

# Performance of Phase Change Materials in Parabolic Solar Coffee Drying: A Chemometric Approach

Yeni Eliza Maryana<sup>1,2</sup> , Daniel Saputra<sup>3\*</sup> , Gatot Priyanto<sup>4</sup> , Kiki Yulianti<sup>4</sup> , Agusriansyah Saputra<sup>1</sup> 

<sup>1</sup>Doctoral Program of Agricultural Sciences, Universitas Sriwijaya, Palembang, South Sumatera, Indonesia

<sup>2</sup>The Agency for Agricultural Assembly and Modernization, South Sumatera, Indonesia

<sup>3</sup>Department of Agricultural Engineering, Faculty of Agriculture, Sriwijaya University, Jl Raya Palembang-Indralaya KM 32, Indralaya, South Sumatera, Indonesia

<sup>4</sup>Department of Agricultural Product Technology, Faculty of Agriculture, Sriwijaya University, Jl Raya Palembang-Indralaya KM 32, South Sumatera, Indonesia

\*Corresponding author: [drdsaputra@unsri.ac.id](mailto:drdsaputra@unsri.ac.id)

Editor: Samuel Pereira de Carvalho 

Received in October 17, 2025 and approved in April 13, 2026

## ABSTRACT

The integration of phase change materials (PCMs) into solar drying systems has been shown to improve drying efficiency, temperature stability, and product quality. This study investigates the performance of PCMs incorporated into a parabolic solar dryer to enhance thermal efficiency and overall drying performance. Two types of PCMs, paraffin (PRF) and used cooking oil (UCO), were compared to assess their effects on drying tunnel temperature and moisture content of coffee cherry. Experimental data were analysed using descriptive statistical methods with GraphPad Prism 10, while principal component analysis (PCA) was conducted using RStudio version 2025 to identify key variables influencing the system's thermal and drying characteristics. The results showed that the drying system with used cooking oil PCM produced the highest and most stable temperature (34.93–43.43°C), followed by the system without PCM (25.31–40.48°C), and the system with paraffin PCM (31.32–38.31°C). The moisture content of coffee cherries decreased significantly from 28.83–32.03% (wb) on day 1 to 11.23–12.17% (wb) on day 5, with the used cooking oil-based PCM treatment yielding the lowest moisture content of 11.23% (wb), which complied with the Indonesian National Standard. Furthermore, principal component analysis (PCA) revealed that the used cooking oil PCM had the most dominant effect on increasing the drying chamber temperature and accelerating moisture reduction compared to systems using paraffin PCM or without PCM. Future research should undertake a more comprehensive evaluation of the system's performance in coffee cherry drying, including colour change analysis, thermal efficiency, drying rate, and exergetic performance.

**Key words:** Parabolic solar dryer; PCM; PCA; used cooking oil (UCO); paraffin (PRF).

## 1 INTRODUCTION

Indonesia is the second-largest coffee producer in Asia and Oceania, with total production in the 2022/2023 season increasing by 2.4% to 12 million bags (Ngure & Watanabe, 2024). One of the leading coffee-producing regions is South Sumatra Province, where coffee has become the primary plantation commodity. In 2022, coffee production in South Sumatra is projected to exceed 200,000 tons, with most rural farmers relying on it as their primary source of livelihood (Statistics Indonesia, 2024). According to SNI 01-2907-2008, coffee ready for sale must have a maximum moisture content of 12.5% and a distinctive aroma without any musty or rotten odour (Badan Standar Nasional, 2008). The post-harvest process includes sorting ripe cherries, pulping to separate beans from the mesocarp and exocarp, soaking to remove mucilage through natural degradation, enzymatic fermentation, or mechanical methods, followed by washing and drying (Sanz-Urbe et al., 2017). Freshly harvested coffee cherries typically exhibit an initial moisture content exceeding 12.5% (Ghosh & Venkatachalapathy, 2014). Therefore, drying is an essential step to meet the standard requirements and to prevent quality deterioration caused by microbial growth, mycotoxin-producing fungi, and enzymatic activity (Chiewchan, Mujumdar & Devahastin, 2015).

Excessive drying temperatures may degrade coffee quality, altering attributes such as flavor, pH, acidity, total dissolved solids, volatile compounds, antioxidant content, and colour (López-Parra et al., 2024). Moreover, the drying process is energy-intensive. Farmers commonly rely on traditional methods such as open-air sun drying; however, this approach is less than ideal due to its long drying duration, dependence on weather conditions, inconsistent outcomes, and vulnerability to cross-contamination from dust, pests, and rodents (Kebede et al., 2025). Therefore, improved drying technologies are needed that are not only faster and more energy-efficient but also capable of preserving the physical, chemical, and sensory qualities of coffee beans (Al-Ghamdi et al., 2024).

Solar bubble drying technology offers a more environmentally friendly alternative compared to conventional methods. This technology is able to maintain product quality and nutritional content, making it a promising option for farmers. Its flexible and simple design also supports economic feasibility (Acar, Dincer & Mujumdar, 2022; Aktar et al., 2022; Jyoti et al., 2023). In this system, products are placed in a closed space (poly tunnel) to protect them from cross-contamination, while parabolic dish collectors and solar panels are used to capture solar radiation (Maryana et al., 2023, 2025). The heat interaction configuration applied in this study was mixed-mode, combining several mechanisms such

as convection and solar radiation. Mixed-mode solar drying is more advantageous because it allows both mechanisms to operate simultaneously (Mehta *et al.*, 2022). The technology developed in this study integrates a drying chamber, parabolic dish solar collectors, an air recirculation system, and a phase change material (PCM) thermal energy storage unit into a single system, resulting in a mixed-mode solar bubble dryer (Baniasadi, Ranjbar & Boostanipour, 2017).

The use of solar bubble dryers integrated with phase change materials (PCMs) has been proven to enhance drying efficiency, air temperature stability, and final product quality. PCM integration, commonly utilizing paraffin or organic substances such as OM49, serves as a latent heat storage medium that stabilizes the drying air temperature during operation. Numerous studies have demonstrated that the addition of PCMs can improve the thermal efficiency of drying systems by approximately 1.5–3% and shorten drying time by 20–30% compared to systems without PCM integration (Ajithkumar & Ganeshkumar, 2025; Murugesan *et al.*, 2024; Poonia, Singh & Jain, 2022). Organic PCM has been demonstrated to maintain stable drying temperatures in indirect solar dryers, resulting in dried sweet potatoes with superior nutrient retention compared to conventional drying methods (Ajithkumar & Ganeshkumar, 2025). Additionally, PCM systems are capable of storing thermal energy during daylight hours and releasing it during nighttime, thereby enabling extended dryer operation for an additional 5–6 hours after sunset while maintaining drying chamber temperatures approximately 6°C above ambient conditions (Poonia, Singh & Jain, 2022). Moreover, the presence of PCMs helps maintain lower drying air humidity and ensures more uniform heat distribution, thereby preserving key product quality attributes such as colour, texture, and nutritional content (Salama *et al.*, 2024).

Used cooking oil (UCO) is one type of domestic and industrial waste that is produced in large quantities, but improper management can cause environmental pollution, especially in water bodies and soil. The use of waste as raw material for thermal energy storage applications is a promising solution to reduce environmental impact while creating added value from materials that were previously considered useless. Used cooking oil (UCO) exhibits significant potential as an alternative PCM material for thermal energy storage systems. Research findings indicate that waste coconut cooking oil possesses thermal characteristics supportive of PCM functionality, with a latent heat of fusion of 97.7 kJ/kg and a thermal conductivity of approximately 0.155 W/m.K, values comparable to those of pure coconut oil (De Silos, Ocampo & Remarim, 2019). During repeated frying cycles, alterations in fatty acid composition occur, resulting in an increased concentration of methyl arachidate and methyl heptadecanoate, two

components that play a crucial role in enhancing phase stability and heat storage capacity (Irsyad *et al.*, 2023).

Overall, the integration of PCMs into solar bubble dryers offers an efficient and sustainable solution for drying agricultural products in tropical regions characterized by high variability in solar radiation. Based on previous research, the use of dish-shaped parabolic collectors, air circulation systems, and phase change materials (PCMs) in solar dryers has been shown to enhance both product performance and quality. However, most existing studies have focused on these modifications separately, with limited research addressing the integration of air circulation systems, PCMs, and dish-shaped parabolic solar collectors within a single system. Therefore, further application and development are required to optimize solar bubble drying technology. The study aimed to investigate the performance of phase change materials (PCMs) integrated into a parabolic solar dryer system to enhance thermal efficiency and drying performance during the drying process.

## 2 MATERIAL AND METHODS

### 2.1 Raw material

Fresh coffee cherries were sourced directly from farmers in Pagaralam, South Sumatra, Indonesia. The selected cherries were fully ripe, characterized by a bright red color, slightly soft texture, and dense feel. The sorted cherries underwent pretreatment by washing with clean water to remove dirt, dust, and residual soil adhering to the surface. Subsequently, the drying process was conducted using a solar bubble dryer integrated with phase change materials (PCMs), specifically paraffin (PRF) and used cooking oil (UCO).

### 2.2 Experimental setup and measuring tools

The mixed-mode solar dryer was designed and constructed at the Agricultural Assembly and Modernisation Centre in Kayu Agung City, South Sumatra Province, Indonesia. Figure 1 presents a photograph of the experimental setup. The system consists of four main components: a drying chamber, an air circulation system, a solar thermal receiver equipped with a parabolic solar collector, and a phase change material (PCM) unit for thermal energy storage. Table 1 summarises the specifications of each component. The parabolic dish solar collector was specifically designed to optimise solar energy utilisation through a centralised reflection system. The main structure of the collector is fabricated from 0.8 mm-thick stainless steel plates, shaped into a parabolic dish with a diameter of 2.4 m and a height of 0.5 m. Stainless steel was selected as the reflective surface material due to its high

reflectivity and cost efficiency. The heat receiver, a cylindrical component made from the same 0.8 mm stainless steel plate, is positioned at the focal point above the reflective surface. The geometry and placement of this receiver play a critical role in determining the overall thermal efficiency of the parabolic dish collector.

The Parabolic Solar Dryer is a tunnel-type closed solar drying system that utilises solar radiation as its primary heat source. The parabolic design concentrates solar radiation onto a thermal receiver that converts it into usable heat energy. This heat is continuously supplied to the drying chamber, ensuring that the coffee cherries are dried uniformly and hygienically. The system is equipped with Phase Change Materials (PCMs), specifically paraffin and used cooking oil, which function as latent heat storage media. The used cooking oil-based PCM was prepared by filtering 18.5 L of used cooking oil to remove impurities, followed by mixing with 10.5 kg of stearin and heating at 60–70°C under continuous stirring until a homogeneous. For the paraffin-based PCM, 10 kg of paraffin was placed into the PCM storage tank. The integration of PCMs helps stabilise the drying air temperature during periods of reduced solar intensity, such as cloudy weather or late afternoon conditions. The tunnel structure (bubble tunnel) is constructed from transparent plastic material, allowing direct transmission of solar radiation, while a blower-assisted forced convection mechanism enhances airflow and accelerates the drying process.

The distribution of environmental air temperature at various measurement points during the drying process is presented in Figure 2. The observations show that the temperature inside the drying tunnel was consistently higher than at other measurement points, with a temperature range of 31–40°C. The highest temperature in the drying tunnel was recorded at 13:30, at 40°C. Meanwhile, the environmental air temperature showed the lowest value among all measurement points, ranging from 28–35°C with the peak temperature occurring at 14:00–14:30. The temperatures at the inlet and outlet showed relatively similar patterns, ranging from 26–38°C and 27–38°C, respectively. In general, all measurement points showed an upward trend in temperature from morning to noon and a decline after 14:30. The temperature difference between the drying chamber and the ambient temperature indicates the effectiveness of the system in accumulating heat for the drying process.

In this study, data collection focused on measuring the temperature and moisture content of coffee cherries during the drying process. The experiment compared two types of phase change materials (PCMs), paraffin and used cooking oil, to evaluate their influence on thermal performance and drying efficiency. Various measuring instruments and sensor devices were installed at key points throughout the system. Nine type-K thermocouples were strategically placed at the air inlet, middle drying tunnel, and air outlet of the drying chamber to monitor temperature distribution and temporal fluctuations.

**Table 1:** Specifications of the component material for the parabolic solar dryer.

| No | Units               | Details/Specification                                                                                                                                                                                                    |
|----|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1  | Drying tunnel       | Dimension (L x W x H) = 3.5 x 1.5 x 0.75 m<br>Bottom layer = Polyvinyl chloride film (PVC, 520 µm)<br>Cover layer = UV-Low density polyethylene film (LDPE)<br>3 Outlet holes (D) = 0.25 m<br>2 Inlet holes (D) = 0.33 m |
| 2  | Axial blower        | Fan motor = 220 V, 40.5 W                                                                                                                                                                                                |
| 3  | Solar panel         | Polly, 100 W, 12V/24V                                                                                                                                                                                                    |
| 4  | Parabolic collector | Dimension (D x H) = 2.4 x 0.5 m<br>Solar thermal receiver (D x H) = 0.4 x 0.1 m stainless steel<br>Absorber = stainless steel                                                                                            |
| 5  | PCM tank            | Dimension (D x H) = 0.4 x 0.6 m<br>Frame covered = stainless steel<br>60 tubes aluminum, diameter 31.75 mm                                                                                                               |
| 6  | Pump                | Power = 60 W, 12 V<br>Flowrate = 1.5L/min                                                                                                                                                                                |
| 7  | Battery             | 12 V, 100 AH                                                                                                                                                                                                             |
| 8  | Thermocouple        | type-K<br>Max measurement -200°C – 1372°C                                                                                                                                                                                |



**Figure 1:** Photographs of the experimental parabolic solar dryer facility showing (a) the back view, (b) the interior, (c) the right-side view, and (d) the dried coffee cherries.

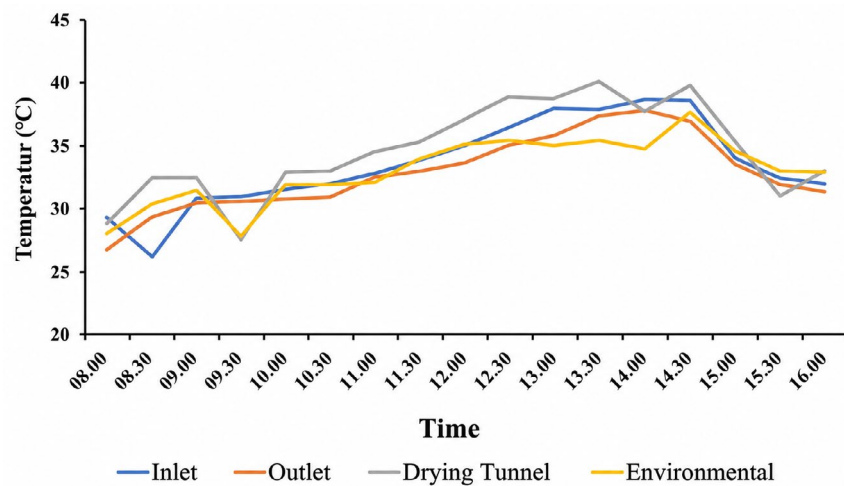


**Figure 2:** Environmental Air Temperature Conditions at Various Locations.

### 2.3 Temperature (TEM)

A total of 50 kg of coffee cherries were used as the test material and evenly spread on the drying floor with a thickness of 2–3 cm. To monitor temperature distribution and fluctuations during the drying process, nine type-K thermocouples were installed at specific measurement points, including the air inlet

duct, air outlet duct, and the center of the coffee cherry layer. Temperature data were recorded at 60-minute intervals from 09:00 to 16:00 WIB each day until the moisture content of the coffee beans reached a minimum value of 12.5% (%wb). The recorded temperature values represent the average of the readings obtained from the nine type-K thermocouples.

## 2.4 Moisture Content (MC)

The moisture content of the coffee cherries was determined based on the weight loss after oven-drying at 105°C for 16 hours, following the Indonesian National Standard (BSN, 2008; Suherman et al., 2025; Yusibani et al., 2022). The moisture content ( $MC$ ) was calculated using Equation 1:

$$MC = \frac{W_w - W_d}{W_w} \times 100 \quad (1)$$

where  $MC$  is the moisture content of coffee cherries on a wet basis (% wb);  $W_w$  is the initial weight of the coffee cherries before drying (g); and  $W_d$  is the final weight of the coffee cherries after drying (g).

## 2.5 Principal component analysis (PCA)

Principal Component Analysis (PCA) was conducted to evaluate the correlations and identify patterns of relationships among the dependent variables measured across all treatments using multivariate statistical techniques (Saputra et al., 2025). This analysis was carried out based on a correlation matrix constructed from 32 observation samples, consisting of 8 time points in each treatment with 5 measured variables, using RStudio software version 2025. The main objective of applying PCA in this study was to reduce complex data dimensions into a number of simpler principal components without losing significant information from the original data. In addition, this analysis was also used to identify the most significant variables in explaining the observed variations and to visualise sample clustering based on similar characteristics. The PCA results are presented in the form of scatter plots and biplots that describe the distribution of samples and the relative contribution of each variable to the first (PC1) and second (PC2) principal components.

## 2.6 Data analysis

The data were analysed using descriptive statistical methods with GraphPad Prism 10 software, while principal component analysis (PCA) was performed using RStudio version 2025.

# 3 RESULTS

## 3.1 Temperature of drying tunnel conditions

Figures 3 (A) and (B) show the temperature variations in the drying tunnel for three system configurations: without PCM (CLL.TEM), with used cooking oil PCM (UCO.TEM), and with paraffin PCM (PRF.TEM). The temperature in the drying chamber without PCM ranged from 25.31 to 40.48°C, with the maximum value occurring at 13:00. In contrast, the system using used cooking oil PCM achieved higher and

more stable temperatures, ranging from 34.93 to 43.43°C, with the peak temperature observed at 14:00. Meanwhile, the system integrated with paraffin PCM maintained temperatures between 31.32 and 38.31°C, also reaching its maximum at 14:00. These results indicate that both PCM types improved thermal stability compared to the control system, with used cooking oil showing slightly superior thermal performance in sustaining higher drying temperatures.

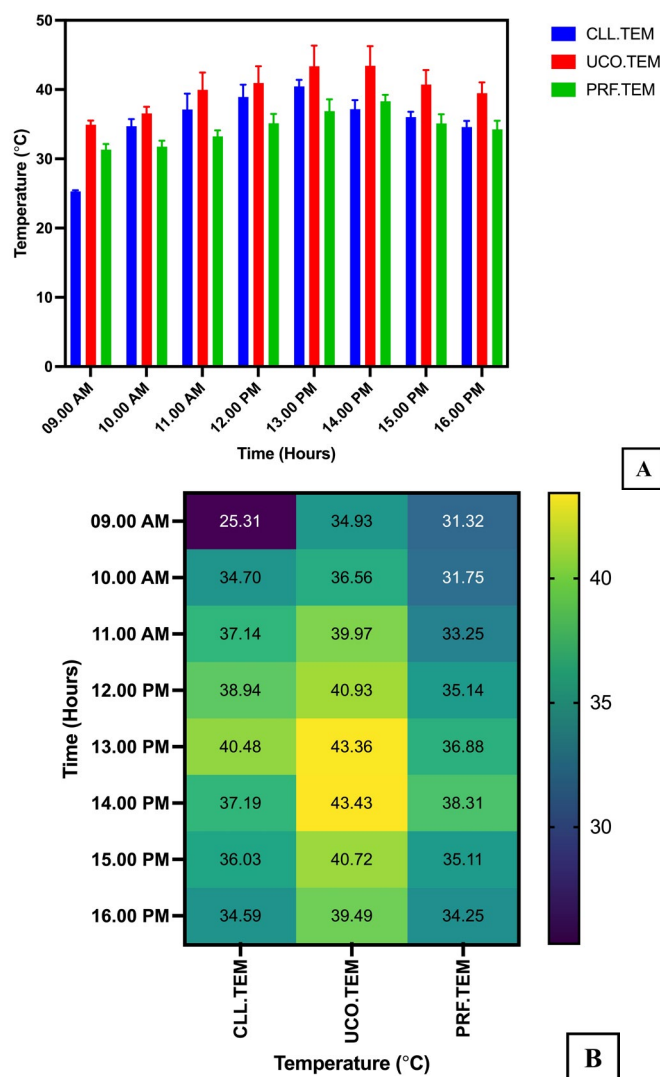


**Figure 3:** Variation of average air temperature for different phase change materials (PCMs) integrated with parabolic solar drying: (A) bar chart and (B) heatmap.

The values represent mean  $\pm$  standard deviation ( $n = 4$ ). CLL.TEM – collector temperature (without PCM); UCO.TEM – used cooking oil temperature; PRF.TEM – paraffin temperature.

## 3.2 Moisture content of cherry coffee

Figures 4 (A) and (B) illustrate the changes in moisture content of coffee cherries during a five-day drying process using used cooking oil PCM (UCO.MC) and paraffin PCM

(PRF.MC). Overall, the moisture content decreased gradually from the first to the fifth day in line with the increase in drying duration and drying chamber temperature. On the first day, the average moisture content remained relatively high, ranging from **28.83% (wb) to 32.03% (wb)**, but it declined significantly to **11.23–12.17% (wb)** by the fifth day. The moisture content of the coffee cherries has met the SNI 01-2907-2008 quality standard, which specifies a maximum moisture content of 12.5%, with the used cooking oil PCM treatment producing the lowest final moisture content of 11.23% (wb). A faster reduction in moisture content was observed in the system utilising used cooking oil PCM compared to paraffin PCM. This finding indicates that the used cooking oil PCM was more effective in maintaining higher and more stable drying temperatures, as previously shown in the temperature profile data, thereby enhancing the rate of water evaporation and improving overall drying efficiency.

### 3.3 Principal component analysis

The results of the principal component analysis (PCA) presented in Tables 2 and 3 indicate that the two principal components (PC1 and PC2) together explain 82.00% of the total variance in the dataset, with PC1 and PC2 accounting for 52.58% and 29.42%, respectively. This finding suggests that most of the variability in the integrated parabolic solar dryer system with phase change materials (PCMs) can be effectively described by these two components (Saputra et al., 2024). Based on the eigenvector loadings, PC1 exhibits strong positive correlations with the drying tunnel temperatures of all systems, namely the control (CLL.TEM = 0.538), the used cooking oil PCM (UCO.TEM = 0.527), and the paraffin PCM (PRF.TEM = 0.567). Accordingly, PC1 primarily represents the thermal performance of the drying system. In contrast, PC2 is mainly associated with the moisture content of cherry coffee, showing a strong positive loading for the paraffin PCM system (PRF.MC = 0.736) and a negative loading for the used cooking oil PCM system (UCO.MC = -0.600).

The PCA score plot in Figure 5 (A) demonstrates that the data points at each observation time (09:00–16:00) form distinct clusters that gradually shift from left to right along PC1, indicating progressive changes in the thermal and humidity characteristics during the drying period. Furthermore, the biplot in Figure 5 (B) shows that the UCO.TEM and UCO.MC variables are closely aligned with long vector directions, signifying a strong negative correlation between drying temperature and moisture content in systems employing used cooking oil PCM. This suggests that the enhanced heat storage and release capacity of used cooking oil PCM contributes to a more effective reduction in moisture content. Conversely, the PRF.TEM and PRF.MC variables display divergent orientations with relatively shorter vector lengths, implying a weaker relationship between temperature and moisture

reduction in systems using paraffin PCM. Additionally, the CLL.TEM variable (without PCM) is positioned near the origin of the axes, indicating that it contributes moderately to the overall variance of the dataset.

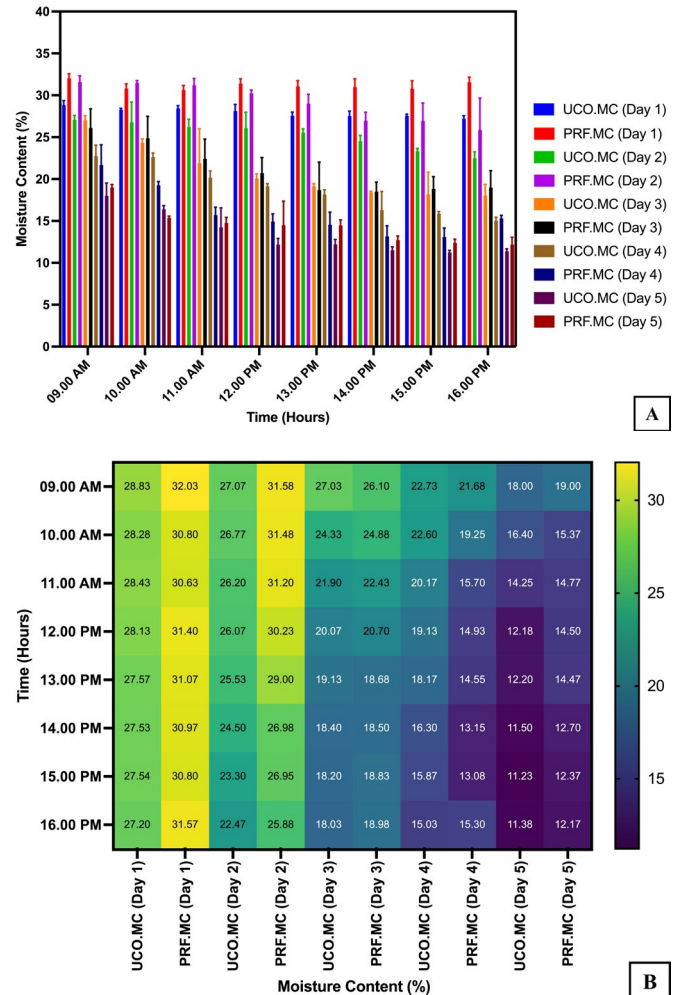


**Figure 4:** Variation of moisture content for different phase change materials (PCMs) integrated with parabolic solar drying, (A) bar chart and (B) heatmap.

The values represent mean  $\pm$  standard deviation ( $n = 4$ ). UCO.TEM – used cooking oil moisture content; PRF.TEM – paraffin moisture content.

**Table 2:** Eigenvalue, percentage, and cumulative variation of different phase change materials (PCMs) integrated with parabolic solar drying.

|     | Eigenvalue | Percentage of Variance (%) | Cumulative (%) |
|-----|------------|----------------------------|----------------|
| PC1 | 2.628      | 52.58                      | 52.58          |
| PC2 | 1.471      | 29.42                      | 82.00          |
| PC3 | 0.447      | 8.95                       | 90.95          |
| PC4 | 0.343      | 6.86                       | 97.81          |
| PC5 | 0.109      | 2.19                       | 100.00         |

**Table 3:** Eigenvectors of different phase change materials (PCMs) integrated with parabolic solar drying

|                                            | PC1    | PC2    |
|--------------------------------------------|--------|--------|
| Collector temperature (CLL.TEM)            | 0.538  | 0.040  |
| Used cooking oil temperature (UCO.TEM)     | 0.527  | 0.293  |
| Paraffin temperature (PRF.TEM)             | 0.567  | 0.098  |
| Used cooking oil moisture content (UCO.MC) | 0.327  | -0.600 |
| Paraffin temperature (PRF.MC)              | -0.040 | 0.736  |

## 4 DISCUSSION

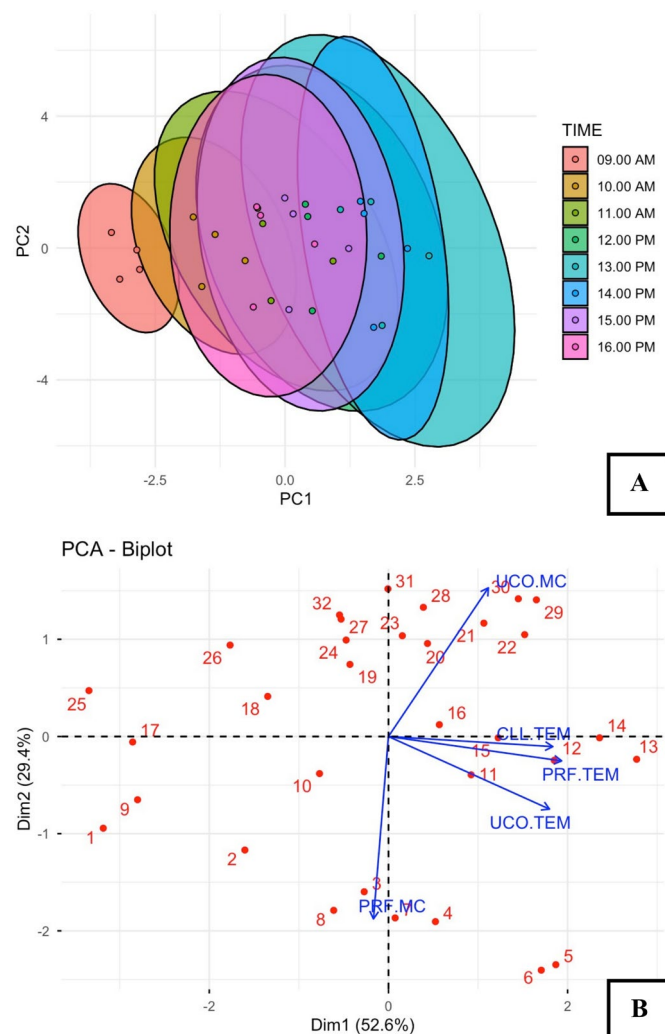
### 4.1 Temperature

The integration of Phase Change Materials (PCMs) into parabolic solar dryer systems has been shown to significantly enhance thermal performance and drying efficiency in coffee processing. PCMs function as latent heat storage media, absorbing excess heat during periods of high solar radiation and gradually releasing it when the heat intensity decreases. This thermal buffering mechanism helps maintain a more stable drying temperature, thereby accelerating the drying rate and preserving the physical and chemical quality of the coffee (Maryana et al., 2023; Moradi et al., 2025; Prasad et al., 2025). The results of this study demonstrate that incorporating PCMs into parabolic solar dryers provides substantial thermal advantages, as evidenced by the improved temperature stability within the drying tunnel compared to systems operating without PCMs. These results are consistent with previous studies, which reported that during the coffee bean drying process using an integrated Phase Change Material (PCM) system, the drying air temperature remained more stable throughout the day, particularly during the afternoon when solar radiation intensity typically declines (Deshmukh & Kherde, 2025; Senthil et al., 2021; Suherman et al., 2025).

The used cooking oil-based PCM (UCO.TEM) exhibited a higher and more stable temperature profile in the drying chamber compared to other treatments, maintaining a temperature range of 34.93–43.43°C. This range is considered optimal for preserving the physical and chemical quality of coffee beans during the drying process. The stable thermal conditions achieved through the use of used cooking oil PCM contributed to an increased drying rate and a notable reduction in total drying time (Mondragon et al., 2023). Although paraffin-based PCM is widely recognized as an effective heat storage material, the use of used cooking oil offers a more sustainable and economically viable alternative, with thermophysical properties well suited to the temperature range required for efficient coffee drying. Furthermore, the integration of used cooking oil PCM effectively minimized thermal fluctuations in the drying chamber, thereby helping to maintain product quality and consistency in the final dried coffee beans (Bhandari et al., 2025; Maryana et al., 2025).

### 4.2 Moisture content

The used cooking oil-based PCM demonstrated superior performance in maintaining a more consistent drying

**Figure 5:** PCA of different phase change materials (PCMs) integrated with parabolic solar drying, (A) scatter plot and (B) biplot.

CLL.TEM – collector temperature (without PCM); UCO.TEM – used cooking oil temperature; PRF.TEM – paraffin temperature; UCO.TEM – used cooking oil moisture content; PRF.TEM – paraffin moisture content.

temperature, reducing thermal fluctuations, and preserving the quality of coffee cherries compared to both the system without PCM and the system using paraffin-based PCM (Majeed, Faraj & Hussien, 2024; Ouauouja *et al.*, 2025). The used cooking oil PCM was also able to sustain a higher drying temperature than paraffin PCM, resulting in a more efficient water evaporation process from the coffee cherries. Measurements indicated that the final moisture content of coffee dried with paraffin PCM was slightly higher, suggesting a slower drying rate compared to the used cooking oil PCM, although still faster than the system without PCM (Murugesan *et al.*, 2024). Research by Radhakrishnan *et al.* (2024) on mango pulp drying shows that a combination of sensible and latent heat storage (lauric acid PCM) significantly increases the drying rate to 0.76 kg of moisture per hour with a maximum drying efficiency of 14.2%, and reduces drying time by 70.5% compared to open-air drying. Overall, the integration of PCM in the solar drying tunnel system proved effective in accelerating the reduction of cherry coffee moisture content, with used cooking oil-based PCM exhibiting superior thermal stability and drying performance relative to paraffin-based PCM (Maryana *et al.*, 2025; Sharma *et al.*, 2024).

### 4.3 PCA

The temperature variable vectors (CLL.TEM, UCO.TEM, and PRF.TEM) are located close to each other in the positive quadrant of PC1 with relatively small angles between them. Based on the principles of biplot interpretation, small angles between vectors indicate strong positive correlations between the variables (Yan & Rajcan, 2002). This shows that the three PCM treatments have similar temperature response patterns to environmental conditions, albeit with different magnitudes. This finding is in line with the results of a study by Tyagi *et al.* (2024), which reported that the integration of PCM in solar drying systems can stabilise temperature fluctuations and improve the thermal efficiency of the system. Another interesting aspect can be seen in the position of the moisture content vectors. The UCO.MC vector was in the positive quadrant of PC1 and PC2, while the PRF.MC vector was in the negative quadrant of PC2. The difference in the position of these two vectors indicates that the two types of PCM have different drying characteristics. UCO-based PCM shows a stronger positive correlation with the temperature variable than paraffin PCM, implying higher effectiveness in the moisture removal process. These results are consistent with the research by Manikandan, Devarajan and Vickram (2025), which states that used cooking oil PCM can increase thermal efficiency by 20–25% compared to conventional systems.

The biplot's vector lengths also show how much each variable contributes to data variability. The UCO.MC variable has a relatively long vector, indicating a significant contribution to the variation in PC1 and PC2. Conversely,

the shorter PRF.MC vector indicates a lower contribution to both principal components. According to Abdi and Williams (2010), the length of the vector in the PCA biplot reflects how well the variable is represented in the reduced dimension space. The strong positive correlation between the temperature variable and UCO.MC in the same quadrant indicates that the increase in temperature in the PCM waste oil treatment effectively contributes to a decrease in the water content of the product. This can be explained by the thermal properties of waste oil, which, when combined with stearin, produces PCM with optimal latent heat storage capacity for drying applications in the 60–70°C temperature range (Sharma *et al.*, 2024). Furthermore, Goyal and Muthusamy (2023), in their comprehensive review, emphasize that selecting a PCM with a melting point that matches the operational temperature range of the drying system is a critical factor in optimizing the performance of solar dryers.

Based on the PCA analysis results, it was found that the drying system using used cooking oil PCM contributed the most to the overall data variability, particularly in the first principal component (PC1). This finding indicates that the used cooking oil PCM had the most dominant influence on increasing the drying chamber temperature and accelerating the reduction of coffee bean moisture content. This superior performance reflects the material's strong thermal storage and release capability, which effectively stabilizes heat transfer during drying. In contrast, the systems using paraffin-based PCM or without PCM exhibited a weaker correlation between temperature and moisture content, suggesting less efficient thermal regulation and drying performance. These findings have important implications for the development of sustainable and environmentally friendly solar drying systems, given that used cooking oil is an abundant and low-cost waste material. The results of this study are in line with the concept of circular economy, which emphasises the reuse of waste materials for thermal energy storage applications (Manikandan, Devarajan & Vickram, 2025).

## 5 CONCLUSIONS

This study demonstrated that integrating phase change materials (PCMs) into a parabolic solar dryer improved coffee cherry drying performance. The used cooking oil-based PCM produced higher and more stable temperatures, resulting in the lowest final moisture content, while paraffin PCM also enhanced drying temperatures compared to the system without PCM. PCA confirmed that used cooking oil PCM had the strongest effect on increasing drying chamber temperature and accelerating moisture reduction, indicating its potential as an effective and low-cost thermal energy storage material.

## 6 ACKNOWLEDGEMENTS

The authors thank the reviewers who are willing to participate in this study. This research was funded by the Ministry of Research and Higher Education, Republic of Indonesia, under the research grant Penelitian Disertasi Doktor (PDD) with contract number 090/E5/PG.02.00.PL/2024.

## 7 AUTHOR CONTRIBUTIONS

Conceptual Idea: Saputra, D.; Maryana, Y.E.; Priyanto, G.; Yuliati, K.; Saputra, A.; Methodology design: Saputra, D.; Maryana, Y.E.; Data collection: Maryana, Y.E.; Saputra, D.; Data analysis and interpretation: Maryana, Y.E.; Saputra, A.; and Writing and editing: Maryana, Y.E.; Saputra, A.; Saputra, D.; Priyanto, G.; Yuliati, K.;

## 8 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

## 9 REFERENCES

- Abdi, H., & Williams, L. J. (2010). Principal component analysis. *Wiley Interdisciplinary Reviews: Computational Statistics*, 2:433-459.
- Acar, C., Dincer, I., & Mujumdar, A. (2022). A comprehensive review of recent advances in renewable-based drying technologies for a sustainable future. *Drying Technology*, 40(6):1029-1050.
- Ajithkumar, A., & Ganeshkumar, P. (2025). Impact of organic PCM on drying kinetics and nutritional quality of sweet potato in indirect solar dryer. *Journal of Energy Storage*, 132:117716.
- Aktar, S. et al. (2022). Solar bubble dryer: Alternative to sun drying for reducing drying losses in Bangladesh. *Bangladesh Journal of Agriculture*, 47(1):1-15.
- Al-Ghamdi, S. et al. (2024). Advancements in coffee manufacturing: From dehydration techniques to quality control. *Food Engineering Reviews*, 16(4):513-539.
- Badan Standar Nasional. (2008). *Standar Nasional Indonesia Biji Kopi SNI 01-2907-2008*.
- Baniasadi, E., Ranjbar, S., & Boostanipour, O. (2017). Experimental investigation of the performance of a mixed-mode solar dryer with thermal energy storage. *Renewable Energy*, 112:143-150.
- Bhandari, P. et al. (2025). Thermo-physical properties evaluation of commercially available phase change material and engine oil. *Case Studies in Thermal Engineering*, 72:106357.
- Chiewchan, N., Mujumdar, A. S., & Devahastin, S. (2015). Application of drying technology to control aflatoxins in foods and feeds: a review. *Drying Technology*, 33(14):1700-1707.
- De Silos, P. Y. L., Ocampo, A. A., & Remarim, A. M. E. (2019). Thermal energy storage using phase change material derived from waste cooking oil: A case study. *International Journal of Technology and Engineering Studies*, 5(4):129-138.
- Deshmukh, A. V., & Kherde, S. M. (2025). Enhancing energy storage and drying efficiency in a cabinet solar dryer using nano-enhanced PCM with FMWCNT. *Journal of Renewable Energies*, 24:25-35.
- Ghosh, P., & Venkatachalapathy, N. (2014). Processing and drying of coffee – a review. *International Journal of Engineering Research & Technology*, 3(12):784-794.
- Goyal, R. K., & Muthusamy, E. (2023). Thermo-physical properties of heat storage material required for effective heat storage and heat transfer enhancement techniques for the solar cooking applications. *Sustainable Energy Technologies and Assessments*, 56:1-17.
- Irsyad, M. et al. (2023). Experimental study of the thermal properties of waste cooking oil applied as thermal energy storage. *Results in Engineering*, 18:10108.
- Jyoti, Y. K. et al. (2023). Enhancement of thermal and techno-economic performance and prediction of drying kinetics of paddy dried in solar bubble dryer. *Energy Nexus*, 11:100224.
- Kebede, A. Y. et al. (2025). Performance evaluation of diminutive solar dryer for drying of green coffee beans: In Ethiopian highlands. *Case Studies in Thermal Engineering*, 65:105653.
- López-Parra, M. B. et al. (2024). The impact of the drying process on the antioxidant and anti-inflammatory potential of dried ripe coffee cherry pulp soluble powder. *Foods*, 13:1114.
- Majeed, A. H., Faraj, J. J., & Hussien, F. M. (2024). Enhancing solar drying efficiency through indirect solar dryers integrated with phase change materials. *International Journal of Heat and Technology*, 42(1):121-131.
- Manikandan, S., Devarajan, Y., & Vickram, S. (2025). Advancing thermal energy storage with industrial and agricultural waste-derived phase change materials: A path towards sustainable energy systems. *Process Safety and Environmental Protection*, 198:107068.

- Maryana, Y. E. et al. (2023). A review of the inflated solar dryer for improving the quality of agricultural product. *IOP Conference Series: Earth and Environmental Science*, 1160:12075. 2023.
- Maryana, Y. E. et al. (2025). Performance evaluation of an inflated solar dryer integrated with phase change materials for enhanced drying of cherry coffee. *International Journal of Design and Nature and Ecodynamics*, 20(1):179-186.
- Mehta, P. et al. (2022). Performance improvement and advancement studies of mixed-mode solar thermal dryers: A review. *Environmental Science and Pollution Research*, 29(42):62822-62838.
- Mondragon, R. A. et al. (2023). Spent coffee grounds biochar composite phase change material design challenges in a lab-scale solar water heater system for thermal energy storage. *ASEAN Journal of Chemical Engineering*, 23(1):77-93.
- Moradi, M. et al. (2025). Optimizing solar drying efficiency: effects of PCM and IR on energy and exergy performance. *PLOS ONE*, 20(6):e0325042.
- Murugesan, G. K. et al. (2024). Experimental investigation on a solar dryer assisted with minimum phase change material (PCM) placed on the inner walls of drying chamber. *Journal of Energy Storage*, 98:113069.
- Ngure, G. M., & Watanabe, K. N. (2024). Coffee sustainability: Leveraging collaborative breeding for variety improvement. *Frontiers in Sustainable Food Systems*, 8:1431849.
- Ouaouja, Z. et al. (2025). Phase change materials for cold thermal energy storage applications: a critical review of conventional materials and the potential of bio-based alternatives. *Journal of Energy Storage*, 110:115339.
- Poonia, S., Singh, A. K., & Jain, D. (2022). Performance evaluation of phase change material (PCM) based hybrid photovoltaic/thermal solar dryer for drying arid fruits. *Materials Today: Proceedings*, 52:1302-1308.
- Prasad, P. D. et al. (2025). Enhancing solar dryer performance with phase change material. *International Journal of Research Publication and Reviews*, 6:2654-2666.
- Radhakrishnan, G. G. et al. (2024). Phase-change material-based solar dryer: An experimental investigation for drying mango pulp. *Solar Energy*, 277:1-7.
- Salama, R. S. et al. (2024). Integrated solar dryer and distillation system with PCM and injection, powered by PVT panels and solar concentrator. *Scientific Reports*, 14:22036.
- Sanz-Urbe, J. R. et al. (2017). Postharvest processing – revealing the green bean. In Folmer, B. (Ed.). *The Craft and Science of Coffee*. London, England: Academic Press, p.51–79.
- Saputra, A. et al. (2025). Spectroscopic and chemometric characterization of storage-induced changes in Pempek Palembang using FT-IR and PCA. *International Journal of Design & Nature and Ecodynamics*, 20(6):1323-1332.
- Saputra, A. et al. (2024). Identifikasi asam amino pembentuk tekstur dan viskositas daging ikan belida (*Chitala lopis*), Ikan Patin (*Pangasius pangasius*), dan Ikan Gabus (*Channa striata*). *Samakia : Jurnal Ilmu Perikanan*, 15(1):121-130.
- Senthil, R. et al. (2021). Experimental study on solar heat battery using phase change materials for parabolic dish collectors. *International Journal of Renewable Energy Development*, 10(4):819-825.
- Sharma, A. et al. (2024). A comprehensive review of critical analysis of biodegradable waste PCM for thermal energy storage systems using machine learning and deep learning to predict dynamic behavior. *Heliyon*, 10(3):e25800.
- Suherman, S. et al. (2025). Investigation of a mixed-mode solar dryer assisted with an air recycling system and phase change material unit for coffee beans drying: An experimental study. *Renewable Energy*, 254:123762.
- Statistics Indonesia. (2024). *Indonesian coffee statistics 2023*.
- Tyagi, V. V. et al. (2024). Sustainable growth of solar drying technologies: Advancing the use of thermal energy storage for domestic and industrial applications. *Journal of Energy Storage*, 99:113320.
- Yan, W., & Rajcan, I. (2002). Biplot analysis of test sites and trait relations of soybean in Ontario. *Crop Science*, 42(1):11-20.
- Yusibani, E. et al. (2022). Physical properties of Sidikalang robusta coffee beans medium roasted from various colors of coffee cherries. *Journal of Physics: Conference Series*, 2243:012046.