American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-15, Issue-8, pp-01-07
www.ajer.org
Research Paper Open Access

Drying Analysis with Phase Change Material (PCM) for Agro and Marine Industry

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ABSTRACT: *Solar drying is a promising environmentally friendly post-harvest technology; however, temperature fluctuations caused by dependence on solar radiation remain a major limitation. This study investigates the improvement of thermal performance in an indirect solar dryer through the integration of Phase Change Material (PCM) as a latent heat storage medium. Experimental tests were conducted on moringa leaves and skipjack tuna meat by comparing drying systems with and without PCM. Temperature profiles in the drying chamber were monitored at several measurement points (T2, T3, and T4) throughout the drying period. The results show that the system without PCM experienced significant temperature fluctuations, while the incorporation of PCM effectively reduced temperature variation and improved heat distribution uniformity. In the drying of skipjack tuna meat, the PCM-assisted system achieved peak temperatures above 90 °C and exhibited a slower temperature decrease after peak solar radiation. These findings confirm that PCM acts as an effective thermal buffer, enhancing thermal stability and drying continuity, thereby improving the performance of solar drying systems and the potential quality of dried products.*
KEYWORDS: *Solar Drying, Phase Change Material, Temperature Stability, Moringa Leaves, Skipjack Tuna.*

Date of Submission: 25-07-2026 Date of acceptance: 06-08-2026

I. INTRODUCTION

Drying is a crucial step in post-harvest processing of agricultural and fishery products to reduce moisture content to safe storage levels[1]. The use of solar dryers offers advantages in terms of sustainability and energy efficiency, but their performance is still limited by direct dependence on solar radiation intensity[2]. This radiation variability causes temperature fluctuations in the drying chamber, which impacts the inconsistency of the drying rate and potentially reduces product quality. This condition is a major challenge in developing solar dryers that can operate stably and produce products with uniform quality[3].

In an effort to overcome the problem of temperature fluctuations, various studies had integrated Phase Change Materials (PCMs) into solar drying systems[4]. PCMs have the ability to absorb latent heat when the temperature increases and release it again when the temperature decreases, thus potentially increasing the thermal stability of the drying system[5]. Several studies had reported that the use of PCMs can reduce temperature fluctuations, extend the effective drying duration, and increase the efficiency of solar energy utilization[6]. However, most previous studies are still limited to one type of material or only evaluate the thermal performance in general, without conducting direct comparisons on materials with different physical characteristics.

Experimental studies directly comparing the performance of indirect solar dryers with and without PCM on both plant and animal materials simultaneously are still relatively limited[7]. Moringa leaves are herbal ingredients that are sensitive to temperature fluctuations, while tuna meat has a high water content and protein content that is greatly influenced by temperature stability during drying[8]. These differences in characteristics require a more comprehensive evaluation approach to the performance of the drying system. Therefore, this study has novelty in the comparative experimental analysis of the performance of indirect solar dryers with and without PCM on two types of materials with different characteristics, with a focus on temperature profiles, thermal stability, uniformity of heat distribution, and the role of PCM as a thermal buffer in improving the continuity of the drying process.

II. EXPERIMENTS

II.1 Dryer Design

The drying device used in experiment is an indirect solar dryer consisting of a solar collector, a multi-level drying chamber, and a PCM-based heat storage unit. The PCM is placed in the hot air flow path to maximize the absorption and release of latent heat[9].

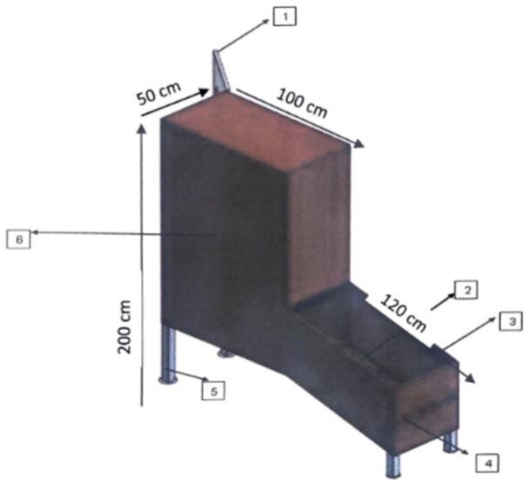

Fig. 1. Research tool design

Caption:

1. Drying room access door
2. Drying air input
3. Solar collector input
4. Dryer stand
5. Phase Change Material (PCM) Capsules
6. Drying room walls

Figure 2 below shows the geometric design of the dryer simulation used in the Computational Fluid Dynamics (CFD)-based numerical analysis using ANSYS software. This geometric model represents the main configuration of the dryer which includes the air inlet, drying chamber, and the arrangement of drying racks inside the drying chamber. The geometric design is made in two dimensions (2D) as an approach to analyze the distribution of air flow and temperature inside the dryer efficiently. This geometry will be used as the basis for the dryer manufacturing process.

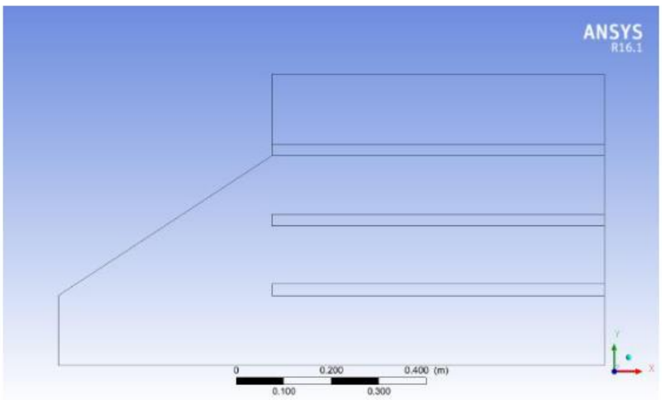

Fig. 2. Simulation design of dryer[9]

II.1.1 Research tools

The tools used in this study consist of the main device for the drying process, measurement instruments, and supporting devices for data analysis and numerical simulation. The main device includes an indirect solar dryer designed with a multi-level drying chamber and equipped with a solar collector as a heat source. For research with heat storage, the drying system is equipped with Phase Change Material (PCM) which functions as a latent heat storage medium, Table 1 below provides a description.

Table. 1. List of research tools along with their main specifications and functions

No.	Tool Name	Main Specifications	Function
1	Infrared thermometer	Range 0–200 °C, non-contact	Measuring the surface temperature of the test material and drying equipment components
2	Pyranometer	Range 0–2000 W/m²	Measuring the intensity of solar radiation received by the solar collector
3	Meter	Length ±5 m	Measuring the dimensions of the dryer
4	Anemometer	Range ±0–30 m/s	Measuring air flow velocity
5	Electric drill	Portable drill	Assist in assembling the dryer
6	Saw	Handsaw	Cutting the tool frame material
7	Grinder	Hand electric grinder	Tidying and cutting components
8	Hammer	Hand hammer	Assist in assembling the tool frame

II.1.2 Research materials

The materials used in this study consist of primary test materials and supporting materials. The primary test materials include moringa leaves and tuna meat which are used as drying objects to represent plant and animal materials with different physical characteristics. In addition, this study will use Phase Change Material (PCM) as a latent heat storage medium to increase the temperature stability of the drying system. Other supporting materials include dryer construction materials, such as metal plates, solar collector cover glass, and thermal insulators, which are used in the assembly and operation of the solar dryer.

II.2 Testing Procedures

Testing was conducted under two operating conditions: without PCM and with PCM. Each test was conducted once for each drying rack, with measurement intervals from 9:00 AM to 3:00 PM. Temperatures were measured at points T2, T3, and T4 using a digital temperature measuring instrument.

II.3 Analysis Parameters

The main parameters will be analyzed are the temperature profile, temperature fluctuations over time, and the uniformity of temperature distribution between drying racks. The research method in this study was designed to produce a quantitative, systematic, and replicable analysis in evaluating the performance of a solar dryer. The approach will be used is an experimental data analysis to obtain a comprehensive picture of the thermal behavior and drying characteristics in the drying chamber. Furthermore, a comprehensive literature review was conducted to strengthen the theoretical basis, ensure methodological consistency, and position this research within the context of the development of latent heat storage-based solar dryer technology.

III. RESULTS AND DISCUSSIONS

III.1 Characteristics of Drying Moringa Leaves

The results of the drying temperature test for moringa leaves without the use of PCM presented in Table 2 and Figure 3 show that the temperature of the drying room experiences quite significant fluctuations on each drying rack (T2, T3, and T4).

Table. 2. Results of temperature measurements on the solar collector and drying chamber operated without using Phase Change Material (PCM)

Time	Drying Room Temperature		
	T2	T3	T4
09.00 – 10.00	24,3	23,9	22,7
10.00 – 11.00	24,6	18,9	31,7
11.00 – 12 00	15,8	17,2	22,1
12.00 – 13.00	12,7	15,5	22,0
13.00 –14.00	19,5	24,9	30,5
14.00 – 15.00	12,7	26,2	25,0

Temperatures fluctuated with solar radiation intensity, with relatively large temperature differences between racks during the midday and evening periods. This condition indicates uneven heat distribution and poor thermal stability in the drying system without PCM, potentially leading to differences in the drying rate of moringa leaves between racks.

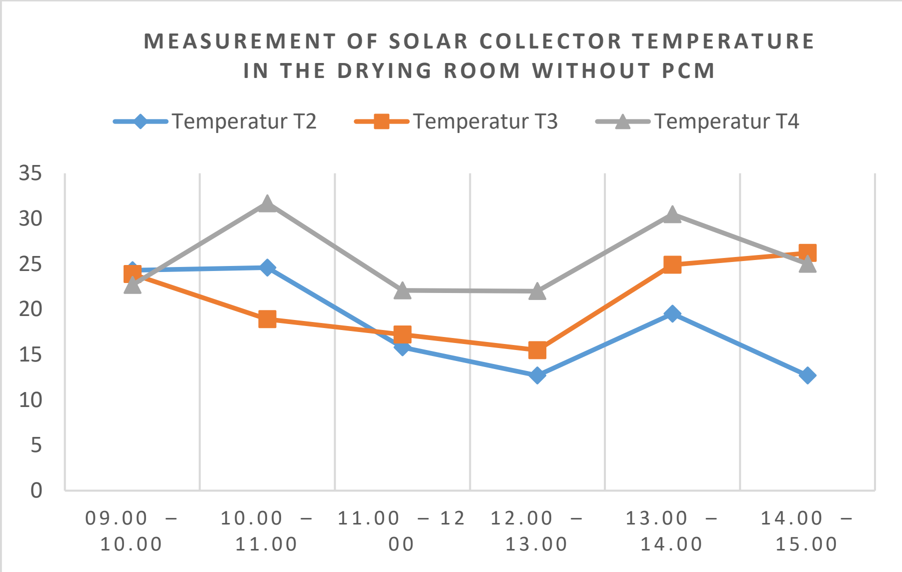

Fig. 3. Temperature of solar collector and drying room for drying moringa leaves without Phase Change Material (PCM)

The use of PCM in drying moringa leaves, as shown in Table 3 and Figure 4, produced a more stable and uniform temperature profile.

Table. 3. Distribution of temperature of solar collector and drying chamber in the process of drying moringa leaves with Phase Change Material (PCM)

Time	Drying Room Temperature		
	T2	T3	T4
09.00 – 10.00	28,0	25,6	29,5
10.00 – 11.00	24,3	22,6	24,8
11.00 – 12 00	18,5	19,8	33,8
12.00 – 13.00	18,5	18,8	21,2
13.00 –14.00	31,3	34,4	35,9
14.00 – 15.00	23,3	33,1	25,7

Temperature fluctuations between time intervals and between shelves were significantly reduced. Quantitatively, the temperature difference between T2, T3, and T4 in the system with PCM was smaller than in the system without PCM. This indicates that PCM functions effectively as a thermal buffer, absorbing heat when the temperature rises and releasing it when solar radiation decreases, thus maintaining the continuity of the drying process.

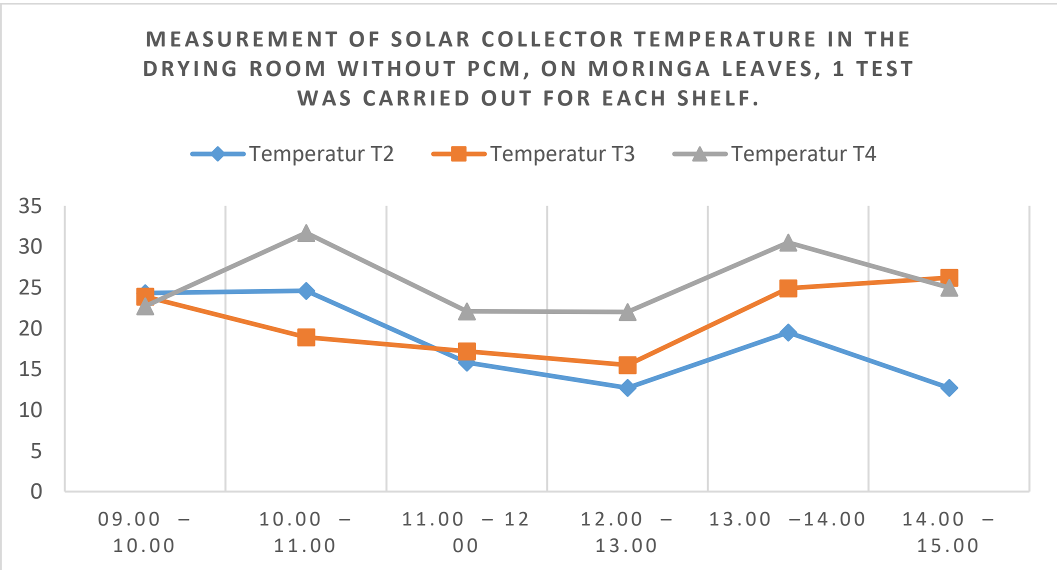

Fig. 4. Temperature of solar collector and drying chamber in the process of drying Moringa leaves using Phase Change Material (PCM)

III.2 Characteristics of Fish Meat Drying

When drying tuna meat without PCM, the temperature measurement results presented in Table 4 and Figure 5 show quite sharp temperature fluctuations with temperatures ranging between 39–58 °C.

Table. 4. Temperature of solar collector and drying chamber for drying tuna meat without PCM

Time	Drying Room Temperature		
	T2	T3	T4
09.00 – 10.00	39,4	44,8	47,1
10.00 – 11.00	47,1	53,2	52,1
11.00 – 12 00	57,6	52,2	53,9
12.00 – 13.00	56,9	58,2	55,2
13.00 –14.00	52,5	54,2	52,6
14.00 – 15.00	46,1	44,1	42,9

Maximum temperatures generally occur during the midday period followed by a relatively rapid drop in the afternoon. This fluctuation has the potential to affect the quality of tuna meat, which is sensitive to temperature changes, and indicates uneven heat distribution across the drying racks.

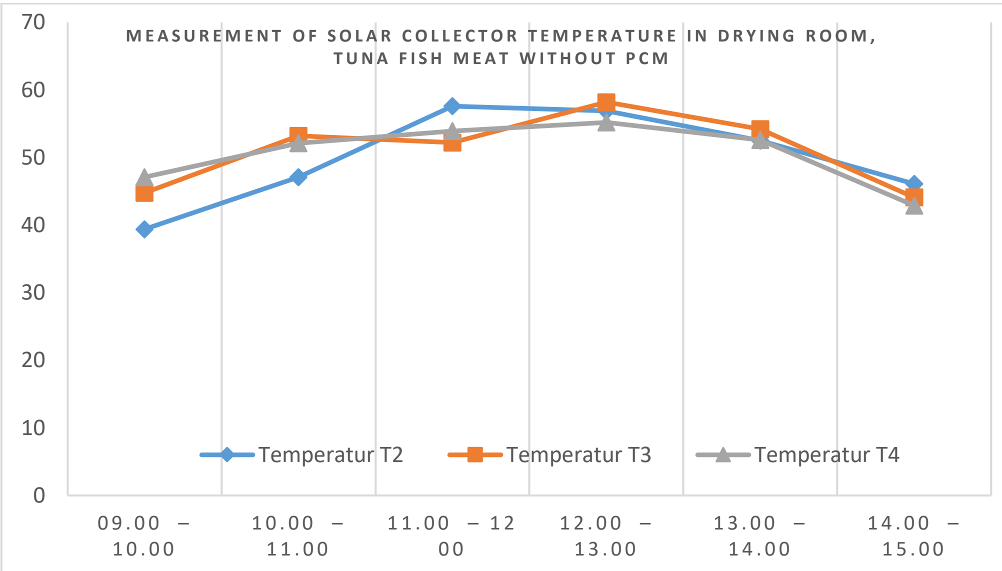

Fig. 5. Graph of temperature measurement results in the process of drying tuna meat without Phase Change Material (PCM)

The application of PCM in drying tuna meat provides a significant increase in thermal performance, as seen in Table 5 and Figure 6.

Table. 5. Temperature of solar collector and drying chamber for drying tuna meat with PCM

Time	Drying Room Temperature		
	T2	T3	T4
09.00 – 10.00	43,0	53,3	59,4
10.00 – 11.00	58,2	55,1	61,0
11.00 – 12 00	56,9	55,8	61,3
12.00 – 13.00	52,1	91,2	88,8
13.00 –14.00	51,3	51,5	51,4
14.00 – 15.00	50.2	52.5	55,6

The drying chamber temperature with PCM reached a maximum of over 90°C during peak solar radiation and showed a slower decline thereafter. This pattern indicates the PCM's latent heat release process, which maintained the drying chamber temperature within the effective range despite decreasing radiation intensity. Furthermore, the temperature difference between shelves in the system with PCM was smaller than in the system without PCM, indicating improved heat distribution uniformity.

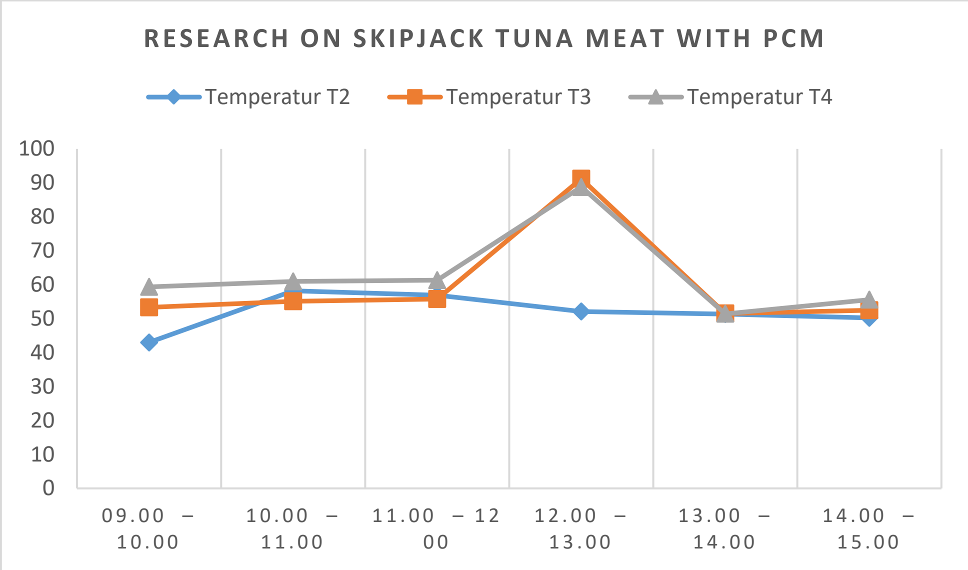

Fig. 6. Graph of temperature measurement results in the process of drying tuna meat with Phase Change Material (PCM)

III.3 Comparative Analysis and Discussion of Thermal Performance

Overall, the comparison between the systems without PCM and with PCM showed that the integration of PCM was consistently able to reduce temperature fluctuations, increase thermal stability, and improve the uniformity of heat distribution in both types of test materials. The role of PCM as a latent heat storage medium was proven effective in extending the effective drying duration and maintaining the continuity of the drying process. These findings confirm that the use of PCM is a potential approach to improve the performance of indirect solar dryers, especially for materials with different characteristics such as moringa leaves and tuna meat.

Table. 6. Quantitative summary of performance comparison of dryers without PCM and with PCM

Thermal Performance Parameters	Without PCM	With PCM	Physical Implications
Main heat source	Direct solar radiation	Solar radiation + latent heat PCM	PCM functions as a thermal buffer
Temperature range of drying room (moringa leaves)	Widely fluctuating, unstable	Narrower and more stable	More even drying
Temperature fluctuations over time	High	Low	PCM dampens temperature changes
Temperature difference between shelves (T2–T4)	Relatively large	Smaller	More homogeneous heat distribution
Temperature range of drying room (skipjack tuna)	±39–58 °C	Stable with peak >90 °C	PCM increases the thermal capacity of the system
Maximum temperature	Limited by momentary radiation	>90 °C at peak period	Latent heat storage and release
The rate of decrease in afternoon temperature	Fast	Slower	PCM releases latent heat
Thermal stability of the drying chamber	Low	High	The drying process is more continuous
Potential for drying uniformity	Low	High	Reduces the risk of over/under drying
General drying performance	Less than optimal	More optimal	PCM improves process efficiency

Table 6 shows that the integration of Phase Change Material (PCM) provides consistent thermal performance improvements across all observed parameters. The system without PCM exhibited high temperature fluctuations and uneven heat distribution, both in the drying of moringa leaves and tuna meat. In contrast, the system with PCM had better temperature stability, a smaller temperature difference between shelves, and the ability to maintain effective temperatures for a longer duration. Physically, this performance improvement is due to the PCM's latent heat storage and release mechanism, which allows the PCM to function as a thermal buffer in the solar drying system.

IV. CONCLUSION

The integration of Phase Change Material (PCM) in an indirect solar dryer has been shown to improve the thermal performance of the drying system. The use of PCM reduces temperature fluctuations, improves heat distribution uniformity, and maintains temperature stability during the drying process. In the drying process of tuna meat, the maximum temperature achieved exceeded 90°C with a slower temperature reduction rate compared to the system without PCM. These results indicate that PCM has the potential to improve the efficiency and quality of the drying process of agricultural and fishery products.

SUGGESTION

Further research is recommended to examine the effect of varying PCM type and mass, as well as integrating moisture content and product quality analysis. A combination of experimental testing with numerical simulation (CFD) is also recommended for a more in-depth analysis of temperature distribution and airflow.

ACKNOWLEGMENT

This research is funded by Teuku Umar University, Ministry of Higher Education, Science and Technology, in accordance with the 2025 Prototype Research Implementation Assignment Agreement (PPRO) Number: 127/UN59.L1/AL.04/PL/2025, dated July 1, 2025.

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