uncertainties in experimental results are affected by errors in primary measurements. The analysis of experimental errors is verified according to reference [3]. The uncertainties and relative errors in measurements of solar radiation intensity and air temperature difference across the collector in January 2026 are summarized in Table 4.

Table 4: Measurement relative errors and uncertainties.

Parameter	Maximum Value for the Four Days	Uncertainty	Relative Error (%)
Solar radiation (W/m^2)	743.5	± 10	1.34
Temperature difference across the collector ($^{\circ}\text{C}$)	20.2	± 1	4.95

5 Conclusion

This study experimentally compared the thermal performance of a conventional air-cooled solar collector with that of a solar collector incorporating beeswax as a latent heat storage material (PCM). The results demonstrate the ability of beeswax to effectively store and release thermal energy, thereby extending the operating period of the solar collector beyond sunset. Solar radiation was shown to play a key role in the charging and discharging processes of the PCM, directly influencing the outlet air temperature. Experimental results indicate that it is possible to achieve an air temperature difference of 5.4°C at the outlets of the two collectors for one hour after sunset, thereby confirming the potential of beeswax to improve the thermal performance of solar air heating systems.

Overall, the findings demonstrate that beeswax is a promising renewable and bio-based phase change material for low-temperature thermal energy storage applications. Its use in solar air collectors represents a sustainable approach to improving energy availability during periods of low or no solar radiation while contributing to the development of environmentally friendly thermal energy storage technologies.

Future work will focus on further enhancing the performance and practical applicability of the proposed system. Particular attention will be given to the development of beeswax-based composite PCMs with improved thermal conductivity, the optimization of the collector design and thermal insulation to maximize heat storage and recovery, and the investigation of the long-term thermal and chemical stability of beeswax under repeated charging and discharging cycles. In addition, numerical modeling coupled with experimental validation will be employed to optimize system parameters under different climatic conditions. Future studies will also explore the integration of the proposed collector into solar drying, space heating, and agricultural processing applications, as well as assess its techno-economic feasibility and environmental benefits to support large-scale implementation.

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Availability of Data and Materials: The data that support the findings of this study are available from the Corresponding Author, [Ousseynou Diao], upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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