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Drying Conditions in a Solar Dryer System and its Influence on the Moisture Content of Dried Banana

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ABSTRACT

This work presents the dynamics of solar radiation, temperature, and relative humidity within a five-day period inside and outside a solar dryer. Solar irradiation within the observation period followed a cyclic pattern, peaking midday and fluctuating late afternoon. A similar cyclic trend was noticed for the temperature inside the dryer. Meanwhile, the temperatures measured outside the dryer were significantly lower and showed less distinct increases and fluctuations. Moreover, relative humidity measurements inside the solar dryer revealed more defined fluctuations. A drastic decrease in relative humidity occurred as time approached midday, and an eventual increase was noted towards the evening. Finally, the dynamics of moisture content removal in the banana were observed to be related to the mentioned parameters. Inside the solar dryer, moisture content removal tends to drastically occur at midday when the solar radiation and temperature peak, and the relative humidity is at its lowest. More efficient moisture content removal was observed inside the solar dryer compared to the ambient environment. Interestingly, the daily increment in the reduction of moisture content varies, showing the third day with the most drastic moisture content reduction.

Keywords: *Solar dryer system, moisture content, dried banana, solar radiation, relative humidity*

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1 Introduction

Solar drying is a longstanding practice in removing the moisture content of crops and other agricul-tural products (Ndukwu et al. 2023). Technically, solar drying is described as a method of removing moisture from crops or other materials by direct or indirect exposure to sunlight (Rizalman et al. 2023). This method involves solar dryers that use solar heat to remove the moisture from the crops while controlling the environmental conditions, including the humidity and airflow of the system. Typically, solar dryers are designed and employed to isolate the drying environment from the ambient conditions, affording a controllable and efficient drying system (Udomkun et al. 2020). Apart from being cost-effective, solar drying is highly sustainable and environmentally friendly since it exploits renewable energy with no carbon emissions, contrary to fire, mechanical, electrical, or gas dryers. It also improves the hygiene and preserves the quality of crops by protecting them from dust, insects, and other environmental contaminants. Moreover, solar drying systems are highly scalable and can be tailored for home use or scaled up for huge commercial agricultural operations. Although the utilization of solar dryer systems is already an established part of post-production and agricultural systems, optimizations and understanding the interconnectedness of parameters that influence the drying process are still limited (Abdul Razak et al. 2021). These parameters include the airflow and ventilation, dryer architecture, sunlight intensity, drying temperature, relative humidity, and product moisture content (Ruzikulov et al. 2023). Understanding the relationship among these parameters and how they vary at certain periods canmeters and how they vary at certain periods can provide valuable insights into optimizing solar drying operations and improving product quality.

Bananas have long been a staple crop in many Asian countries including the Philippines and Thailand (Kraithong & Issara 2021). Its cultivation contributes significantly to the region's agricultural exports and gross domestic product making it a significant crop subject to innovations and research development. In 2025, the market size of bananas is estimated to be around USD 141.97 billion. This is projected to increase to USD 147.74 billion by 2030 (Mordor Intelligence, 2025). Due to its high nutritional value and cultural significance, a number of products have been derived from this fruit, including flavoring powders, banana flours, chips, and dried snacks (Martínez et al. 2024). For instance, dried banana production is growing in the banana-based product industry. The dried banana market globally was valued at approximately USD 1.15 billion in 2023 and is anticipated to grow to USD 1.98 billion by 2033, exhibiting a CAGR of 5.7% from 2024 to 2033 (DataHorizzon Research, 2025). The success of the dried banana industry lies critically in maintaining the quality of the product. Moreover, monitoring the moisture content of the banana during the drying process is also crucial to achieve the desired quality of the product.

In this study, we analyze the behavior of key drying parameters in a solar dryer system over specific time windows, with a focus on solar radiation, temperature, and relative humidity during a five-day period. The dynamics of these parameters within a typical solar day are also explored to understand their impact on drying efficiency better. Additionally, we examine the effect of solar drying on the moisture content of dried bananas and provide a comparative analysis with samples dried under open-air conditions. While a related work focusing on drying tomatoes in the same solar dryer design with similar drying parameters has already been published, no work has been published concerning the drying of bananas in the same dryer This investigation, therefore, aims to enhance understanding of the factors influencing solar drying per-formance with banana for future optimization and enhanced solar drying strategies.

2 Materials and Methods

2.1 Solar dryer setting and design

The solar dryer used in this study was a mixed-mode solar dryer, combining both direct and indirect solar radiation. The dryer consisted of a transparent polycarbonate cover, a black-painted absorber plate, and a drying chamber. The dimensions of the dryer were 20m x 8m x 3.5m (L x W x H). This design was chosen based on recent advances in solar dryer technology that optimize energy efficiency and drying uniformity. The illustration of the solar dryer with various perspectives is presented in Figure 1.

The heat transfer in a solar dryer occurs in three primary mechanisms: conduction, convection,

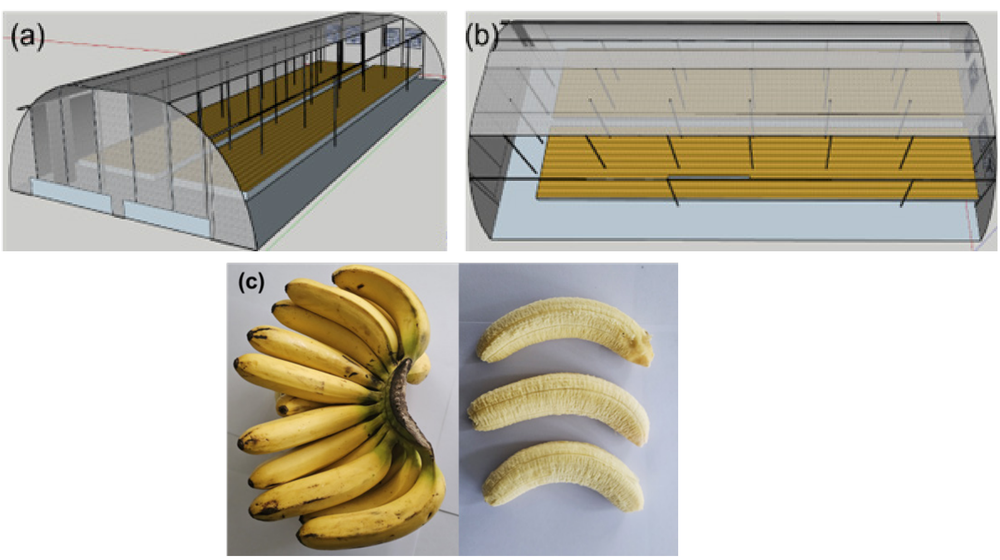

Figure 1. Illustration of the (a) two-point perspective and (b) top-view perspective of the drying environment inside the solar dryer. (c) Photograph of the actual banana samples used in the study.

and radiation. Each mechanism contributes to the drying process by facilitating the transfer of heat from the sun to the product being dried as well as the subsequent removal of the product's moisture content. Figure 2 presents the schematic diagram of energy transfer within the solar dryer, where V_{in} and V_{out} represent the inflow and outflow of the air, while h_c and h_w represent the coefficients of convection in the cover and due to wind, respectively. The coefficient of radiation is represented by h_r.

2.2 Instrumentation and Parameter Measurements

Fresh bananas (Cavendish, *Musa acuminata*) were obtained from a local farm as shown in Figure 1c. The bananas were peeled, sliced to 5mm thickness, and divided into two groups: solar drying and open-air drying (control). The drying process was conducted over five consecutive days in the first half of August. Measurements were taken hourly from 7:00 AM to 6:20 PM each day. Solar radiation (W/m²) was measured using a pyranometer (Kipp & Zonen CMP3, accuracy ±5%). Temperature was recorded inside and outside the dryer using Type-K thermocouples (accuracy±0.75%). Relative humidity (RH) was measuredinside and outside the dryer using capacitive humidity sensors (Vaisala HMP60, ±3%). For the moisture content, the banana samples were placed in the dryer at fixed positions. They were weighed periodically at about two-hour intervals using a digital balance (Kern 474-42, accuracy ± 0.1 g). Controlled samples (open-air, sundried) were also weighed at similar intervals and compared against the samples dried in the solar dryer. The moisture content was estimated by comparing the difference between the mass of the banana samples before and after each measurement. During the observation period, the air flow speed was maintained at 0.5 m/s using a DC fan controlled by a micro-controller to ensure consistent ventilation.

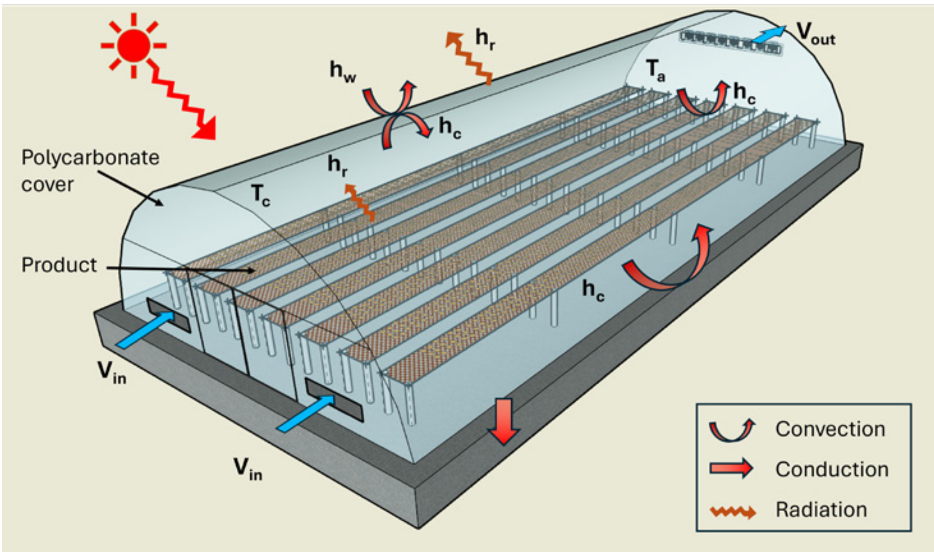

Figure 2. Schematic representation of heat transfer processes within the solar dryer

2.3 Statistical Analysis

The statistical analysis of the dataset, including temperature, relative humidity, and moisture content of the samples dried using the solar dryer and the traditional drying method, was conducted using JASP software. Upon analysis, it was determined that the dataset did not satisfy the assumptions required for parametric tests, such as normality and homogeneity of the variances. As a result, a nonparametric alternative was chosen. The Mann-Whitney U test was applied to compare differences between groups for each variable. The Mann-Whitney U test is particularly suitable for non-normally distributed data as it evaluates whether one group tends to have higher or lower values compared to another without relying on the assumptions of a normal distribution. [*Field, A. (2013). Discovering Statistics Using IBM SPSS Statistics (4th ed.). SAGE Publications.*]

Data preparation and analysis of the above-mentioned variables in JASP involved the following steps. First, the dataset was imported and inspected for consistency and completeness, followed by exploratory data analysis (EDA) to assess the

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distribution of variables and identify potential outliers. Then, normality of each variable was tested using the Shapiro-Wilk test. At the same time, the homogeneity of each variable was tested using Levene's Test, which confirmed that parametric assumptions were violated. Subsequently, the Mann-Whitney U test was conducted for each variable, with the significance level (α) set at 0.05. The results provided insights into the differences between the two independent groups in terms of their median values, which were further interpreted in the context of the study objectives and discussed in the subsequent sections of the paper.

3 Results and Discussions

3.1 Variations of solar radiation

Figure 3 presents the relationship between solar radiation and drying time over a five-day period. The amount of solar radiation (W/m²), which quantifies the sun's energy that reaches the area of interest, was measured within the drying period, starting at around 7:00 AM to 6:00 PM, with data taken at hourly intervals for five consecutive days. The graph shows a repeating pattern of rising solar radiation in the morning and then declining toward the evening. Consistent peaks were observed around midday, corresponding to when the sun is at its highest point in the sky, where there is maximum solar radiation output. Generally, each observed day follows a similar solar radiation pattern, but minimal radiation fluctuations vary slightly from day to day. Moreover, small dips and fluctuations in the solar radiation throughout the day were observed, which could be attributed to the isolated cloud cover or atmospheric conditions that obstruct the sunlight

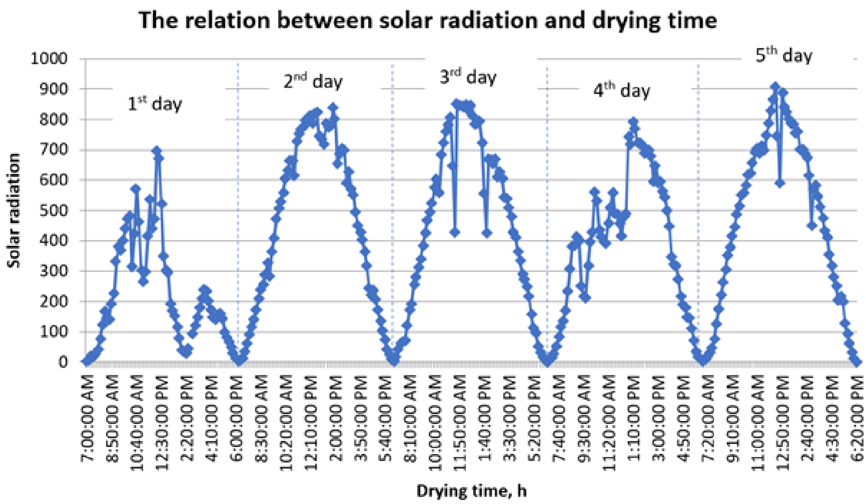

Figure 3. Variations in solar radiation recorded throughout each day over a 5-day period within the solar dryer.

from reaching the ground. These results further imply that higher solar radiation can be harnessed around midday or noon, while lower radiation is available in the morning and late afternoon. This suggests that to maximize drying efficiency, it is necessary to conduct the drying at around midday or noon. These consistent patterns can be used to plan optimal drying times when solar radiation is considered.

3.2 Variations of temperature inside and outside (ambient) the solar dryer

Figure 4 shows the relationship between temperature and drying time inside and outside a solar dryer over a 5-day period. The blue line represents the temperature inside the solar dryer, while the orange line represents the temperature of the ambient conditions outside the dryer. The Mann-Whitney U test was used to assess differences in the temperature between two independent groups, namely the traditional and solar drying method. The test statistic (W) was 3209.500, and the p-value is reported as less than 0.001, indicating a statistically significant temperature difference between the two groups. Since the p-value is smaller than the common threshold of 0.05, we reject the null hypothesis, concluding that there is a significant difference in temperature inside the solar dryer compared to the outside temperature.

Inside the solar dryer, temperatures show a

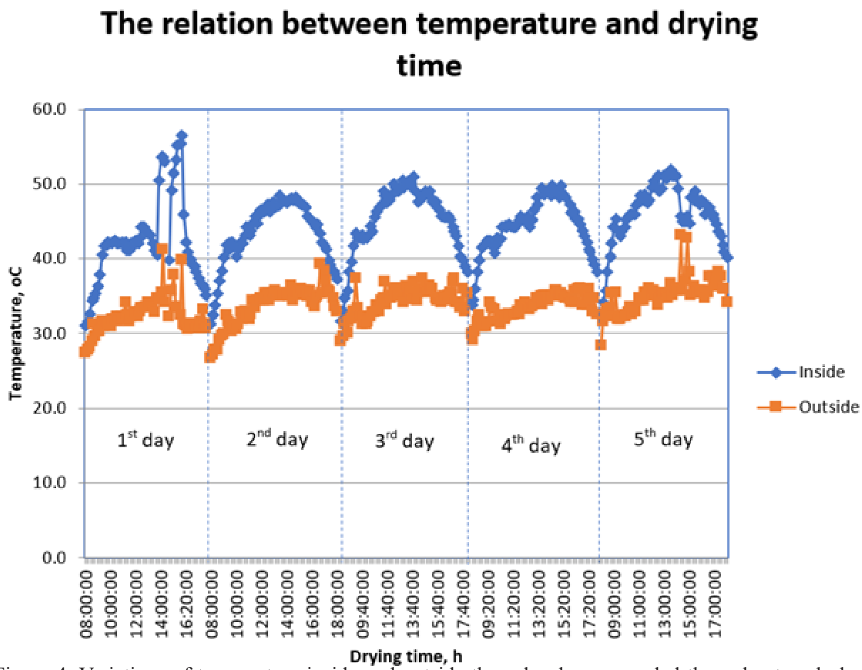

Figure 4. Variations of temperature inside and outside the solar dryer recorded throughout each day over a 5-day period.dryer.

significant daily fluctuation, ranging between 30°C and 55°C, with peaks occurring around midday and declines during the late afternoon and evening. This profile is consistent with the sun's position and solar radiation intensity, which peaks around noon and decreases as the day progresses, suggesting that the solar radiation patterns are more likely to influence temperature dynamics. Meanwhile, ambient (outside) temperatures exhibit smaller fluctuations compared to the temperatures inside the dryer. The external temperatures remain relatively stable, ranging between 25°C and 35°C, only throughout the observation time. The less dynamic temperature variations outside the solar dryer could be attributed to the uncontained radiation and rapid dissipation of heat in the open environment (Shrestha et al. 2019). The difference in the temperature profile between the two locations clearly highlights the amplification effect of the solar dryer in the hourly increase and decrease in temperature. The apparent difference between the fluctuations inside and outside temperatures also indicates the solar dryer's ability to regulate and retain heat (Hegde et al. 2015). Compared to more gradual external fluctuations, the sharp peaks inside suggest that the solar dryer effectively captures and traps solar energy, maintaining higher internal temperatures, even during declining external heat.

3.3 Variations of relative humidity inside and outside (ambient) the solar dryer

Figure 5 shows the relationship between relative humidity and drying time inside and outside the solar dryer over a 5-day period. The blue line represents the relative humidity inside the solar dryer, while the orange line shows the relative humidity in the ambient environment (outside). A cyclical pattern was observed both inside and outside the solar dryer. The Mann-Whitney U test was used to compare the relative humidity between two independent groups, the traditional and solar drying methods. The test statistic (W) was reported as 746.000. The p-value is less than 0.001, which indicates a statistically significant difference between the two groups for relative humidity.

Relative humidity peaks in the evening and early morning hours, both inside and outside the dryer, while it lowers at periods when solar radiation is at its peak. This indicates that the increased temperature provided by the high solar radiation effectively reduces the moisture content of the air in both locations. However, the more pronounced fluctuations inside the solar dryer indicate that the controlled environment efficiently facilitates moisture removal compared to ambient conditions, eventually creating a drier atmosphere for the crops. Moreover, upon closer inspection, the relative

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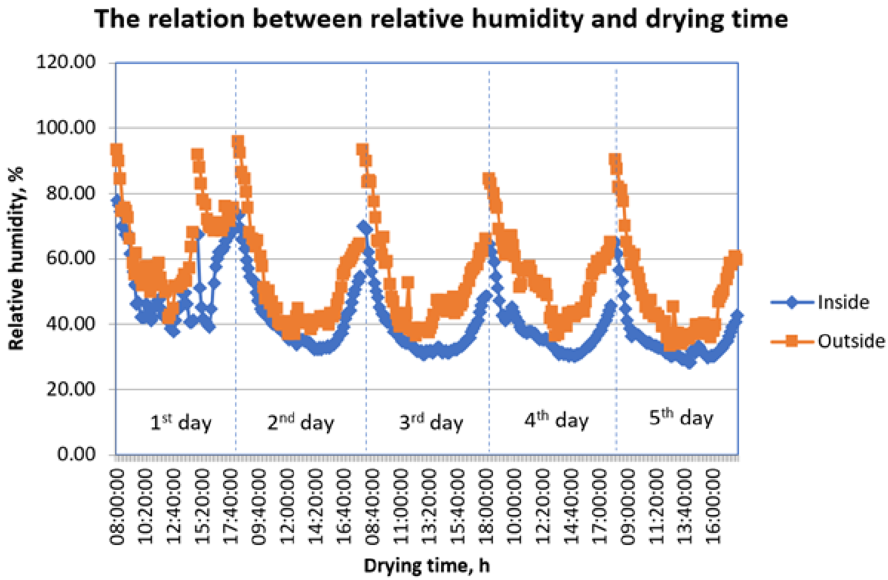

Figure 5. Variations of relative humidity inside and outside the solar dryer recorded throughout each day over a 5-day period.

humidity patterns over the 5-day period were more consistent inside the solar dryer than in the ambient environment, suggesting stable and more predictable RH dynamics inside the solar dryer.

Compared to outside conditions, the significant reduction in relative humidity inside the solar dryer during the day creates a more effective drying environment. Lower humidity inside the dryer means that moisture from the crops can evaporate more quickly, improving drying efficiency (Xu et al. 2021). This drier environment inside the dryer accelerates moisture loss from the crops, leading to faster drying times compared to crops left in ambient conditions, especially during peak drying times. The control over humidity is essential for high-quality drying, as it prevents the risk of mold growth and other moisture-related spoilage that can occur at higher humidity levels (Bradford et al. 2018). However, it is worth noting that this behavior is a close consequence of the cyclical pattern of the solar radiation availability. During the day, when solar radiation and temperature increase, the relative humidity inside the dryer drops sharply. Conversely, when temperatures drop and solar energy is unavailable during the night and early morning, relative humidity inside the dryer increases. This further implies that interventions should be done during this period to prevent moisture-related damage and contamination.

3.4 Reduction of moisture content in banana inside and outside (ambient) the solar dryer

The removal of moisture content in bananas inside and outside the solar dryer in a five-day interval was examined and presented in Figure 6. The Mann-Whitney U test was also used to assess differences in moisture content between two independent groups. The test statistic (W) was 558.000, and the p-value is reported to be 0.004, which indicates a statistically significant difference in moisture content between the two groups. Since the p-value is smaller than the common threshold of 0.05, by rejecting the null hypothesis, we can conclude that there is a significant difference in moisture content between the banana placed inside the solar dryer compared to that of the traditional air-drying method.

The moisture content of the banana samples exhibited a consistent reduction down to 15% inside the solar dryer. In comparison, a much higher moisture content of about 25% was retained on the banana dried in the ambient environment. This shows the more efficient drying capacity of the solar dryer. It is worth noting that the third day exhibited the highest removal of moisture content (about 20% reduction) in the solar dryer, highlighting that the third day of drying is crucial in the progression of moisture content removal. Upon closer inspection, we can also see steeper slopes occurring after 8:00 am and before 4:00 pm, indicating that the removal of moisture happens between these periods. Before and beyond these periods, plateaus in the graph were noted, signifying no significant reduction

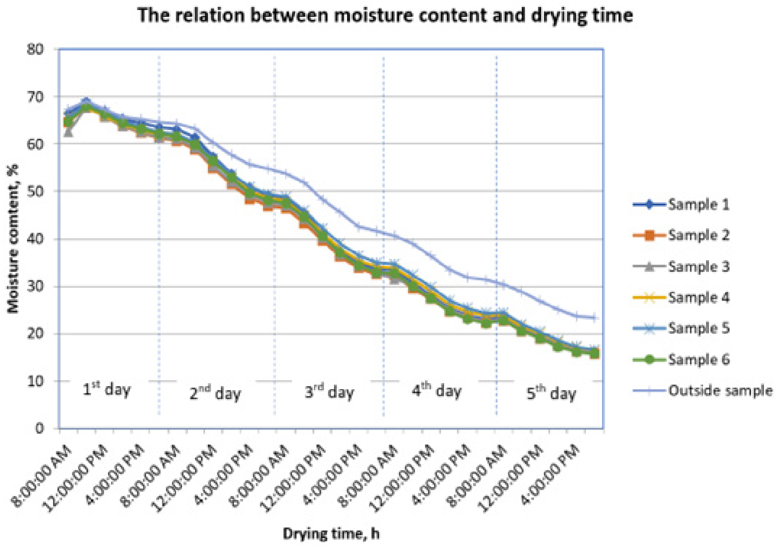

Figure 6. Variations of relative moisture inside and outside the solar dryer recorded throughout each day over a 5-day period.

of the moisture content during nighttime in the solar dryer. It can be noted that when the moisture content was observed to decline drastically at the daily time window, the relative humidity decreased, and the temperature and solar radiation increased. This implies that the drastic removal of moisture in the banana during this period is driven by these conditions. The increase in the solar radiation availability, increases the solar dryer's temperature, and reduces the relative humidity, eventually leading to a more efficient removal of moisture content in the banana. The observed drastic reduction at around midday, where the increase in solar radiation and temperature is at the peak, further supports this observation. This relationship may not be very defined in the moisture content removal in the banana conducted in the ambient environment (outside) due to the minimal fluctuations in the ambient temperature.

While more detailed in situ physical and chemical characterizations are required to inspect this phenomenon, we speculate a number of possible reasons for this observation. The first reason could be attributed to the rapid moisture evaporation in the first three days. This moisture content possibly originates from the superficial moisture of the banana. After the third day, significant moisture content was removed, and the moisture bound within the cellular structure of the banana was left, making the succeeding moisture reduction slower. On another perspective, the moisture content inside the fruit decreases as the banana dries, reducing the difference in vapor pressure between the banana and the surrounding air. This lower gradient slows down the drying process, particularly beyond the third day. Moreover, if the banana dries, it develops a drier and harder outer layer that may act as a barrier that prevents moisture from evaporating inside the banana. This further reduced the drying efficiency after the third day.

The daily moisture removal rate was determined and presented in Figure 7. Both samples, dried both within and outside the solar drying system, exhibited a positive slope in the moisture removal curve, indicating a continuous loss of water throughout the drying process. Notably, the samples dried within the solar dryer demonstrated a significantly higher daily moisture removal rate compared to those dried outside. This observation is consistent with the observed drying conditions inside the dryer, wherein higher temperatures and a reduction in humidity were observed. Lower humidity creates a steeper moisture gradient between the sample and the surrounding air, driving faster water evaporation. The enhanced air movement in the chamber may also help remove the moisture in the drying environment and the samples, resulting in drier air, and promoting faster evaporation. This suggests that the solar drying system effectively enhanced the drying kinetics.

4 Summary and Conclusion

We analyzed the dynamics of solar radiation, temperature, and relative humidity over a five-day period inside and outside a solar dryer. Solar radiation exhibited a cyclic pattern, peaking midday and fluctuating in the afternoon.

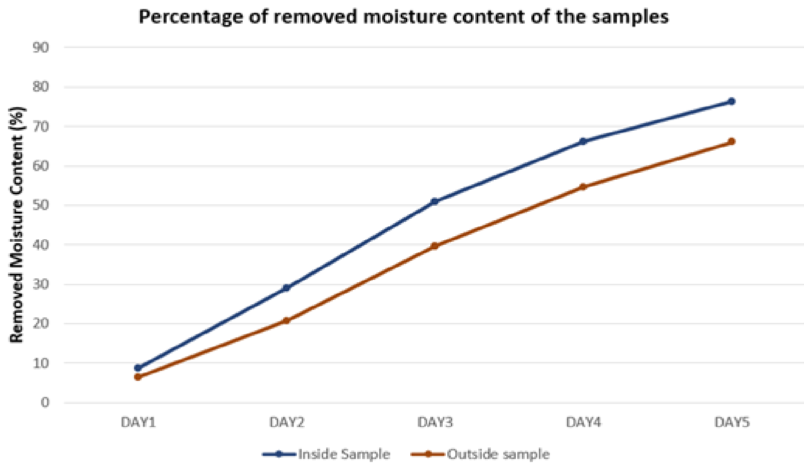

Figure 7. Variations of relative moisture content removed from the samples inside and outside the solar dryer recorded throughout each day over a 5-day period.

Temperature inside the dryer supported this trend,

whereas outside temperatures were lower and showed less pronounced fluctuations due to rapid heat dissipation in the open environment. Relative humidity inside the dryer inversely correlated with temperature, decreasing sharply at midday and rising in the evening, which could be associated with the consistent moisture removal facilitated by higher temperatures. Moisture content in bananas decreased most significantly at midday when solar radiation and temperature peaked, with minimal changes during the evening and early morning. Notably,the third day exhibited dramatic moisturereduction, while the second, fourth, and fifth days showed consistent trends. These findings demonstrate the critical interplay of solar radiation, temperature, and humidity in optimizing drying efficiency. They also highlight the advantages of a solar dryer over ambient drying by providing controlled conditions that enhance moisture removal and reduce drying duration.

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