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EXPERIMENTAL STUDY ON SOLAR DRYING OF ARABICA COFFEE BEANS: ACHIEVING STANDARD MOISTURE CONTENT USING A DRYING CHAMBER COLLECTOR

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Abstract. Drying technology plays a critical role in preserving and enhancing the quality of agricultural products, particularly in the post-harvest handling of Arabica coffee. In this experimental study, Arabica coffee beans were dried using a solar drying chamber equipped with a collector system to achieve standard moisture content. A total of 6000 grams of coffee beans were dried over 28 hours, with the system operating under an average chamber temperature of 40°C and a peak solar radiation intensity of 1122 W/m² occurring at 12:00 PM. The drying process utilized an air velocity of 9.2 m/s to enhance heat and mass transfer within the chamber. Among all trays tested, tray 2 produced the best quality beans with a final moisture content of 11.8%, aligning with the recommended standard for green coffee storage. These results demonstrate that integrating high air velocity and optimized collector design in a solar drying chamber can significantly reduce moisture content while maintaining bean quality, thereby offering an effective and sustainable alternative to conventional drying methods.

Keywords : Arabica Coffee, Air Velocity, Drying Chamber, Moisture Content, Solar Drying

1. INTRODUCTION

Coffee is one of the most widely traded agricultural commodities in the world and plays a crucial role in the economies of many developing countries [1–3]. In Indonesia, Arabica coffee is a prominent export product, especially from highland regions, where its unique flavor and aroma characteristics are preserved [4], [5]. Post-harvest processing is essential to maintain the quality of coffee beans, and among the various stages, drying is particularly influential [6–9]. The drying process not only determines the moisture content but also affects the physical appearance, biochemical composition, and storage stability of the beans[10–13].

Traditionally, coffee beans are dried using open sun drying methods [13], [14]. While this technique is cost-effective and accessible for smallholder farmers, it has several disadvantages: it is highly weather-dependent, requires large drying areas, and often results in uneven drying and potential contamination from dust, pests, and microbial activity [15], [16]. Under ideal conditions, sun drying may take 2 to 3 weeks to reduce the moisture content of coffee beans to the standard range of 11–12% wet basis, suitable for storage and export [17], [18] However, in practice, fluctuating environmental conditions frequently compromise efficiency and product quality [19]

To improve drying efficiency and consistency, solar dryers have been developed and classified into direct, indirect, and hybrid modes [20–23]. These systems aim to reduce drying time and enhance quality by creating controlled microclimates within drying chambers [24], [25]. Notably, the integration of solar collectors and forced air convection systems has emerged as a promising alternative to traditional methods [26], [27]. Forced convection can significantly improve heat and mass transfer by increasing the air velocity across the drying surface, accelerating moisture removal, and allowing for better control of drying parameters [26], [28].

Recent studies have demonstrated the importance of airflow variation in solar drying systems [29].

investigated the effect of different air velocities (1–3 m/s) on the drying performance and quality of Arabica coffee beans [29]. Their results showed that varying airflow had a significant impact on drying time and moisture content, with lower velocities yielding better moisture control while higher velocities slightly reduced efficiency [29]. Meanwhile, Kebede et al., evaluated a diminutive solar dryer with an integrated reflector and blower system in the Ethiopian highlands. Their study achieved a final moisture content of 10% in only two days, highlighting the effectiveness of optimized collector design and airflow control in maintaining coffee quality [30].

Building on this foundation, the present study focuses on an experimental evaluation of Arabica coffee drying using a solar drying chamber equipped with a collector system and operating at an air velocity of 9.2 m/s, substantially higher than in many previous studies. The research explores how collector orientation, surface material, and solar exposure time affect the internal temperature, humidity, and drying kinetics within the chamber. A batch of 6000 g of Arabica coffee beans was dried over 42 hours, and key performance indicators such as moisture content, drying rate, solar radiation, and chamber conditions were closely monitored. This study aims to contribute to the ongoing optimization of sustainable, off-grid drying technologies that enhance quality and efficiency in coffee processing, particularly in rural or electricity-scarce regions.

2. METHODS

2.1. Materials

The coffee beans used in this study were Arabica variety, sourced from Pangalengan, West Java. The cherries were harvested at optimal ripeness and underwent standard post-harvest processing, including de-pulping, washing, and an 8-hour fermentation period to remove mucilage. After fermentation, the beans were rinsed and prepared for drying. The beans were spread in a thin layer (0.5-1 cm thickness) on drying trays to ensure uniform exposure to hot air during the drying process.

2.2. Equipment

The drying system consisted of a single-unit solar coffee dryer, specifically designed to optimize heat transfer and air circulation. The main components are illustrated in Figure 1. The drying chamber measured approximately 900 × 800 × 1200 mm. The outer casing was constructed from aluminum sheets and insulated with glass wool to minimize heat loss. The interior walls were lined with aluminum foil to maintain cleanliness and prevent contamination of the coffee beans.

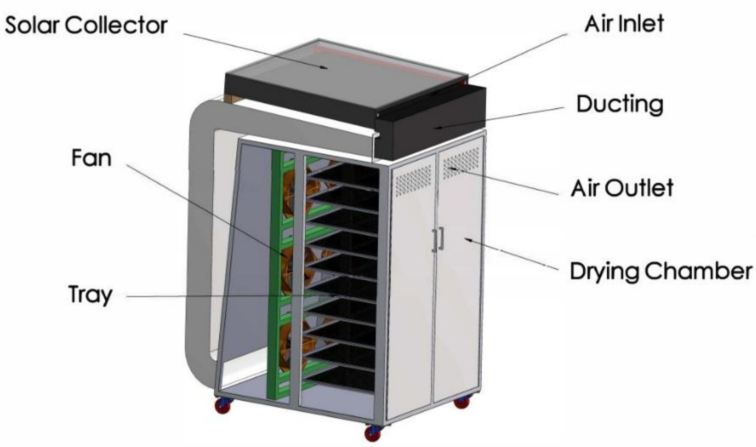

Figure 1. Coffee drying unit utilizing forced convection

The solar collector was built using a single layer of glass and a black-painted metal absorber plate designed to maximize solar energy capture. The collector was integrated into the drying system to ensure a continuous supply of heated air. An axial blower fan was installed to force hot air from the collector into the drying chamber at a velocity of 9.2 m/s. This setup was intended to enhance the convective drying process and ensure even moisture reduction across all trays. Temperature and relative humidity inside the drying chamber were monitored using thermocouples connected to a data logger. Solar radiation intensity was measured using a solar power meter, and bean moisture content was assessed periodically using a moisture analyzer.

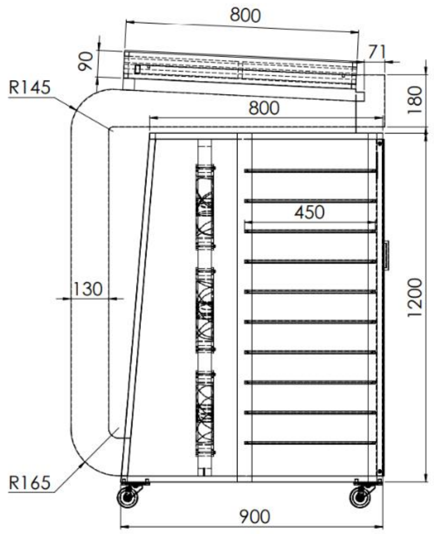

Figure 2. Assembly design of the solar-powered coffee drying unit

2.3. Experimental Procedure

The drying experiments were conducted daily from 08:00 a.m. to 03:00 p.m. to take advantage of peak solar irradiance with a temperature of 46.5°C. Each test involved drying 6000 grams of Arabica coffee beans in the chamber until they reached a target moisture content of approximately 11.8% wet basis, suitable for safe storage and quality preservation. The coffee beans were evenly distributed in a thin layer (0.5–1 cm) on the drying trays to ensure uniform exposure to the heated air circulating inside the chamber.

Throughout the drying process, key environmental and operational parameters such as chamber temperature, relative humidity, solar radiation intensity, and ambient conditions were recorded every 15 minutes using thermocouples and a data logger system. The experiment focused on evaluating the system's drying efficiency by monitoring moisture reduction rate, drying time, and the stability of chamber conditions, aiming to demonstrate the effectiveness of the solar dryer in producing high-quality coffee with improved energy efficiency.

3. RESULTS AND DISCUSSION

3.1 Thermal Performance of the Solar Drying System

The performance of the solar drying chamber was significantly influenced by daily solar radiation patterns. As shown in Figure 3, solar radiation exhibited a bell-shaped curve across all five days, with peak intensities occurring between 11:00 AM and 12:30 PM. Day 4 recorded the highest radiation intensity, peaking at 1122 W/m², while Day 1 exhibited the lowest values. These variations directly impacted the thermal response of the dryer components and ultimately affected the drying process efficiency.

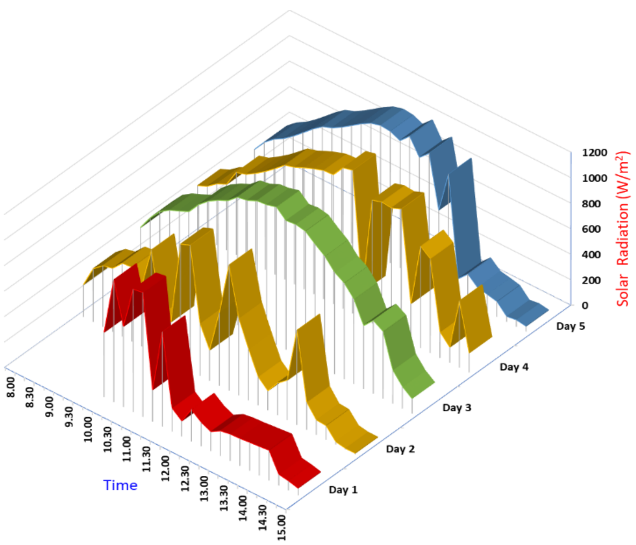

Figure 3. Daily solar radiation of the mobile solar dryer

Figure 4 presents the temperature distribution within the Phase Change Material (PCM) housing, which acts as a thermal energy buffer. PCM housing temperatures steadily increased during daylight hours and remained relatively stable in the afternoon, particularly on days 2 to 5. Peak PCM temperatures ranged from 60°C to 72.25°C, demonstrating the effectiveness of the PCM in storing and gradually releasing heat energy. This buffering capability helped mitigate temperature drops and extended the chamber's thermal activity beyond peak solar hours.

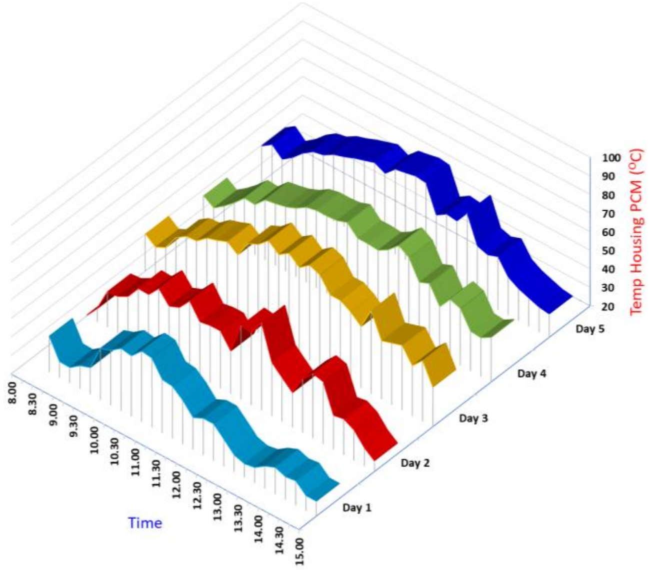

Figure 4. PCM (phase change material) housing temperature - mobile solar dryer

In parallel, Figure 5 highlights the performance of the aluminum absorber plate, which is crucial for converting solar radiation into heat. During Days 4 and 5, absorber plate temperatures consistently exceeded 72°C during midday hours, indicating a high absorption efficiency. This high-temperature gradient between the absorber and the drying air facilitated effective heat transfer into the chamber.

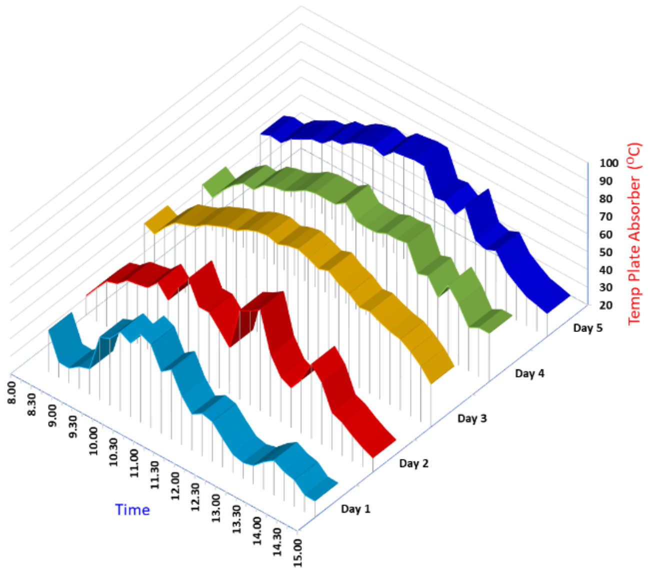

Figure 5. Aluminum absorber plate temperature - mobile solar dryer

The internal drying chamber temperatures, as illustrated in Figure 6, ranged from 40°C to 46.5°C, with an average peak of around 46.5°C. This temperature range is considered optimal for drying Arabica coffee, supporting both rapid moisture reduction and quality preservation. Notably, Days 3 through 5 maintained higher and more consistent chamber temperatures compared to the first two days, correlating with higher radiation intensity and improved absorber/PCM response.

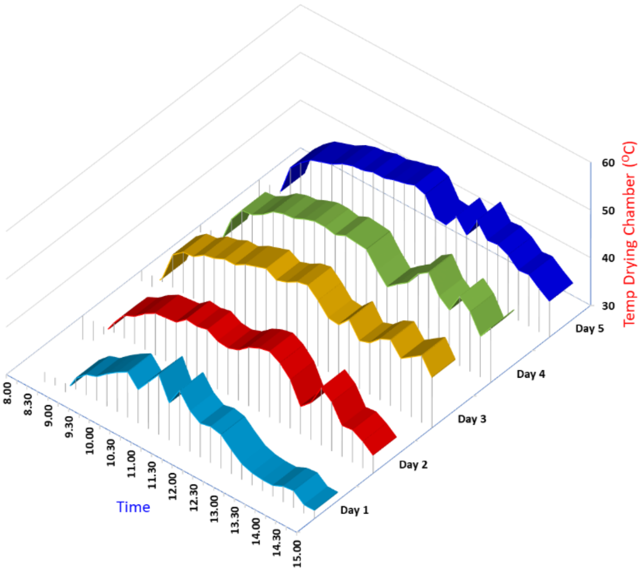

Figure 6. Drying chamber temperature

3.2. Drying Behavior and Process Efficiency

The combination of solar collector design, PCM integration, and forced air convection at 9.2 m/s contributed to efficient and uniform drying across all trays. The high air velocity improved heat and mass transfer inside the chamber, ensuring consistent exposure of beans to hot air and preventing uneven moisture removal. The drying chamber was equipped with 12 perforated trays, arranged vertically from Tray 1 (bottom) to Tray 12 (top). Tray 2, referred to in the results section, was positioned as the second-lowest tray. The vertical arrangement was used to evaluate the effect of airflow and temperature distribution on drying performance at different heights. Among all trays tested, tray 2 consistently produced beans with a final moisture content of 10%, aligning with storage standards for green coffee.

While Days 1 and 2 experienced slightly lower solar input, the drying system still managed to sustain chamber temperatures above 40°C, aided by the thermal insulation and latent heat release from the PCM. This resilience suggests that the system remains functional under moderate environmental conditions, making it suitable for variable tropical climates.

The experimental drying duration of 28 hours to reach 11.8% moisture content is notably shorter than traditional sun drying methods, which can take several weeks under fluctuating weather. This reduction in drying time not only enhances processing efficiency but also minimizes the risk of contamination and quality degradation due to prolonged exposure. To prevent rehydration or moisture absorption during non-drying periods (evenings and nights), the coffee beans were stored in a sealed, clean, and dry container each day after drying. The storage area was kept at room temperature and protected from ambient humidity exposure, ensuring that the drying progress remained stable across the entire process.

Overall, the results confirm that integrating solar energy with thermal storage and forced convection provides a reliable and energy-efficient solution for post-harvest coffee processing. For future development, additional studies may explore optimizing PCM volume, airflow direction, or collector surface treatment to further enhance system performance and potentially enable nighttime drying cycles.

3.3. Thermal Performance of the Solar Drying System

The performance of the solar dryer was strongly influenced by the daily pattern and intensity of solar radiation. During the four days of testing, solar radiation peaked between 11:00 AM and 1:30 PM, reaching a maximum of 1122 W/m² on day 4. Day 1 showed the most irregular radiation pattern, with abrupt drops likely caused by transient cloud cover, which impacted the heat gain of the system.

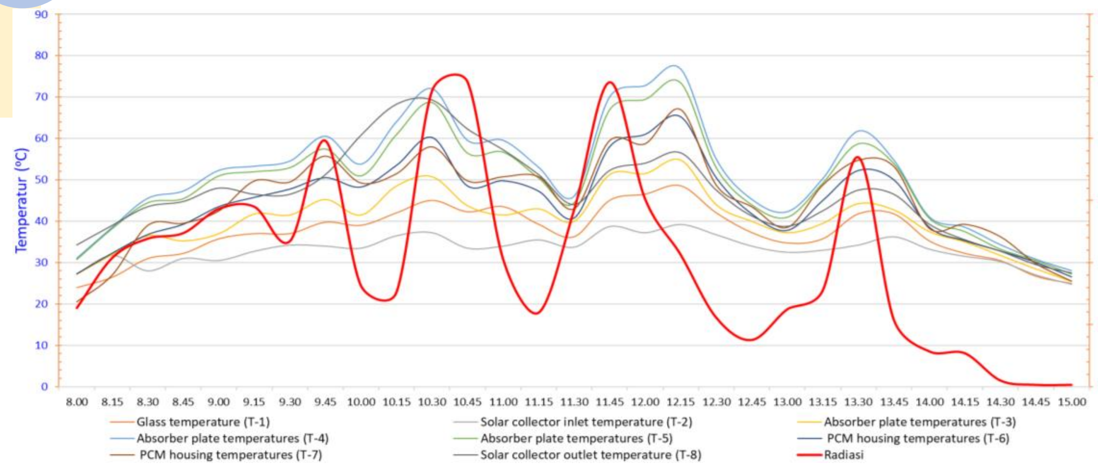

Figure 7. Graph of glass temperature, collector, absorber plate, pcm housing, and solar radiation (day 1)

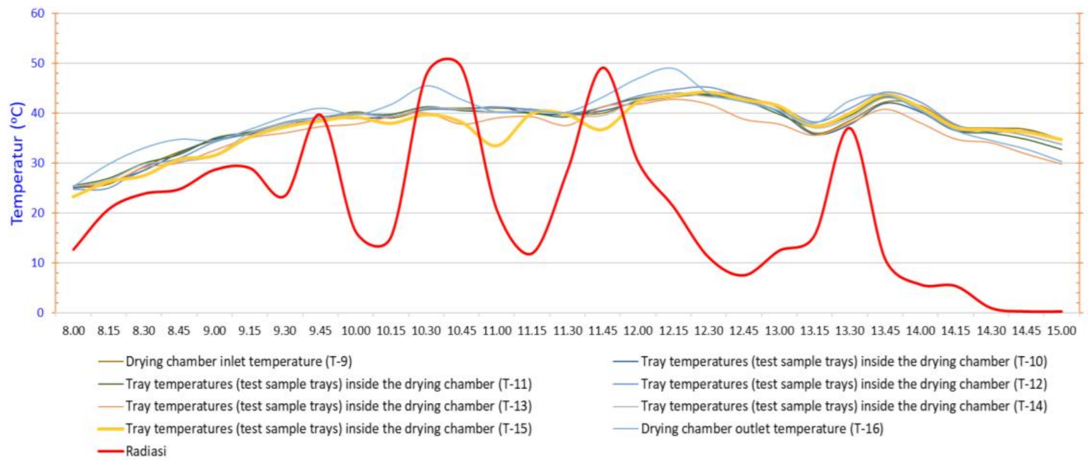

Figure 8. Graph of drying chamber temperature, tray temperature, and solar radiation (day 1)

The absorber plate responded quickly to changes in radiation, with maximum temperatures exceeding 75°C on Days 2 and 4. This confirms the effectiveness of the black-painted metal surface in absorbing solar energy and transferring it to the airflow. Meanwhile, the PCM housing exhibited a delayed yet stable rise in temperature, peaking at 72.25°C on day 3. This delayed thermal response highlights the role of PCM as a thermal buffer that stabilizes the drying environment during periods of fluctuating solar input.

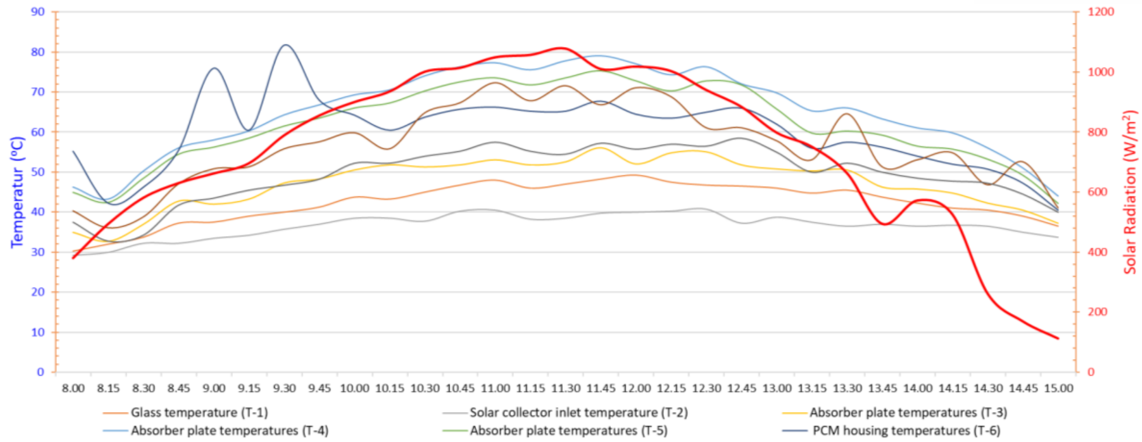

Figure 9. Graph of glass temperature, collector, absorber plate, pcm housing, and solar radiation (day 2)

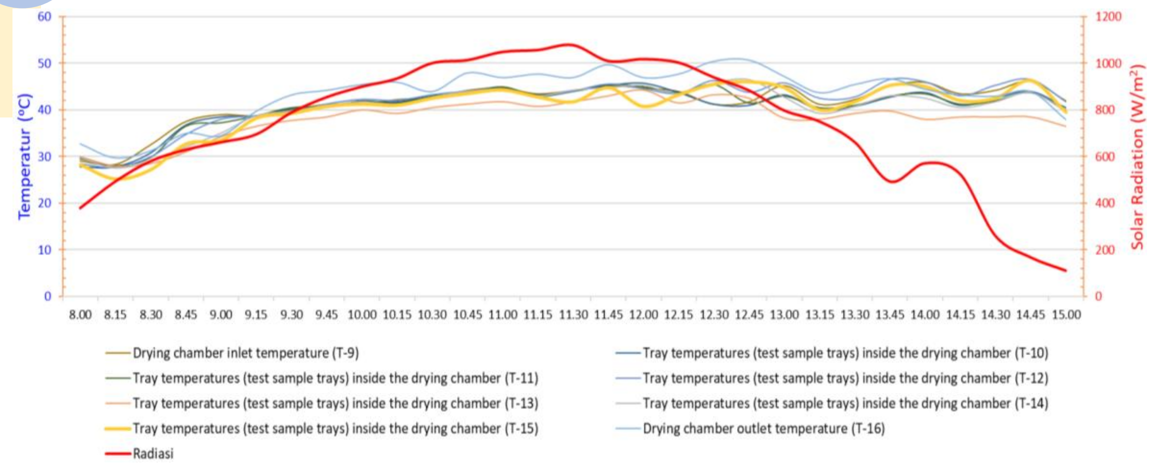

Figure 10. Graph of drying chamber temperature, tray temperature, and solar radiation (day 2)

Temperature differences between the collector inlet and outlet remained consistent at 30-55°C during peak radiation hours, indicating efficient heat transfer. Additionally, the drying chamber maintained average internal temperatures ranging from 40°C to 46.5°C, optimal for drying Arabica coffee while preserving quality.

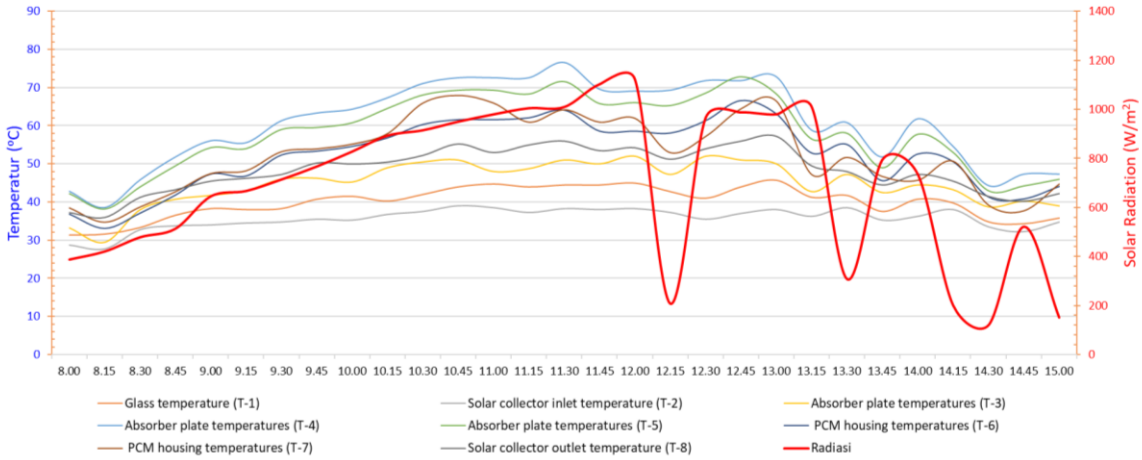

Figure 11. Graph of glass temperature, collector, absorber plate, pcm housing, and solar radiation (day 3)

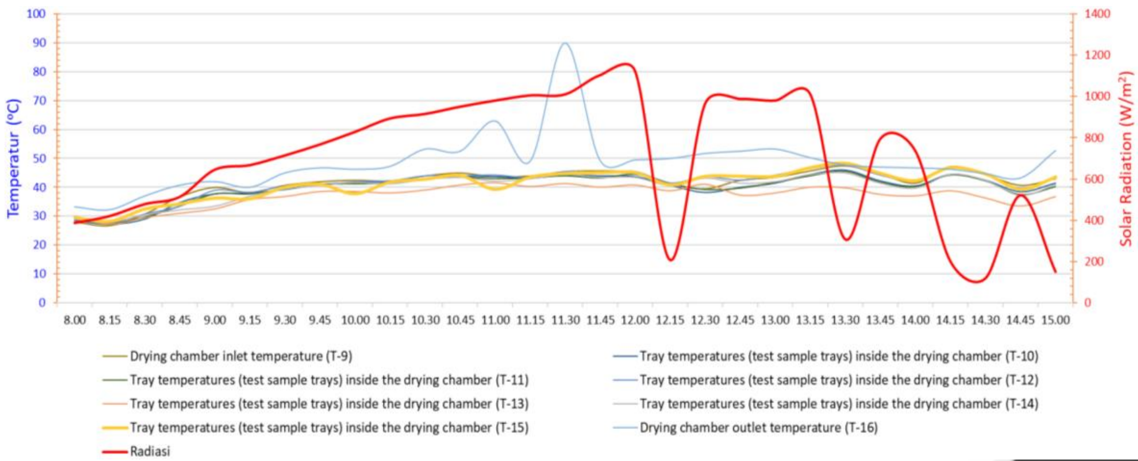

Figure 12. Graph of drying chamber temperature, tray temperature, and solar radiation (day 3)

Day 4 demonstrated the most stable thermal performance across all components, with minimal fluctuation in absorber plate and PCM temperatures. The combination of strong solar input, thermal insulation, and PCM heat storage contributed to this consistency, making the system reliable under varying climatic conditions.

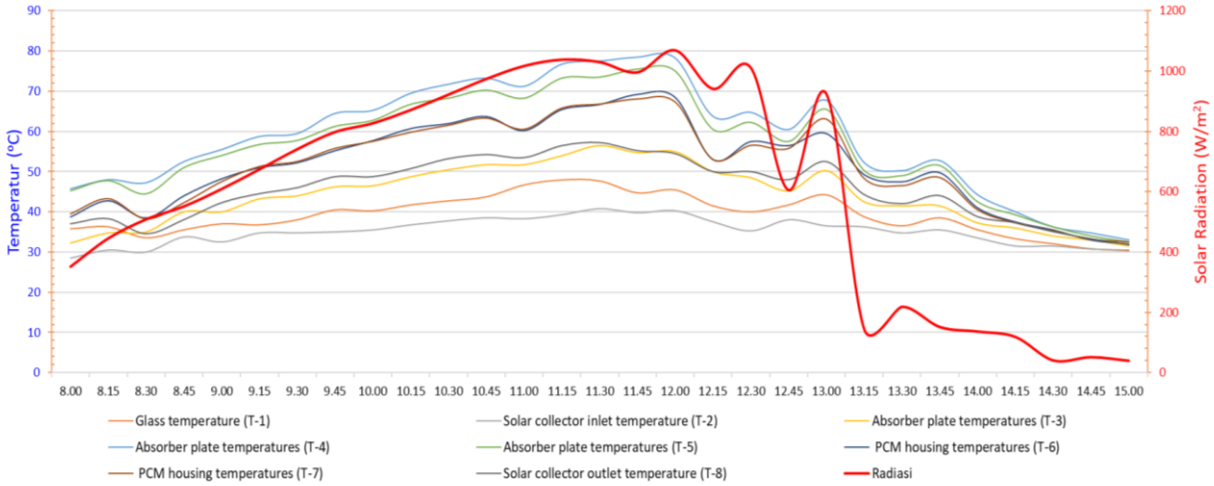

Figure 13. Graph of glass temperature, collector, absorber plate, pcm housing, and solar radiation (day 4)

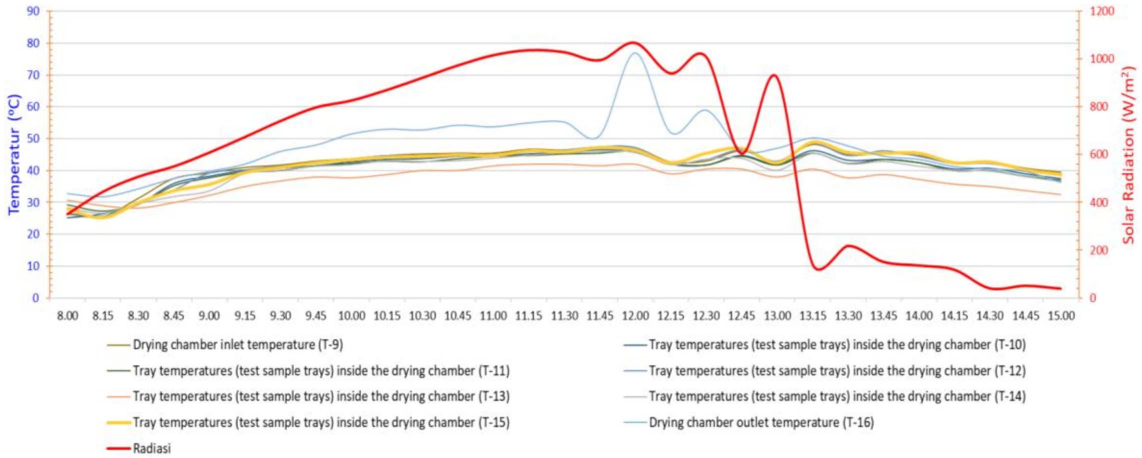

Figure 14. Graph of drying chamber temperature, tray temperature, and solar radiation (day 4)

3.4. Drying Behavior, Efficiency, and Implications

Temperature measurements at various trays inside the drying chamber (T-10 to T-15) showed a fairly uniform distribution, generally ranging between 40°C and 45°C. Slight variations in trays T-12 and T-14, which exhibited earlier temperature peaks, suggest minor positional effects related to airflow distribution. Nevertheless, the overall thermal uniformity ensured even drying across all trays.

These results indicate a vertical moisture gradient, where lower trays (Tray 1–4) generally achieved better drying performance compared to upper trays (Tray 9–12). This gradient can be attributed to the vertical upward flow of heated air inside the chamber, which loses temperature and velocity as it rises. Notably, tray 2 produced the lowest final moisture content (10.0%), representing the optimal tray position under the current system configuration. This superior result to the main heat source and air inlet, resulting in high and stable air temperatures.

In contrast, tray 1, although closest to the heat source, showed slightly higher moisture content (11.8%), possibly due to limited air circulation right at the chamber floor or heat being lost to the base. Trays in the upper part (Tray 10–12) performed less effectively due to reduced temperature and airflow intensity as the air rises and heat dissipates. These findings underline the importance of tray position optimization in vertical dryers and justify the need for improved airflow balancing or chamber redesign to reduce positional drying variation.

The correlation between radiation and temperature in system components was evident, particularly in absorber and collector outlet temperatures, which closely mirrored solar intensity patterns. However, the PCM helped mitigate abrupt temperature drops in the drying chamber such as those observed around noon on Day 1 and Day 4 by gradually releasing stored heat.

The 9.2 m/s forced air velocity played a key role in sustaining even temperature distribution. This high airflow rate enhanced convective heat and mass transfer, preventing hotspots or cold zones in the chamber. As a result, the drying process was efficient and consistent throughout the 28 hours total duration. Compared to traditional open-sun drying, which may take up to two weeks depending on the weather, the experimental dryer significantly reduced drying time while improving hygiene and quality control. The final moisture content of 11.8% especially consistent in Tray 2 meets the standard for green coffee storage and ensures better shelf life. These findings validate the integration of solar thermal collectors, PCM storage, and forced convection as an effective post-harvest drying solution. This design is particularly relevant for off-grid rural communities, providing a clean, low-cost, and scalable alternative for sustainable coffee processing.

Despite its promising performance, the current system relies heavily on consistent daytime solar radiation, which can be limiting during extended cloudy or rainy periods. The absence of nighttime drying capability also restricts throughput. Additionally, the system has not yet been tested with different crop types or under extreme humidity conditions, which could affect its generalizability. Future work should focus on developing hybrid energy inputs (e.g., integrating biomass or electric heaters), automated drying control systems, and exploring multi-layer PCM designs to improve energy retention. Field trials in diverse climatic zones are also recommended to validate scalability and robustness of the system.

4. CONCLUSION

This experimental study demonstrates the effectiveness of a solar drying chamber equipped with a collector system, phase change material (PCM), and high-velocity forced convection in reducing the moisture content of Arabica coffee beans to the desired level. The system successfully dried 6000 grams of coffee beans to a final moisture content of 11.8% within 28 hours, a significant improvement compared to traditional open-sun drying methods that may take several days. The use of a 9.2 m/s axial blower fan enhanced convective heat and mass transfer, ensuring uniform drying across trays and reducing the risk of quality degradation due to uneven moisture distribution.

The integration of thermal insulation, PCM heat storage, and solar radiation collection provided consistent thermal performance even under fluctuating environmental conditions. Tray 2 consistently yielded the highest quality beans, confirming the chamber's uniformity and design reliability. These findings support the adoption of solar-powered, energy-efficient drying systems for post-harvest coffee processing, especially in rural or off-grid areas. Future research may focus on optimizing PCM mass, improving airflow design, and extending system functionality to enable nighttime drying, further enhancing its sustainability and scalability.

5. ACKNOWLEDGEMENT

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